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Maize Yield and Soil Penetration Resistance in Different Soil Tillage and Cover Crop Systems

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HIGHLIGHTS

- Mix and oats showed the highest biomass production
- Soil tillage and winter cover crops did not change maize yield
- No-tillage had the highest soil penetration resistance in 0.10-0.20 m soil layer
- Soil chiseling reduced soil penetration resistance but did not increase crop yield

Abstract: No-tillage (NT) is a conservation practice adopted by 60% of the Brazilian farmers. Due to unsuitable management, compaction problem reported in soils under NT has increased. The study aimed to evaluate the influence of different soil tillage and different winter cover crops in long-term on crops biomass and maize yield and on soil penetration resistance (PR), in two crop seasons. The long-term experiment is located at the UTFPR Dois Vizinhos experimental station, with a combination of five soil tillage: NT; NT chiseled up to 0.35 m deep (Jumbo), annually (NTCa) and triennially (NTCt); NT with minimum tillage chiseled up to 0.35 m deep (Terrus), annually (NTMTa) and triennially (NTMTt); and four winter cover crops: black oats, common vetch, forage radish, and a mixture of oats + vetch + radish (mix). Dry matter production of cover crops was higher in oats and the mix, and in NTMTa in both years (2021 and 2022). Soil chiseling reduces PR, however over time, an increase was observed. NT showed higher PR, especially in the 0.15-0.20 m soil layer, but it did not impact crop production. Maize yield was not influenced by cover crops or soil tillage. NT proved to be the most efficient soil management, as its performance in maize yield was similar to the others, indicating the way forward in the pursuit of a more sustainable agriculture.

Keywords: *Zea mays* L.; no-tillage; chiseling; soil management.

INTRODUCTION

The success of any crop involves knowledge and study of the characteristics of soil and climate, as well as using conservation practices, such as no-tillage (NT) [1], which recommends crop rotation, minimal soil disturbance and permanent soil covering [2]. NT is adopted by 60% of grain farmers in Brazil [1], and has been consolidated as a path to be followed in agriculture, as it reduces the contamination risk of water sources by reducing surface water runoff, increases productivity, resulting in economy inputs due to nutrient cycling in the system, and also provides environmental preservation due to the carbon sequestration from the atmosphere [3]. Combined with NT, the use of cover crops increases the NT benefits to the soil and crop productivity, such as nutrient cycling, decrease in soil temperature and water loss due to evaporation, increase in aggregates stability and in formation of biopores due to their root system, and in soil organic matter stock [4].

Among the crops impacted by soil management, worldwide, maize is the most produced cereal worldwide, with great importance in the Brazilian agribusiness for generating employment all over the country [5], it also has several uses and applications [6]. Brazilian average yield of maize grains in the 2022/23 summer crop, was 6.15 Mg ha^{-1} according to [7], highlighting the state of Paraná yield with averages over 9.9 Mg ha^{-1} [8].

However, when the management of the production system is not adequate, with insufficient straw input to the soil and lack of crop rotation, the soil structure can be compromised by the soil compaction [9]. The characterization of soil compaction is based on an increase in soil mass and a reduction in the pore space, resulting from the history of excess pressure loads [10], becoming a limiting factor for plant growth [9]. Soil compaction causes an increase in soil density and soil resistance to root penetration and a decrease in pore space and soil water infiltration [11]. In this way, there is a concentration of roots in superficial soil layers [12], limiting root development, decreasing the absorption of water and nutrients [12,13], and consequently crop yield [14]. In the maize crop, soil compaction changes the initial development, reducing the number of leaves, and consequently the shoot and root dry matter from 25 to 100% of its capacity [15]. The shoot and root development are similarly compromised by soil compaction [12,13]. The adoption of mechanical soil chiseling has increased in areas managed using NT since this is an alternative operation with immediate results, to reduce the compacted layer by 0.10-0.25 m [16], which increases soil infiltration and porosity. However, it might also expose the soil and accelerate the organic matter decomposition process [17], due to the mobilization occurring on the surface cover crop.

The term 'chiseled no-tillage' (CNT) was employed by [18] to name the treatment in which the intervention was carried out with a chiseler up to 0.25 m depth in NT. Although the definition of 'chiseling' is 'the operation that promotes decompaction up to 0.35 m depth', while interventions in the compacted layer deeper than 0.35 m are called subsoiling, these two terms have been used interchangeably in the literature. In this study, the intervention was limited to 0.35 m depth, for this reason, we opted for the use of the term chiseling to describe the mechanical intervention practices carried out, since this term is commonly found in the literature, as observed in [17,19,20].

There is a lack of work that investigates forms of soil tillage and the use of sustainable methods, such as the use of cover crops in the soil structure [21]. Seeking to elucidate ways to reduce soil compaction in no-tillage, this study aimed to evaluate the influence of different soil tillage and different winter cover crops in long-term on the crops biomass and yield production and soil penetration resistance, in two crop seasons. The hypothesis raised is that NT will present greater soil penetration resistance compared to other tillage, but it is not critical to the development of cover crops and maize yield, and the cover crops with greater species diversity promotes a reduction in the soil penetration resistance over the long term.

MATERIAL AND METHODS

Experimental area description

The study was carried out at the experimental area of the Federal Technological University of Paraná, in Dois Vizinhos, Paraná State, Brazil (25° 42' 52" S and 53° 03' 94" O, 520 m altitude), during the 2021/22 and 2022/23 crop years. According to the Köppen's classification, the regional climate is Cfa (humid subtropical) [22], with 2,010 mm mean annual rainfall [23]. The local soil is *Latossolo Vermelho* with clayey texture [24], by SiBCS [25], equivalent to Oxisol by Soil Taxonomy [26]. The initial soil resistance penetration was 0.2, 3.0, 3.8, 3.2, 3.0, and 1.9 MPa for 0.00-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.30, and 0.30-0.40 m soil layers, respectively. The rainfall occurrence and distribution throughout the evaluation years in this study are shown below (Figure 1).

