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Soil penetration resistance under different chiseling intensities and no-tillage with a succession of corn and different winter cover crops[1]

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ABSTRACT - In Brazil, most summer crops are grown under no-tillage (NT), however machine traffic and the unplanned use of crop successions can lead to consolidation or compaction of the soil. The aim of this study was to determine the long-term effects of chiseling and cropping systems on the penetration resistance of an Oxisol. The experiment began in March 2015, and included the following tillage systems: (1) no-tillage; (2) no-tillage with chiseling at the start of the experiment using a five-shank chisel plow (A); (3) no-tillage with chiseling at the start of the experiment using a four-shank chisel plow (B); (4) no-tillage with annual chiseling (2015, 2016, and 2017) using chisel plow A; (5) no-tillage with annual chiseling using chisel plow B. The crops used in succession to the corn were black oats, common vetch, forage radish and mixed crops (black oats + common vetch + forage radish). The soil penetration resistance (PR) decreased in each of the treatments compared to the initial condition of the soil. The chiseling treatments had similar values for PR (Tukey's test, $p > 0.05$), indicating ephemeral changes and reconsolidation of the soil in 6 to 12 months. The 0.10-0.20 m layer had the highest PR, close to the critical limit; however, the higher PR values under NT did not affect grain yield in the corn. In conclusion, there is no need for chiseling the soil under NT when a corn/winter cover-crop succession is adopted for three years.

Key words: Black oats. Common vetch. Forage radish. Chisel plow. Oxisol.

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INTRODUCTION

Sustainable food production with minimal impact on the soil and atmosphere can be achieved by means of conservation tillage practices, including no-tillage and minimal mechanical disturbance of the soil (Busari *et al*., 2015). However, improper management of these systems can lead to soil degradation due to the compaction caused by the traffic of agricultural machinery (Bergamin *et al*., 2015), especially in the subsurface layers of the soil (Domit *et al*., 2014; Girardello *et al*., 2011; Nunes *et al*., 2015b; Seidel *et al*., 2017; Silva *et al*., 2017).

The United States has the largest area under no-tillage in the world (over 35 million ha), followed by Brazil, with around 32 million ha (FAO, 2018). In Brazil, 90% of summer crops (soybean, corn and beans) in the state of Paraná are grown under no-tillage, occupying an area of more than 5 million ha (Federação Brasileira de Plantio Direto e Irrigação, 2014), making no-tillage a consolidated management system among local farmers (Shioga *et al*., 2016).

However, the lack of mechanical soil disturbance or machine traffic threatens the sustainability of this system: depending on the sequence of crops (rotation or succession) the soil in these areas can become consolidated or compacted (Llanillo, 2007). Many farmers have therefore turned to chiseling, an operation that requires a lot of power, fuel and time (Girardello *et al*., 2011), as an additional cropping treatment before seeding, with the aim of increasing the physical quality of the soil and ensuring crop productivity. Nevertheless, research such as Nunes *et al*. (2015b); Seki *et al*. (2015), Drescher *et al*. (2016) and Seidel *et al*. (2018) shows that chiseling promotes ephemeral improvements in the quality of clayey soils depending on the variable being analyzed, and does not necessarily increase crop productivity compared to areas of no-tillage where the practice is not adopted.

Evaluating soil penetration resistance is the best parameter for deciding whether to repeat the chiseling, as it shows the restrictive effect of compaction on root development (Cortez *et al*., 2017; Drescher *et al*., 2016; Seidel *et al*., 2017; Tormena *et al*., 2017). Moraes *et al*. (2014) state that the critical limit for soil penetration resistance of 2 MPa should be maintained under the conventional tillage system, while under a no-tillage system this value should be increased to 3.5 MPa.

Periodic chiseling under no-tillage is unnecessary when the cropping system is based on rotation (Moraes *et al*., 2016), especially when a grain succession system includes forage, which promotes positive changes in the physical properties of the soil due to an increase in the amount of straw and to more-aggressive roots (Seidel *et al*., 2018). Therefore, our hypothesis is that periodic soil chiseling under no-tillage is not necessary when the cropping system is based on a corn/winter cover-crop succession. The aim of this study was to determine the long-term effects of chiseling and cropping systems on the penetration resistance of an Oxisol under no-tillage in the south of Brazil.

MATERIAL AND METHODS

Study site

The study was conducted at the experimental area of the Federal University of Technology of Paraná, in Dois Vizinhos (25º4' S, 53º05'W, altitude 526 m) in the state of Paraná, in the south of Brazil. According to the Köppen classification, the climate in the region is humid subtropical (Cfa), with no defined dry season (Alvares *et al*., 2013) and an annual rainfall of 2000 mm.

The local soil is classified as a Red Latosol (Latossolo Vermelho - Embrapa, 2018), equivalent to an Oxisol (Soil Survey Staff, 1999), with a clayey texture (773 g kg^{-1} clay, 224 g kg^{-1} silt, and 3 g kg^{-1} sand). Before setting up the experiment, the area had been cultivated for about 10 years with soybeans under no-tillage, presenting a soil penetration resistance (PR) greater than 3 MPa across the 0.05-0.20 m layers (Fig. 1a).

Experimental design and treatments

The experiment was set up in March 2015 using a randomized block design in a 5 x 4 factorial arrangement (tillage system x crop succession system) with three replications, totaling 60 plots, each 8 x 10 m in size. The five tillage systems were (1) NT: no-tillage, (2) NT-A-1st year: no-tillage with chiseling before the winter cover crop for the first year (2015) only, using chisel plow A, (3) NT-B-1st year: no-tillage with chiseling before the winter cover crop for the first year (2015) only, using chisel plow B, (4) NT-A-annual: no-tillage with annual chiseling before the winter cover crop (2015, 2016, and 2017), using chisel plow A, (5) NT-B-annual: no-tillage with annual chiseling before the winter cover crop (2015, 2016, and 2017), using chisel plow B. Plow A is equipped with five shanks on two chassis, with a spacing of 0.40 m between the shanks and a working depth of approximately 0.40 m. Plow B is equipped with four shanks on a single chassis, with a spacing of 0.70 m between the shanks and a working depth of approximately 0.50 m, and a ripper-roller.

The four crop successions were: (1) black oats (*Avena strigosa* S.) during the winter and corn (*Zea mays* L.) during the summer, (2) common vetch (*Vicia sativa* L.) during the winter and corn during the summer; (3) forage radish (*Raphanus raphanistrum* L.) during the winter and corn during the summer; (4) mixed crops (black oats + common vetch + forage radish) during the winter and corn during the summer. The winter cover crops were sown in July 2015, May 2016, and May 2017.

Figure 1 - Initial characterization of the soil penetration resistance (a) and soil moisture (b) before setting up the experiment

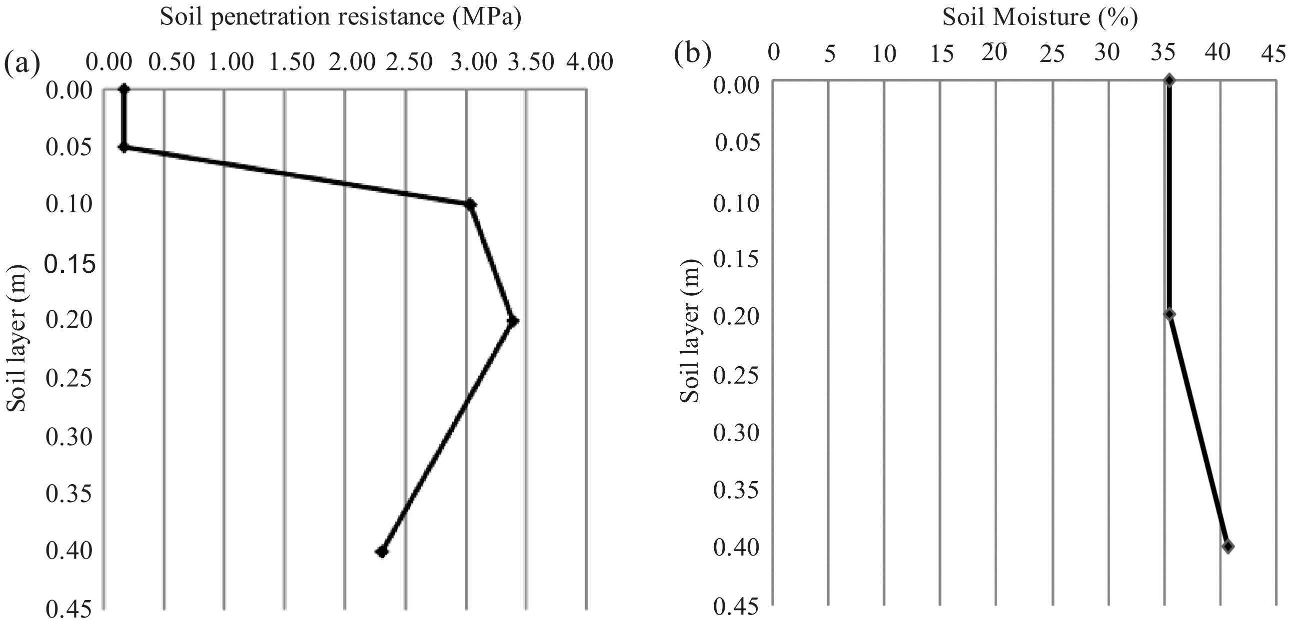


Table 1 - Soil moisture under five tillage systems and four crop successions, in the 0.00-0.20 m and 0.20-0.40 m soil layers, 13, 21, and 31 months after the start of the experiment

Cover crops	Black oats		Common vetch		Forage radish		Mixed (BO+CV+FR)	
Soil layer	0 - 0.2 m	0.2 - 0.4 m	0 - 0.2 m	0.2 - 0.4 m	0 - 0.2 m	0.2 - 0.4 m	0 - 0.2 m	0.2 - 0.4 m
Soil moisture (g kg^{-1}) No-tillage								
13 months	336	342	336	342	336	342	336	342
25 months	367	400	364	388	341	373	357	387
31 months	363	365	340	354	363	366	330	343
CV (%)	5	8	4	7	4	5	4	7
No-tillage – Chiseling with chisel plow A – 1st year								
13 months	345	363	345	363	345	363	345	363
25 months	360	391	357	423	363	429	372	392
31 months	336	332	354	354	306	349	350	377
CV (%)	3	8	2	10	9	11	4	4
No-tillage – Chiseling with chisel plow B – 1st year								
13 months	360	361	360	361	360	361	360	361
25 months	380	394	357	389	363	405	374	416
31 months	371	396	384	387	351	352	317	368
CV (%)	3	5	4	4	2	8	8	8
No-tillage – Chiseling with chisel plow A – annual								
13 months	345	363	345	363	345	363	345	365
25 months	351	397	387	408	368	380	369	395
31 months	358	373	315	364	339	398	355	386
CV (%)	2	5	10	7	4	5	3	4

Continuation Table 1

	No-tillage – Chiseling with chisel plow B – annual							
13 months	360	361	360	361	360	361	360	361
25 months	362	387	358	385	370	396	373	408
31 months	376	367	312	384	339	409	390	378
CV (%)	2	4	8	4	4	6	4	6

CV (%): Coefficient of variance. BO+CV+FR = black oats + common vetch + forage radish

The corn (AG 8780) was sown in September 2015, September 2016, and October 2017 at a spacing of 0.45 m between rows, for a population of 75,000 plants ha^{-1}. When the winter cover plants were at the flowering stage, with maximum biomass accumulation, the area was desiccated with 2.5 L ha^{-1} glyphosate. Nitrogen fertilizer was applied in a single dose of 180 kg N ha^{-1} via urea when the corn was at the vegetative stage (V4).

Soil sampling

The soil penetration resistance (PR) was measured in May 2016 (before the second chiseling), in April 2017 (before the third chiseling) and in November 2017 (seven months after the third chiseling), using a PenetroLOG (Falker®) digital penetrometer with data storage; this has a conical tip of 30º and an area of 129 mm^2. Evaluations were made every 0.01 m to the maximum depth of 0.40 m. For the PR data, the mean values of the 0.00-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.40 m layers were used, while for the soil moisture data, we used the mean values of the 0.00-0.20 and 0.20-0.40 m layers, as shown in Table 1.