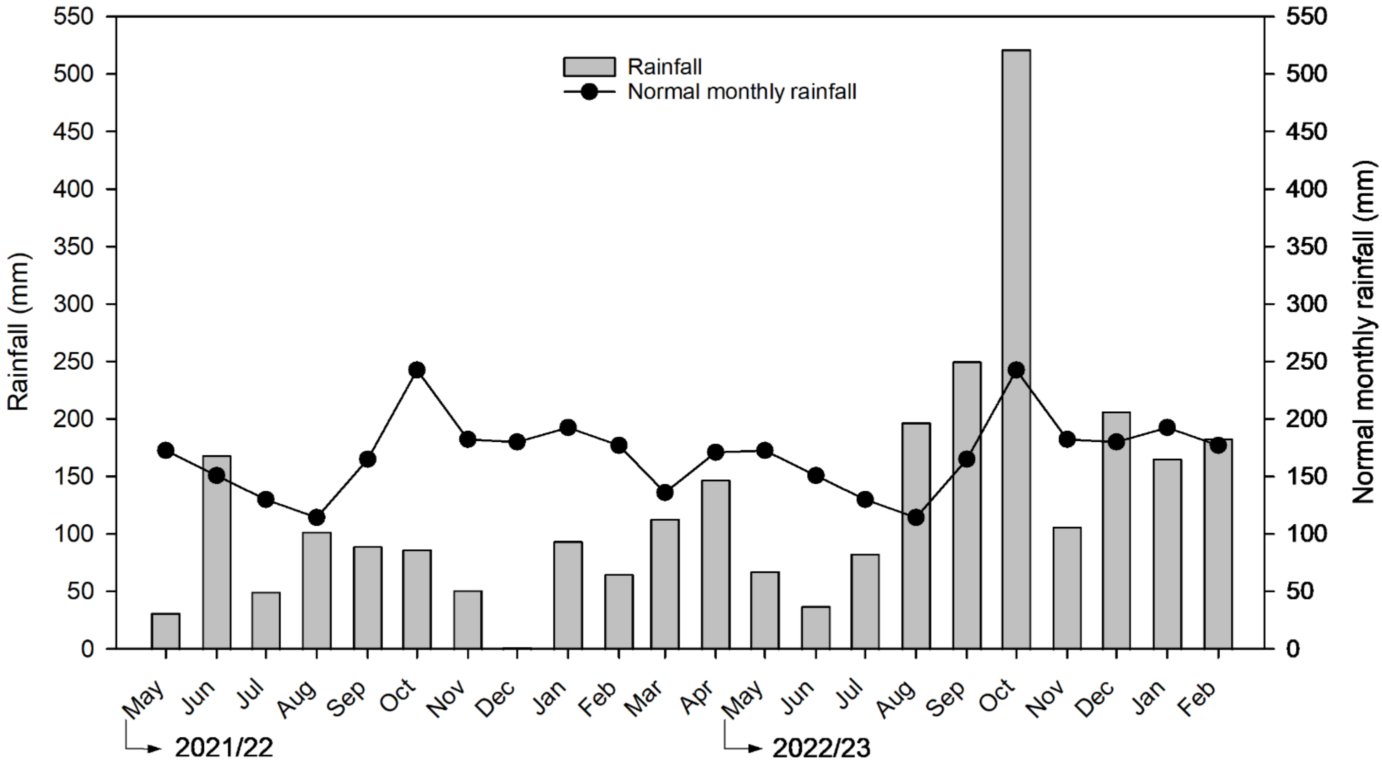

Figure 1. Monthly and climatological rainfall in the 2021/22 and 2022/23 crop seasons.
Source: INMET, National Meteorology Institute [27]; GEBIOMET: Biometeorology Group of Studies [28].

Treatments and Experimental Design

The long-term experiment started in 2015 and comprised five treatments with different soil tillage: no-tillage (NT); NT chiseled with a chisel up to 0.35 m deep and 0.40 m distance between shanks (Jumbo), annually (NTCa) and triennially (NTCt); NT with minimum tillage chiseled with a chisel up to 0.35 m deep and 0.7 m space between shanks (Terrus), annually (NTMTa) and triennially (NTMTt). Since 2021, the interval adopted for the NTMTa was 2 years, with chiseling in 2021 and in 2023 (Figure 2).

The crop succession used in the experiment included winter cover crops, followed by maize (*Zea mays* L.) in summer, and buckwheat (*Fagopyrum esculentum* Moench.) in autumn since 2019 crop season (Figure 2). Also, four treatments of winter cover crops were used, as follows: black oats (*Avena strigosa* Schreb.) BRS 139, common vetch (*Vicia sativa* L.) Ametista, forage radish (*Raphanus sativus* L.) IPR 116, and a mixture of oat + vetch + radish (mix). The experimental design was randomized blocks, in a factorial scheme, with three replications, and plots with dimensions of 5x8 m and an area of 40 m^2. In the 2021/22 and 2022/23 crop seasons, the cover crops were mechanically sowed at the end of May, with 0.17 m space between rows. Sowing density was 90, 40, and 15 kg ha^{-1}, considering black oats, vetch, radish, respectively, following the cultivar recommendation. The mix was sown with a density of 60 kg ha^{-1} and a seed proportion of 60% oats + 30% vetch + 10% radish. Cover crops did not receive any base or topdressing soil fertilization. At the end of the cycle, approximately 105 days, all the plants were rolled and desiccated with glyphosate.

In the 2021/22 crop season, the maize sown was the B2688PWU hybrid, while in the 2022/23 crop season, the BM 812 PRO3 hybrid was sown, both with 0.45 m space between rows and in mid September. For the base fertilization, it was used N-P-K fertilizer with 2-18-18 and rate of 575 kg ha^{-1} (11.5 kg N, 103.5 kg P_2O_5, and 103.5 K_2O) and topdressing fertilization using a N rate of 180 kg ha^{-1}, via 45% N urea, in the mid October, corresponding to the V3 phase of the maize for both crop years. Fertilization recommendation was determined with an expected maize grain yield of 9 Mg ha^{-1} [29]. About phytosanitary management, monitoring was realized regarding weeds, pests, and diseases. Only one application of herbicide was necessary for the 2021/22 crop season, and one insecticide application to control the leafhopper (*Dalbulus maidis*) in both years.

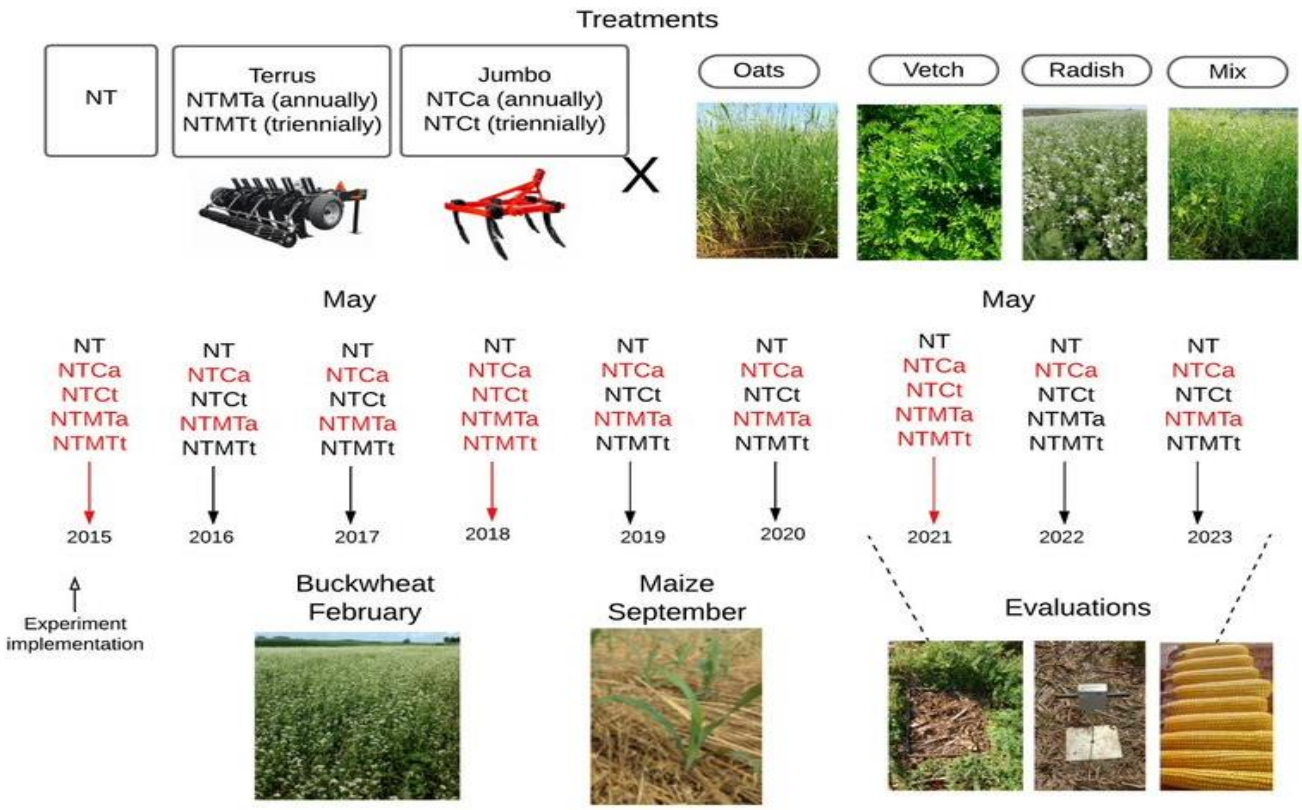

Figure 2. Diagram of the experimental characterization. NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially. Treatments in red indicate the presence and in black the absence of the soil tillage operation in the respective year.

Determination of winter cover crops dry biomass was at the beginning of September in both years, by using a 0.25 m^2 metallic frame and cutting all plants at the soil level, at a random point in each plot. Biomass samples were dried in forced-air circulation oven at 55 °C until constant weight (48-72 h) to determine the dry biomass production (DM).

Soil penetration resistance (PR), in each crop season, was determined at the end of the winter cover crops cycle (early September) and soon after the maize harvesting (early March), when the soil moisture was close to the field capacity. The equipment used was a digital penetrometer, PenetroLOG model by Falker®, equipped with a 30º conic tip and 129 mm^2 cone area, following the ASAE S313.3 norms. Measurements were performed at each 0.01 m, up to 0.40 m deep, at four points per plot to provide area representativeness. For data presentation, the PR values were grouped into six soil layers, namely, 0.0 to 0.05 m; 0.05-0.10 m; 0.10-0.15 m; 0.15-0.20 m; 0.20-0.30 m, and 0.30-0.40 m.