Sampling the plants

In September 2016, the dry biomass of the winter cover crops was determined at two representative points in each plot with the aid of a metal frame of 0.25 m^2. In December 2016, the dry biomass of the corn was determined by collecting five random plants from each plot. These were dried in a forced air circulation oven at around 55 °C for 72 h to constant weight.

In February 2017, the corn yield was determined by manually harvesting the cobs in five linear meters of two rows in each plot. The cobs were then threshed using a stationary thresher and the yields adjusted to a reference humidity of 13%.

Statistical data analysis

The data for each layer (0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-40 m) were separately submitted to analysis of variance (F-test, $p < 0.05$). When the effects of the treatments were significant, the mean values were compared by Tukey's test ($p < 0.05$). The data analysis was carried out using the Sigmaplot statistical software.

RESULTS AND DISCUSSION

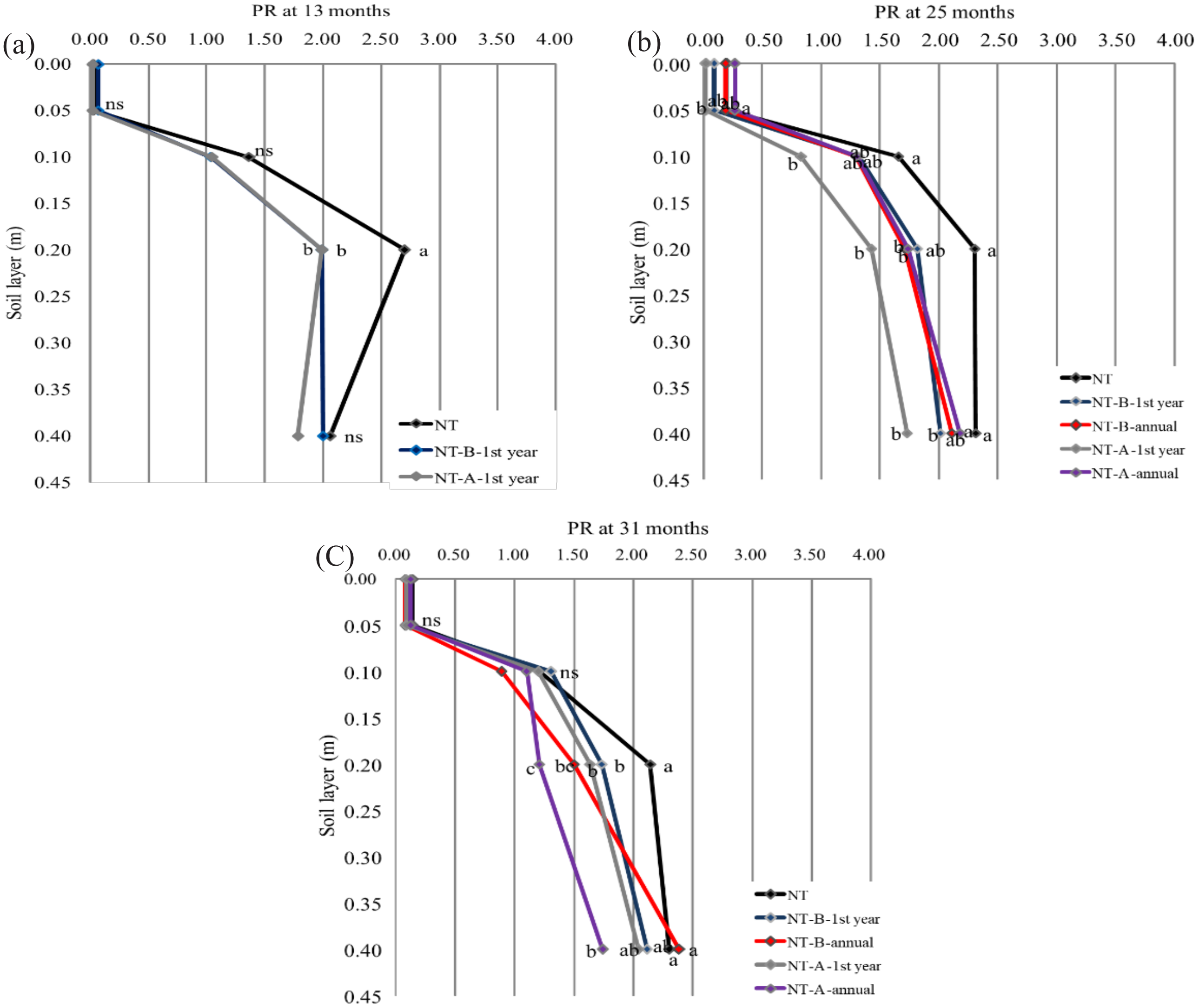
Corn/Black Oats Succession

After 13 months, the only significant differences in PR between the treatments were in the 0.10-0.20 m layer (Fig. 2a), where NT had the highest value (2.10 MPa) compared to NT-A-1st year (1.99 MPa) and NT-B-1st year (1.99 MPa). Values less than 0.50 MPa and 1.50 MPa were seen in the 0.00-0.05 and 0.05-0.10 m layers, respectively, regardless of the treatment, while in 0.20-0.40 m layer the PR values were close to 2 MPa.

At 25 months, there were still significant differences in PR between the treatments, albeit in all of the layers under evaluation (Fig. 2b). As seen at 13 months, each of the treatments continued to show a PR of less than 0.50 MPa in the 0.00-0.05 m layer and less than 1.50 MPa in the 0.05-0.10 m layer, except NT, which had a PR of 1.69 MPa. In the 0.10-0.20 m layer, NT continued to have the highest PR (2.30 MPa) compared to NT-B-annual (1.73 MPa) and NT-A-annual (1.71 MPa), as well as to NT-A-1st year (1.42 MPa), while in the 0.20-0.40 m layer, PR values remained close to 2 MPa (Fig. 2b), as seen at 13 months (Fig. 2a). However, in this last layer, NT and NT-B-annual showed a higher PR (2.31 and 2.18 MPa, respectively) compared to NT-B-1st year (2.01 MPa) and NT-A-1st year (1.72 MPa).