Gravimetric moisture for the 0.0-0.20 and 0.20-0.40 m soil layers was 0.32 and 0.37 g g^{-1}, respectively, in 2021, and 0.30 and 0.35 g g^{-1} in 2022, in the evaluations after the winter cover crops season. While, after the maize harvest, the gravimetric moisture, for the 0.0-0.20 and 0.20-0.40 m soil layers, respectively, was 0.33 and 0.37 g g^{-1} in 2021/22, and 0.33 and 0.35 g g^{-1} in 2022/23.

Maize yield was assessed by the harvest of maize ears in six linear meters, and the grains were weighted and corrected to the standard moisture of 13%, to reach the final yield, extrapolated to one hectare.

Statistical analysis

Data were submitted to analysis of variance, ANOVA (F test, $p<0.05$), and Skott-Knott test to compare the means ($p<0.05$), assisted by the GENES statistics program [30].

RESULTS

For the winter cover crops DM production there was no factorial interaction in both crop years (Table 1). Cover crops and soil tillage differed from each other individually, in 2021 crop season mix and oats had the higher DM production, while vetch had the lowest DM. However, in the 2022 crop season, the DM production was approximately 70% higher for the oats and mix, and two times higher for the radish, while the vetch had a decrease in the DM production of 60%, but among themselves, statistically, they maintained the same results as the previous year.

In 2021 crop season, NT and NTMTt obtained the lowest DM productions, while NTCa, NTCt, and NTMTa, with DM productions ranging between 2.51 Mg ha^{-1} and 2.67 Mg ha^{-1}. However, in 2022 crop season, the highest DM production was found in the NTMTa (5.18 Mg ha^{-1}) and NT (4.44 Mg ha^{-1}), while the other soil tillages showed similar results with the DM production ranging between 2.81 Mg ha^{-1} and 3.97 Mg ha^{-1}.

Table 1. Winter cover crops dry biomass production (Mg ha^{-1}) in different soil tillage.

Soil tillage	**Winter cover crops**				
	Oats	**Mix**	**Vetch**	**Radish**	**Mean**
			Crop season 2021		
NT	2.20	2.50	1.38	1.40	1.87 B
NTCa	3.96	2.97	1.02	2.42	2.59 A
NTCt	2.74	3.79	1.07	2.44	2.51 A
NTMTa	3.25	4.16	1.05	2.21	2.67 A
NTMTt	2.89	3.13	1.17	1.72	2.23 B
Mean	3.01 a	3.31 a	1.14 c	2.04 b	
CV%			24.96		
			Crop season 2022		
NT	5.71	6.92	0.75	4.38	4.44 A
NTCa	2.63	5.02	0.14	3.46	2.81 B
NTCt	5.12	5.18	0.46	3.22	3.49 B
NTMTa	6.83	6.02	0.50	7.36	5.18 A
NTMTt	6.23	5.46	0.52	3.67	3.97 B
Mean	5.30 a	5.72 a	0.48 c	4.42 b	
CV%			31.83		

Means followed by the same capital letter in the column and lower case in the line did not differ statistically by the Skott-Knott test ($p<0.05$). CV%: coefficient of variation. NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially

For the PR after the winter cover crop in 2021 crop season, there was no factorial interaction (Figure 3A and Figure 4A). For the soil tillage (Figure 3A), in the 0-0.05 m soil layer, NT and NTCa had the highest values with PR between 0.14 and 0.17 MPa, and the other soil tillage reached 0.08 to 0.11 MPa. NT had the highest PR in the 0.05-0.30 m soil layer, ranging between 1.5 and 2.21 MPa, while the other soil tillage showed similar results one to the other, with values from 0.97 to 1.25 MPa. In the 0.30-0.40 m soil layer, NT showed PR reduction, which was similar to the values found in NTCt and NTMTt, in which the PR ranged between 1.70 and 1.89 MPa, while in NTCa and NTMTa, the lowest PR values were seen, that is, 1.36 and 1.59 Mpa, respectively.

Regarding the winter cover crops, in 2021, after the cover crop cycle (Figure 4A), there was difference only in the 0.05-0.010 m soil layer, in which oats and mix presented the lowest PR, with values close to 0.80 MPa, and vetch and radish had the highest RP of 0.96 and 0.97 MPa, respectively.

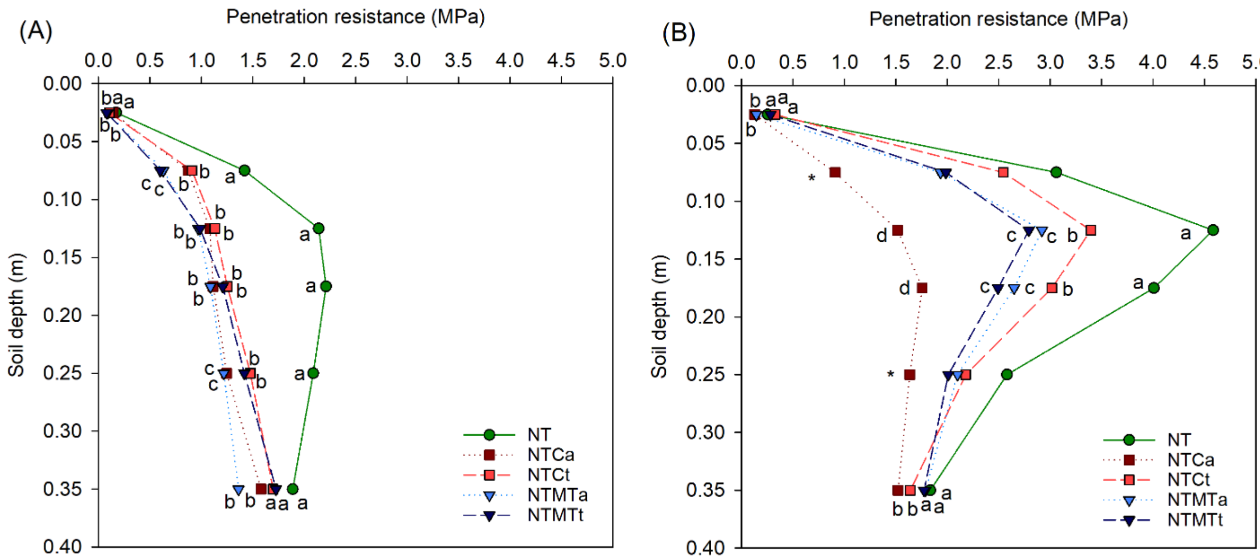

Figure 3. Soil penetration resistance in different soil tillage after the winter cover crops in the 2021 (A) and 2022 (B) crop seasons. *: significant interaction between soil tillage and winter cover crops, in the respective soil layer, by the F-test (p<0.05) (presented in the table 2). Means followed by the same letter, within the soil layer, did not differ by the Skott-Knott test (p<0.05). NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially.

For the PR after the winter cover crop in 2022 crop season, there was no factorial interaction for the 0.00-0.05, 0.10-0.15, 0.15-0.20, 0.30-0.40 m soil layers (Figure 3B and Figure 4B). However, in the 0.05-0.10, and 0.20-0.30m soil layers there was a factorial interaction between the soil tillage and the cover crops (Table 2). In the 0-0.05 soil layer, NTCa and NTMTa showed the lowest PR, with 0,12-0,14 MPa, respectively, differing from the others soil tillages (Figure 3B). NT had the highest PR in the 0.10-0.15 and 0.15-0.20soil layers, ranging from 2.5 to 4.5 MPa, while NTCa showed the lowest RP in those layers, ranging from 0.09 to 1.7 MPa. In the 0.30-0.40 m soil layer, NTCa and NTCt differed from the others with the lowest PR (1.5 and 1.6 MPa, respectively), while NT showed a 1.8 MPa PR, and NTMTa and NTMTt obtained 1.7 MPa. About the crop season, in 2022, it was observed an increase in RP, except for the NTCa, which have similar values in both years.

In the 2022 crop season (Figure 4B), there was no difference between the cover crops in the 0-0.05 m soil layer. While, in the 0.10-0.15 m layer, radish showed the lowest resistance (2.6 MPa) and oats showed the highest value (3.4 MPa). In the 0.15-0.20 and 0.30-0.40 m soil layers, oats and vetch had higher PR, different from mix and radish.

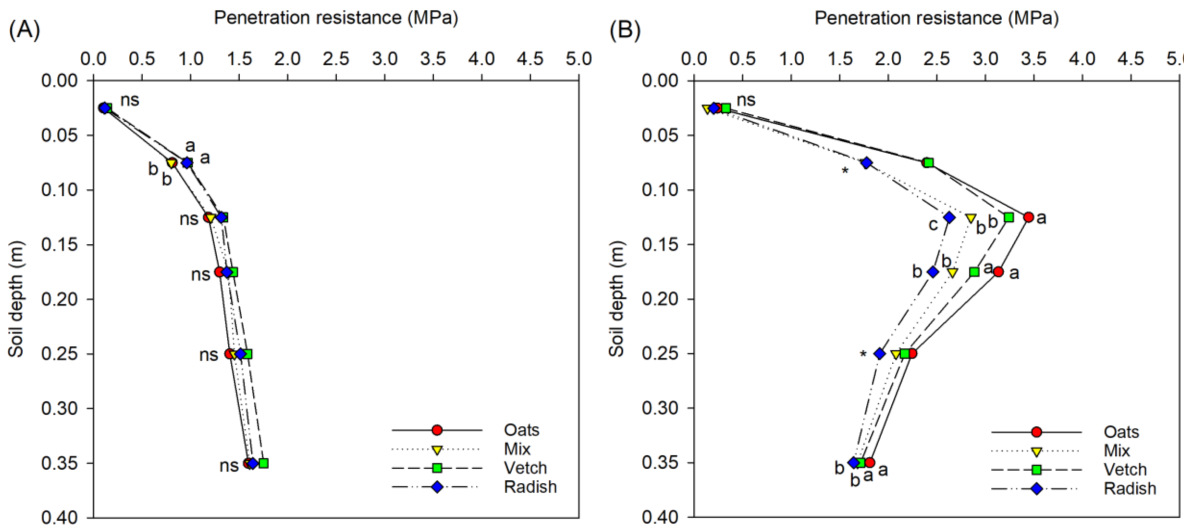

Figure 4. Soil penetration resistance after the winter cover crops in the 2021 (A) and 2022 (B) crop seasons. *: significant interaction between soil tillage and winter cover crops in the respective soil layer by the F-test (p<0.05) (presented in the table 2). Means followed by the same letter, within the soil layer, did not differ by the Skott-Knott test (p<0.05). ns: not significant by the F test (p<0.05).

The PR values in two soil layers showed factorial interaction (Figures 3B and 4B) between the soil tillage and winter cover crops, in the 0.05-0.10 m soil layer (Table 2) for the cover crops. Oats presented the highest PR in NT, NTCt, and NTMTa, while in the mix, NT had the highest PR. Vetch showed a 0.84 MPa PR in NTCa, unlike in the other treatments, as the lowest value, while NT, NTCt and NTMTt had the highest PR values. The PR in radish was only different in NTCa with 0.56 MPa. For the soil tillage, in NT, NTCa, NTMTa, and NTMTt, no difference in PR was observed in relation to the cover crops. however, in NTCt, oats and vetch had the highest RP.