Seven months after the third chiseling (31 months after the start of the experiment) we found that there were no significant differences between the treatments to a depth of 0.10 m (Fig. 2c). The 0.00-0.05 and 0.05-0.10 m layers continued to have PR values below 0.50 MPa and 1.50 MPa regardless of the treatment, as seen after 13 and 25 months (Figs. 2a and 2b, respectively). In the 0.10-0.20 m layer, NT continued to show the highest value for PR (2.14 MPa), while in 0.20-0.40 m layer, the PR values remained close to 2 MPa (Fig. 2c); similar behavior was seen after 13 and 25 months of evaluation (Figs. 2a and 2b, respectively). In the last layer, NT-B-annual and NT presented the highest PR values (2.39 and 2.31 MPa, respectively) compared to NT-A-annual (1.74 MPa).

Figure 2 - Soil penetration resistance (PR) under the corn/black oats succession and different tillage systems, 13 (a), 25 (b), and 31 (c) months after the start of the experiment. Mean values followed by the same letter within a soil layer do not differ significantly by Tukey's test ($p < 0.05$)



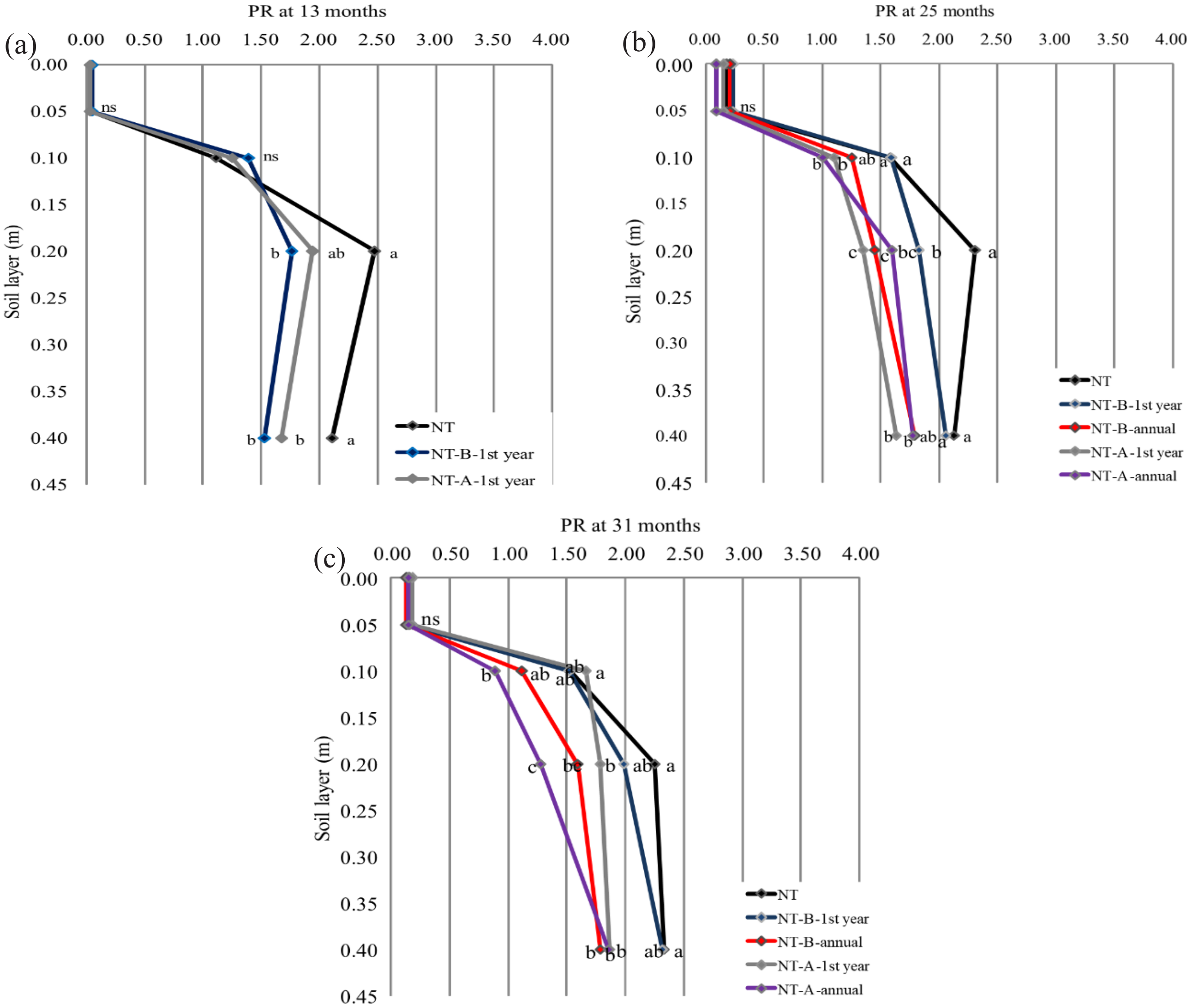
Corn/Common Vetch Succession

At 13 months, PR showed no significant differences between treatments to a depth of 0.10 m (Fig. 3a). Nevertheless, we found respective PR values of less than 0.50 MPa and 1.50 MPa in the 0.00-0.05 and 0.05-0.10 m layers. On the other hand, in the 0.10-0.20 and 0.20-0.40 m layers, NT had the highest PR values (2.48 and 2.11 MPa, respectively) compared to NT-B-1st year (1.76 MPa), NT-A-1st year (1.67 MPa) and NT-B-1st year (1.53 MPa) (Fig. 3a).

After 25 months, PR in the 0.00-0.05 m layer continued to be less than 0.50 MPa, with no difference between the treatments (Fig. 3b), as seen at 13 months. In the 0.05-0.10 m layer NT-B-1st year and NT showed the highest PR (1.59 and 1.57 MPa, respectively) compared to NT-A-1st year (1.10 MPa) and NT-A-annual (1 MPa), while in the 0.10-0.20 m layer NT showed the highest PR (2.30 MPa). In the 0.20-0.40 m layer NT and NT-B-1st year presented the highest respective PR (2.13 and 2.05 MPa) compared to NT-B-annual (1.77 MPa) and NT-A-1st year (1.63 MPa), as shown in Fig. 3b.