Regarding the 0.20-0.30 m soil layer, for the winter cover crops, in the oat the NT, NTCt, and NTMTa had the highest PR, while in the mix, there was no significant difference in PR between the types of soil management. In vetch, NT presented the highest PR, with 2.81 MPa, and NTCa the lowest, with 1.33 MPa. Radish showed a difference when cultivated in NT, with the highest PR, 2.34 MPa. For the soil tillage, in NT, oat and vetch presented the highest PR, while in the NTCa and NTCt, oat and mix had the highest PR. In NTMTa there was no difference among the cover crops, while in NTMTt, the highest PR was found in vetch, with 2.41 MPa.

Table 2. Soil penetration resistance in different soil tillage after the 2022 winter cover crop season, in the 0.05-0.10 and 0.20-0.30 m soil layers

Soil tillage	Winter cover crops				
	Oats	**Mix**	**Vetch**	**Radish**	**Mean**
	Soil penetration resistance (MPa)				
	0.05-0.10 m soil layer				
NT	3.37 Aa	2.86 Aa	3.52 Aa	2.50 Aa	3.06
NTCa	0.84 Ba	1.40 Ba	0.84 Ca	0.56 Ba	0.91
NTCt	3.41 Aa	1.95 Bb	3.06 Aa	1.75 Ab	2.54
NTMTa	2.48 Aa	1.23 Ba	1.94 Ba	2.09 Aa	1.93
NTMTt	1.89 Ba	1.37 Ba	2.71 Aa	1.98 Aa	1.99
Mean	2.40	1.76	2.41	1.78	2.09
	0.20-0.30 m soil layer				
NT	2.80 Aa	2.37 Ab	2.81 Aa	2.34 Ab	2.58
NTCa	1.84 Ba	1.85 Aa	1.33 Cb	1.52 Bb	1.63
NTCt	2.41 Aa	2.38 Aa	2.08 Ba	1.84 Bb	2.18
NTMTa	2.32 Aa	2.00 Aa	2.21 Ba	1.86 Ba	2.10
NTMTt	1.84 Bb	1.79 Ab	2.41 Ba	1.99 Bb	2.01
Mean	2.24	2.08	2.17	1.91	2.10

Means followed by the same capital letter in the column and lowercase in the line did not differ by the Skott-Knott test ($p<0.05$). NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially

For the RP after the maize harvest there was no factorial interaction between soil tillage and cover crops (Figure 5 and 6) in both years. The PR after the maize harvest, in the 2021/22 season crop (Figure 5A), did not present difference between soil tillage in the first 0.10 m soil depth. In the 0.10-0.30 m soil layers, NT had the highest RP, highlighting the 0.15-0.20 m soil layer, in which the PR value observed was 2.3 MPa. In the 0.30-0.40 m soil layer, NTCt and NT showed similar values, with higher PR, around 1.7 MPa compared to the other soil tillage.

In the 2022/23 maize crop season (Figure 5B), the behavior was similar to the previous year, in which no difference was observed between the soil tillage at the first 0.10 m soil depth. NT showed the highest PR (2.7 MPa) in the 0.15-0.20 m soil layer. While, NTCa had the lowest RP, with values close to 1.7 MPa in the 0.10-0.35 m soil layers. Regarding the crop seasons, in 2022/23 there was an increase in the RP values compared to 2021/22, except for the NTCa.

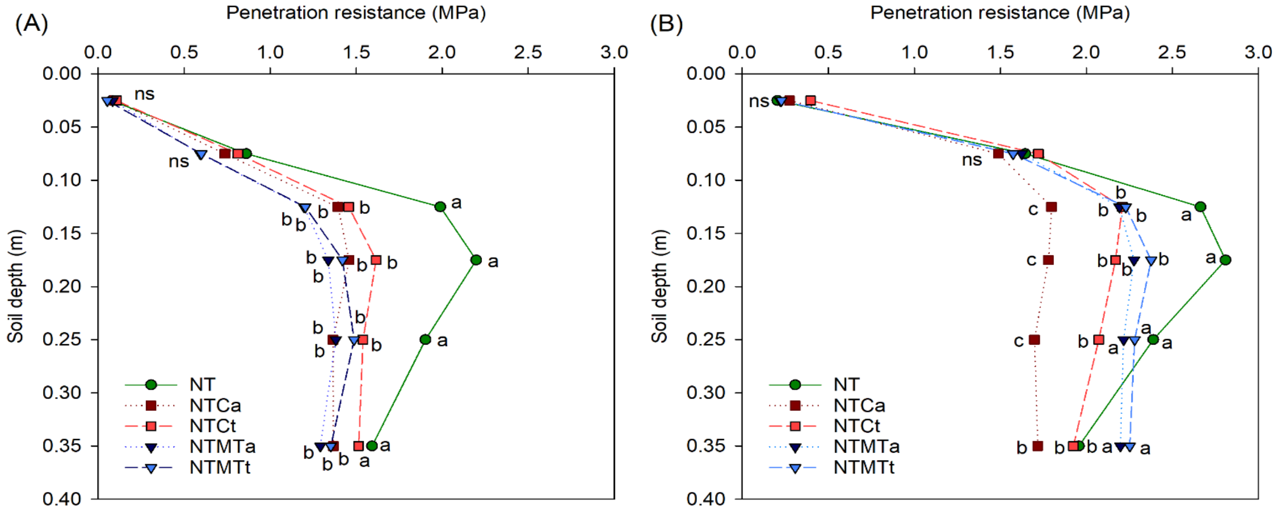

Figure 5. Soil penetration resistance in different soil tillage after the maize harvest in the 2021/22 (A) and 2022/23 (B) crop seasons. Means followed by the same letter, within the soil layer, did not differ by the Skott-Knott test (p<0.05). Ns: not significant by the F test (p<0.05). NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially.

For the RP after maize harvest in the 2021/22 crop season, there was no difference between the winter cover crops in all of the soil layers (Figure 6A). As for the PR in the 2022/23 crop season (Figure 6B), there was difference between the winter cover crops in the 0-0.05, 0.10-0.15, and 0.15-0.20 m soil layers, in which vetch showed higher PR when compared to the others cover crops reaching a PR of 2.5 MPa (0.15-0.20 m soil layer).

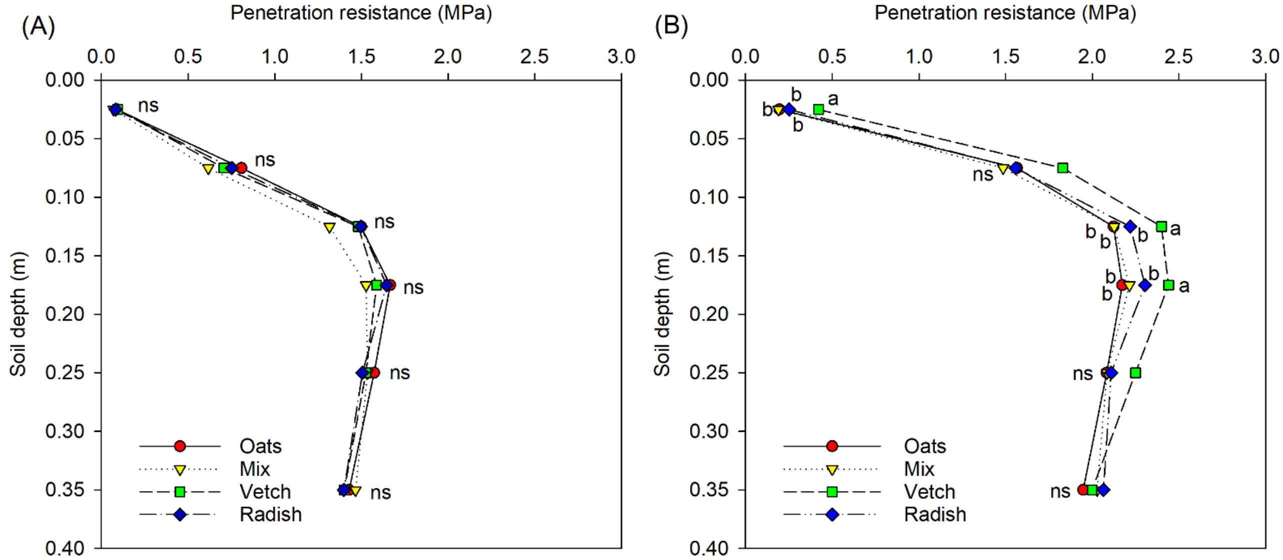

Figure 6. Soil penetration resistance after the maize harvest in the 2021/22 (A) and 2022/23 (B) crop seasons. Means followed by the same letter, within the soil layer, did not differ by the Skott-Knott test (p<0.05). ns: not significant by the F test (p<0.05).

Regarding the maize grain yield there was no factorial interaction between soil tillage and winter cover crops in both crop years (Table 3). In 2021/22 crop season, the maize grain yield ranged from 1.06 to 1.38 Mg ha^{-1} for the winter cover crops, and from 1.19 to 1.34 Mg ha^{-1} for the soil tillage. In the 2022/23 crop season, maize grain yield reached values from 9.34 to 9.85 Mg ha^{-1} for the winter cover crops and from 9.16 to 10.36 Mg ha^{-1} for the soil tillage, without differences.

Table 3. Maize yield in different soil tillage and in succession with winter cover crops

Soil tillage	Winter cover crops				
	Oats	**Mix**	**Vetch**	**Radish**	**Mean**
	Maize grain yield (Mg ha^{-1})				
	Crop season 2021/22				
NT	1.45	1.26	1.03	1.08	1.20 ns
NTCa	0.86	1.12	1.23	1.55	1.19
NTCt	1.31	1.18	0.99	1.35	1.21
NTMTa	1.67	1.36	1.04	1.29	1.34
NTMTt	1.61	1.33	1.04	1.37	1.34
Mean	1.38 ns	1.25	1.06	1.33	1.26
CV%			18.18		
	Crop season 2022/23				
NT	8.19	8.29	9.85	10.29	9.16 ns
NTCa	9.34	8.96	9.39	9.64	9.33
NTCt	10.83	9.67	8.91	9.86	9.82
NTMTa	9.11	10.74	11.06	10.53	10.36
NTMTt	9.21	10.62	9.24	8.92	9.49
Mean	9.34 ns	9.66	9.69	9.85	9.63
CV%			14.15		

ns: not significant by the F test ($p<0.05$). CV%: coefficient of variation. NT: no-tillage; NTCa: no-tillage with chiseling annually; NTCt: no-tillage with chiseling triennially; NTMTa: minimum tillage annually; NTMTt: minimum tillage triennially.

DISCUSSION

Cover crop DM production in 2021 was lower compared to 2022 crop season (Table 1) except for the vetch. However, the lower DM production in 2021 crop season for oats, mix, and radish might be due to the low rainfall in July, August, and September, below the normal climatological (Figure 1), compromising the final crop development. Vetch presented the lowest DM production in both years, due to problems with insects, mainly leafcutter ants and also by characteristics of the culture. However, its effect for RP in 2022 was similar to that of oats in the 0.15-0.20 m soil layer before maize sowing (Figure 5B) and more persistent as it differed from the others when evaluated after the maize crop (Figure 6B). This fact may be related to the low DM production, low soil cover and low soil water content. The DM production in this study was lower than the data observed in [31,32], in conditions considered normal for the development of the species.