Seven months after the third chiseling (31 months after the start of the experiment), PR in the 0.00-0.05 m remained under 0.50 MPa, with no differences between the treatments (Fig. 3c), as seen at 13 months (Fig. 3a) and 25 months (Fig. 3b). In the 0.05-0.10 m layer, PR under NT-A-1st year (1.67 MPa) was greater than under NT-A-annual (0.89 MPa), while in the 0.10-0.20 and 0.20-0.40 m layers, NT showed the highest PR (2.26 and 2.34 MPa, respectively) compared to all the treatments, except for NT-B-1st year (Fig. 3c).

Figure 3 - Soil penetration resistance (PR) under the corn/common vetch succession and different tillage systems, 13 (a), 25 (b), and 31 (c) months after the start of the experiment. Mean values followed by the same letter within a soil layer do not differ significantly by Tukey's test ($p < 0.05$)



Corn/Forage Radish Succession

At 13 months, PR showed no significant differences between treatments in the 0.00-0.05 and 0.20-0.40 m layers, with values less than 0.50 MPa and close to 2 MPa, respectively (Fig. 4a). In the 0.05-0.10 and 0.10-0.20 m layers, NT presented the highest PR (1.82 and 2.68 MPa, respectively) compared to NT-A-1st year (0.75 and 1.79 MPa) and NT-B-1st year (0.76 and 1.57 MPa).

After 25 months, there were significant differences in PR between the treatments in each soil layer under evaluation (Fig. 4b). As seen at 13 months (Fig. 4a), all the treatments continued to have a PR of less than 0.50 MPa in the 0.00-0.05 m layer, whereas in the 0.05-0.10 m layer, the chiseling treatments continued to have a PR of less than 1.50 MPa, particularly NT-A-annual and NT-B-annual which had a lower PR (1.14 and 1.06 MPa, respectively) than did NT (1.54 MPa). In the 0.10-0.20 m layer, as seen at 13 months, NT continued to have the highest PR (2.39 MPa) compared to NT-B-annual (1.45 MPa), T-A-annual (1.61 MPa) and NT-A-1st year (1.67 MPa), while in the 0.20-0.40 m layer the PR values remained close to 2 MPa. However, in the 0.20-0.40 m layer, NT and NT-B-1st year had a higher respective PR (2.39 and 2.09 MPa) compared to NT-B-annual (1.68 MPa), as shown in Fig. 4b.

Seven months after the third chiseling (31 months after the start of the experiment), PR values remained below 0.50 MPa in the 0.00-0.05 m layer regardless of the treatment. Whereas in the 0.05-0.10 m layer, NT-A-annual and NT-B-annual presented the lowest PR values (less than 1 MPa) compared to NT (1.68 MPa) and to NT-A-1st year (1.63 MPa), as shown in Fig. 4c. In the 0.20-0.40 m layer (Figs. 4a and 4b, respectively), as we saw at 13 and 25 months, NT continued to have the highest PR value (2.34 MPa) compared to NT-A-annual (1.40 MPa) and to NT-B-annual (1.31 MPa). On the other hand, in the 0.20-0.40 m layer, NT and NT-B-1st year showed the highest respective PR value (2.35 and 2.58 MPa) compared to NT-A-annual (1.82 MPa) and to NT-A-1st year (1.92 MPa).

Corn/Mixed Crop Succession

After 13 months, the PR showed a significant difference in the 0.00-0.05 and 0.10-0.20 m layers only (Fig. 5a). In both layers, NT had the highest PR compared to all the chiseling treatments; however, in the first layer, the PR was less than 0.50 MPa, while in the 0.10-0.20 m layer, it was close to 3 MPa (Fig. 5a).

At 25 months, the PR showed significant differences between the treatments in the layers below 0.10 m only. It should be noted that in the 0.00-0.05 and 0.05-0.10 m layers, the PR remained below 0.50 MPa and 1.50 MPa, respectively (Fig. 5b); similar results were seen at 13 months (Fig. 5a). In the 0.10-0.20 m layer, NT continued to have the highest PR (2.38 MPa) compared to NT-B-annual (1.58 MPa) and to NT-A-annual (1.71 MPa), showing no difference to NT-B-1st year or NT-A-1st year (Fig. 5b). While in the deepest layer, NT-A-annual and NT-B-1st year showed the highest respective PR (2.61 and 2.09 MPa) compared to NT-B-annual (1.71 MPa).

Figure 4 - Soil penetration resistance (PR) under the corn/forage radish succession and different tillage systems, 13 (a), 25 (b), and 31 (c) months after the start of the experiment. Mean values followed by the same letter within a soil layer do not differ significantly by Tukey's test ($p < 0.05$)

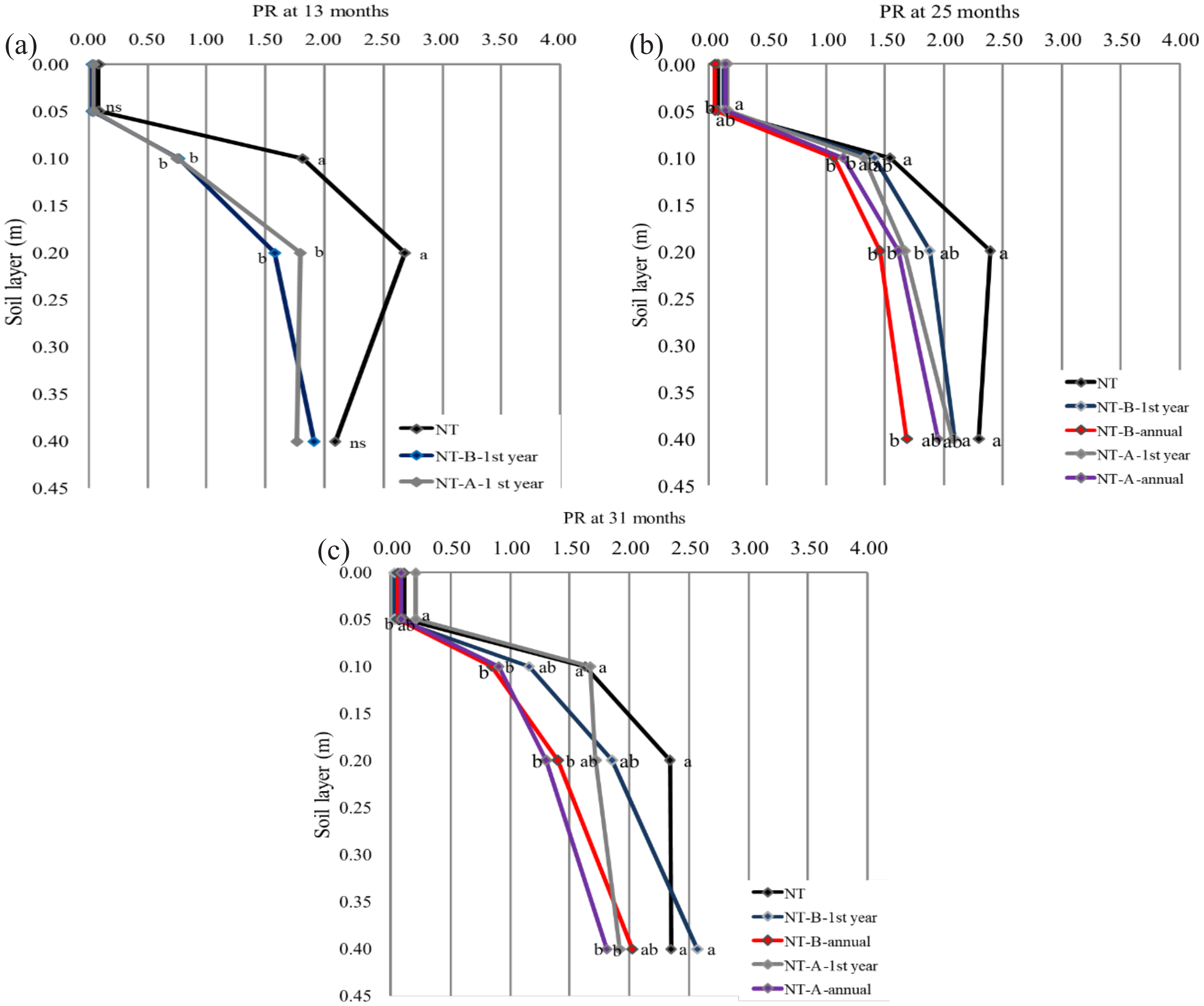


Figure 5 - Soil penetration resistance (PR) under the corn/mixed crop succession and different tillage systems, 13 (a), 25 (b), and 31 (c) months after the start of the experiment. Mean values followed by the same letter within a soil layer do not differ significantly by Tukey's test ($p < 0.05$)

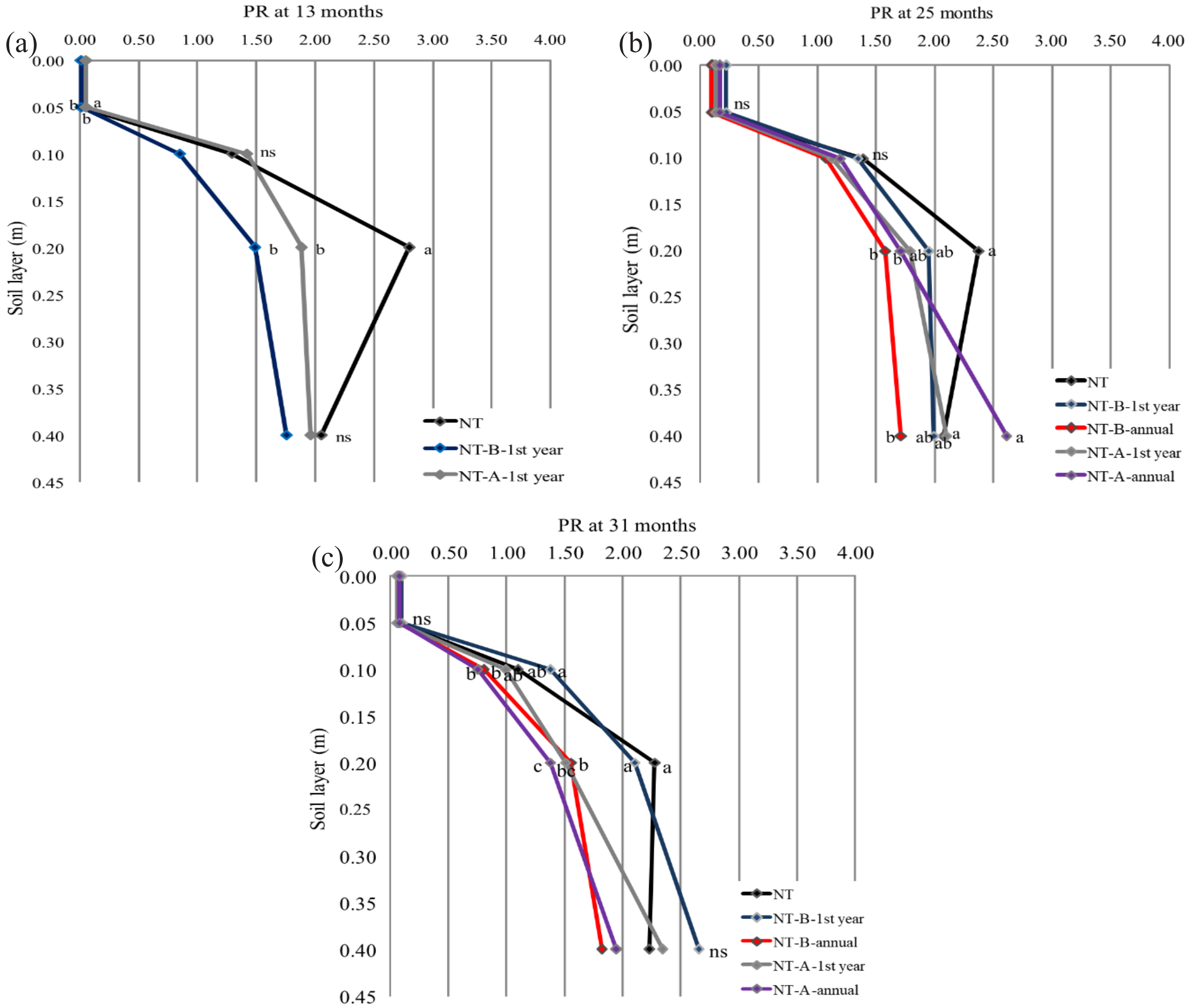


Table 2 - Dry biomass of the winter cover crops and corn, and corn grain yield, under five tillage systems and four crop successions for 2016/2017

	Winter cover crops				
	Black oats	Common vetch	Forage radish	Mixed (BO + CV + FR)	
	Dry biomass of winter cover crops (Mg ha^{-1})				
Tillage system					Mean value
NT	5.1 ± 0.5	2.5 ± 0.7	2.1 ± 1.2	4.6 ± 1.6	3.6^{ns}
NT-A-1st year	5.8 ± 0.9	2.4 ± 0.8	2.5 ± 0.4	5.6 ± 1.7	4.1
NT-B-1st year	6.7 ± 3.3	3.8 ± 2.4	2.5 ± 0.2	4.4 ± 1.1	4.4
NT-A-annual	5.4 ± 1.9	2.3 ± 0.5	3.0 ± 0.9	5.3 ± 1.4	4.0
NT-B-annual	7.2 ± 0.5	2.5 ± 0.4	4.7 ± 2.2	5.7 ± 1.8	5.0
Mean value	6.0 a	2.7 b	3.0 b	5.1 a	

Continuation Table 2

Corn dry biomass (Mg ha^{-1})					
Tillage system					Mean value
NT	13.7 ± 0.7	12.5 ± 1.0	14.2 ± 2.4	17.1 ± 3.6	14.4^{ns}
NT-A-1st year	14.2 ± 2.4	11.8 ± 1.5	12.0 ± 1.7	14.3 ± 1.1	13.1
NT-B-1st year	12.5 ± 2.3	15.2 ± 2.4	12.6 ± 3.5	16.8 ± 3.0	14.3
NT-A-annual	11.7 ± 3.0	13.6 ± 0.6	15.0 ± 3.5	13.7 ± 4.3	13.5
NT-B-annual	12.5 ± 1.8	12.5 ± 2.8	11.8 ± 0.7	11.9 ± 1.3	12.2
Mean value	12.9^{ns}	13.1	13.1	14.8	
Corn grain yield (Mg ha^{-1})					
Tillage system					Mean value
NT	12.6 ± 1.6	13.5 ± 1.0	13.2 ± 0.5	12.2 ± 3.0	12.9 a
NT-A-1st year	10.3 ± 0.1	11.3 ± 0.9	10.3 ± 0.1	10.3 ± 1.8	10.6 c
NT-B-1st year	10.8 ± 0.5	9.9 ± 0.9	11.0 ± 0.8	10.3 ± 0.1	10.5 bc
NT-A-annual	12.6 ± 1.0	11.6 ± 0.5	11.3 ± 1.7	10.8 ± 1.5	11.6 abc
NT-B- annual	12.4 ± 1.1	12.7 ± 1.7	11.4 ± 2.4	12.0 ± 1.6	12.1 abc
Means value	11.7^{ns}	11.8	11.4	11.1	

Mean values followed by the same letter do not differ significantly by Tukey's test ($p < 0.05$). ns: not significant by F-test ($p < 0.05$). ± Standard deviation. BO + CV + FR = black oats + common vetch + forage radish

Seven months after the third chiseling (31 months after the start of the experiment), there was no difference between the 0.00-0.05 and 0.20-0.40 m layers. On the other hand, in the 0.05-0.10 m layer, NT-B-1st year had the highest PR (1.38 MPa) compared to NT-A-annual (0.78 MPa) and NT-B-annual (0.81 MPa), while in the 0.10-0.20 m layer, NT and NT-B-1st year had the highest PR (2.28 and 2.11 MPa, respectively) (Fig. 5c).

Plant parameters

The tillage systems had no effect on dry matter production for either the winter cover crops or the corn in succession (Table 2). However, corn grain yield was higher under NT (12.9 Mg ha^{-1}) compared to NT-B-1st year and NT-A-1st year (10.5 and 10.6 Mg ha^{-1}, respectively). The succession only affected dry biomass production in the winter cover crops, where the black oats and mixed crops had the highest production, of 6.0 and 5.1 Mg ha^{-1}, respectively (Table 2).

Effect of different chiseling intensities and cover crops in soil PR

The greater PR values to a depth of 0.20 m before the start of the experiment (Fig. 1a) are a consequence of the intensity of machine traffic over the years, as also observed by Nunes *et al*. (2015b) and Cortez *et al*. (2017) in a clayey Oxisol under soybean NT. However, under similar conditions of soil moisture (Table 1), we found that after 13 months of corn/winter cover-crop succession with no chiseling (NT), PR values were reduced to around 42% in the 0.05-0.20 m layer (Figs. 2a-5a). This result is in line with that of Calonego *et al*. (2017), who found that aggressive and vigorous roots quickly improved the physical quality of compacted clay soils under NT.

The lowest PR values found in the topsoil (of less than 0.50 MPa), regardless of the system or period (Figures 2-5), are evidence of the positive effect of the winter cover crop and corn dry biomass accumulated on the soil surface (Table 2), which may have dissipated the pressure of the machine traffic (Domit *et al*., 2014; Tormena *et al*., 2017), together with mobilization of the soil, the result of repeated sowing after each harvest (Drescher *et al*., 2016; Nunes *et al*., 2015b).

Cruz *et al*. (2006) state that in tropical soils, an efficient no-tillage system requires the permanent maintenance of dry biomass, which should never be less than 2 Mg ha^{-1}. In our study, the black oats and mixed crops (oat, radish, and vetch) had the highest dry biomass, greater than 5 Mg ha^{-1} (Table 2), showing the particular potential of black oats for protecting the soil and reducing erosion (Pittelkow *et al*., 2015), and for adding more carbon to the agroecosystem (Inagaki *et al*., 2021), ensuring a more robust functioning of the soil ecosystem (Vezzani *et al*., 2018). Cover crops are an important tool in soil management, as shown by Inagaki *et al*. (2021), who demonstrated the positive effects of the forage radish, such as an increase in the stocks of soil organic carbon, in root development, and in cumulative crop yield, making it a suitable option to replace mechanical chiseling in long-term no-tillage.

Reichert *et al.* (2015), in a laboratory trial to investigate the amount of crop residue, found that 12 Mg ha^{-1} corn residue on the surface of the soil can reduce compaction at a depth of 0.20 m. In our study, there was approximately 13 Mg ha^{-1} corn dry biomass (Table 2), which may have reduced the PR in the layers below 0.00-0.05 m, as discussed below.

Under similar conditions of soil moisture (Table 1), we found PR values of less than 1.50 MPa in the 0.05 - 0.10 m layer in most of the treatments regardless of the period. Compared to the initial characterization, when the PR in this layer was 3.04 MPa (Fig. 1a), we saw a reduction of more than 50% in PR values after 13 months (Figs. 2a-5a), except for NT under the Corn/ Forage Radish succession, which showed a reduction of 40% (Fig. 4a). This reduction remained close to or greater than 50% in subsequent evaluations, i.e. after 25 and 31 months, once again highlighting the positive effect of adding large amounts of dry biomass to the soil surface, as noted above, which minimized the compressive effect of traffic at depth. According to studies by Nunes *et al.* (2015b), Costa *et al.* (2016), Calonego *et al.* (2017) and Silva *et al.* (2017), the reduction in PR values is also linked to this layer of the soil (0.05 - 0.10 m), which has the highest root colonization for both winter cover crops and corn.

However, when analyzing the chiseling treatments, we found that when chiseling was carried out in 2015 only (NT-A-1st year and NT-B-1st year), the PR was similar to when chiseling was repeated in both 2016 and 2017 (NT-A-annual and NT-B-annual), indicating reconsolidation of the soil in the 0.05-0.10 m layer over a period of 6 to 12 months. Similar results, related to ephemeral changes in the physical quality of clayey soils under NT with chiseling, were found by Girardello *et al.* (2011); Moraes *et al.* (2014), Nunes *et al.* (2015a), Nunes *et al.* (2015b) and Drescher *et al.* (2016).

According to the initial characterization (Fig. 1a), the 0.10-0.20 m layer presented the closest PR to the critical limit. This was expected because, in general, this layer of soil tends to have a higher degree of compaction under NT (Girardello *et al.*, 2017). The chiseling treatments showed the greatest differences compared to NT, especially at 13 months, when the treatments that included the use of chisel plow A or B afforded a reduction in PR values equal to or greater than 40% regardless of the succession system, while NT resulted in a reduction of 17% to 27% (Figs. 2a-5a).

The smaller reduction in PR under NT may be due to the short time between successions promoting improvements in the soil, and to the lesser root development of the plants used in the successions, especially corn, which tends to concentrate only 17% to 27% of its roots in the 0.10-0.20 m layer (Nunes *et al.*, 2015b). Nevertheless, the later evaluations showed that each of the succession systems continued to promote a reduction in PR under NT; these were equal to or greater than 30% at 25 months, whereas in the chiseling treatments, both chiseling in the first year (NT-A-1st year and NT-B-1st year) and repeated chiseling every year (NT-A-annual and NT-B-annual) maintained a reduction of over 40% (Figs. 2b-5b).

In the 0.20-0.40 m layer, the PR values of the treatments generally remained close to or slightly above 2 MPa regardless of the period (Figs. 2-5). However, compared to the initial characterization (Fig. 1a), after 31 months under NT the PR was almost unchanged regardless of the succession system. The results of the chiseling treatments were noticeably different, i.e. for the majority of succession systems, of the treatments that included chiseling in the first year (NT-A-1st year and NT-B-1st year), only those that used plow A showed a reduction in PR values (between 12% and 19%), while for those that used plow B, the values increased from 12% to 17%. This result shows soil reconsolidation at depth when a chisel plow with shanks spaced at a greater distance (0.70 m) is used, implying less soil disturbance and transference of the load to greater depths, in line with the findings of Girardello *et al.* (2011). On the other hand, in the treatments with annual chiseling (NT-A-annual and NT-B-annual), PR values were reduced by between 12% and 26%, regardless of the type of chisel plow (Figs. 2c-5c). Despite this, in most of the soil layers, there was no difference between chisel plows A and B for most of the cropping systems or periods under evaluation, agreeing in part with the observations of Seidel *et al.* (2018).

Finally, the higher PR values under NT had no effect on corn grain yield, which had the highest production compared to chiseling in the first year (Table 2). Seki *et al.* (2015) and Nunes *et al.* (2015b) agree that PR values in both NT and NT with chiseling did not restrict crop development. Our study therefore confirms the work of Moraes *et al.* (2016), who found that the critical limit for PR in a clayey soil under the NT system is up to 3.5 MPa, regardless of the succession system adopted.

In addition, chiseling increased production costs and the susceptibility to soil compaction due to increased machine traffic, with no improvements in soil penetration resistance in the long term. More importantly, the use of chiseling as a common practice might complicate establishment of a no-tillage system with its well-known benefits.

CONCLUSIONS

1. Our study shows that soil chiseling is unnecessary under NT when a corn/winter cover-crop succession is adopted over three years. However, if chiseling is needed, it should be carried out before the succession system is adopted, due to the benefits from the roots in maintaining and improving penetration resistance;
2. Among the winter cover crops used in succession with corn, both black oats and mixed crops (black oat + common vetch + forage radish) are recommended, since these had the highest dry biomass production, and guaranteed improvements in the physical quality of the soil under NT.

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