In both years, mix and oats showed the highest DM production, confirming data obtained by [33], who also verified higher DM production in mix. This is due to the fact that the association of species makes it possible to join different root systems, which explore the soil layers, with better use of available resources. There was a difference regarding the soil tillage, in contrast with the data found in [34,35], which did not report difference in the DM production of cover crops in relation to soil tillage. It might have occurred due to the fact that the soil tillage effects are more noticeable in drought periods, when it becomes difficult for the roots to explore deeper soil layers, thus reducing the biomass production.

The NTMTa was the most stable among soil tillage, showing good DM production results in both years. In 2021 crop season, with dry conditions on the second half of the cycle, there was a reduction from 5.30 Mg ha^{-1} to 3.01 Mg ha^{-1} (43% decrease) in oats DM production and from 5.72 Mg ha^{-1} to 3.31 Mg ha^{-1} (41% less) in the mix. The general mean in 2021 was 2.37 Mg ha^{-1}, while in 2022 crop season, it was 3.98 Mg ha^{-1}, with a 40% decrease, showing that the effect of the drought affected all the treatments used.

For the mix and oat DM production (Table 1) in 2021 crop season, we observed low PR in the 0.05-0.10 m soil layer (Figure 5A). This could be associated with the roots characteristics of grass species, such fasciculate and aggressive root system, and particularly the mix, the association in the same period of different root systems favors the formation of pores with different sizes, which helps to reduce PR [36].

In the 2022/23 crop season after maize harvest (Figure 6B) we observed that the PR in vetch differed from the other cover crops, with a higher PR in the 0-0.05, 0.10-0.15, and 0.15-0.20 m soil layers. This probably occurred due to the pest presence and the lack of water during the vetch development, which consequently compromised root growth and led to low biomass production, exposing the soil surface, reducing the soil water content. Such reduction in DM production, cumulative over the years, can interfere with the soil physical quality, due to the biological activity reduction, confirming the data reported by [37], in which vetch showed low biomass production and the PR after the vetch cycle presented values similar to those found in this study.

However, we observed that the cover crops residual effects on the soil structure did not show great impact (Figure 5A). This might be due to the fact that they were implemented after the soil tillage, and the effects of such operations were more visible in the soil PR in the short term, since the effects of biological chiseling increase the time of persistence of the effects on the structured induced by the mechanical chiseling [34]. In the PR verified after the cover crop season in 2021 (Figure 5A), we did not observe great variations in the soil layers in all cover crops. This might have resulted from the soil chiseling carried out before its implementation, and the PR measurement was carried out relatively shortly after the intervention. In the following year (Figure 5B), increased PR values were observed in all cover crops, due to the fact that no soil tillage happen in 2022, thus resulting in reduced residual effects of the chiseling, which lasted for at least 10 months [38].

The RP after the cover crop in 2022 crop season (Figure 5B), showed values above the critical limit of 3.5 MPa [38] in the 0.15-0.20 m soil layer for oat, which reduces the plant root growth, but had no effect on maize yield, which did not show significant difference, evidencing that there were no soil layers with compaction that could limit plant development, although conditions of low water availability worsen the effects of soil compaction for plants [39]. The PR after the maize harvesting in the 2021/22 crop season (Figure 4A) showed NT with values over 2 MPa at the 0.10-0.20 m soil layer, which agrees with the data found in [40,41]. At the same soil layer, [42] reported similar values as those obtained in this study regarding the chiseled area. Also, [43] observed similar values in the 0.35-0.40 m soil layer in the chiseled area, reinforcing the data obtained in this study. Treatments with chiseling presented lower PR below 0.10 m depth, since chiseling is an efficient soil decompaction technique that reduces penetration resistance for increasing aeration and porosity [41].

In the 2022/23 crop season (Figure 4B), the PR in NTCa showed the lowest values in the 0.10-0.30 m soil layers, which agrees with data obtained in [19]. At the 0.25 m soil depth, the values found were similar to that obtained after maize harvesting by [44]. However, that author reported 1.8 MPa for the same layer in the NTMTa while this study obtained a PR of 2.2 MPa, and this difference might be related to the management practices adopted.

It was possible to see a decrease of RP in NT, since the initial RP in 2015, mainly 0.10-0.15 and 0.15-0.20 m soil layers, in which the RP values were 3.2 MPa and 3.8 MPa, respectively, while in the 2021/22 and 2022/23 crop seasons, RP was below 2.8 MPa (Figures 4A and 4B). This highlights the great effect of biological chiseling in soil physical properties promoted by the cover crops [34]. In the NT surface layer (Figure 3A and 3B), PR presented values similar to those observed in [45] at the end of the maize cycle in a Latossolo Vermelho. In NT, the highest PR observed was in the 0.15-0.20 m soil layer, confirming values found by [46]. Such data are considered normal in NT for this soil layer due to the machinery traffic, which induces alterations in the soil structure mainly up to 0.20 m soil depth [47], confirming the values reported in [48], which observed higher PR in the same soil layer. Values over 3.5 MPa are considered harmful in systems with soil tillage, but over 3 MPa in NT, since they might limit root growth [49].

The NTCt and NTMTt presented a 3-year interval between each chiseling operation, which was carried out for the last time in 2021 (Figure 2). Therefore, the RP evaluations were one and two years after chiseling, and we observed that these tillage showed gradual increase in the PR data during the interval years of the mechanical chiseling, possibly due to fact that the time of permanence of the chiseling effects is below 12 months [17].

The PR after the cover crop cycle in 2021 (Figure 3A) showed that the treatments that included chiseling presented low PR variation. This might be the result of the perceptible residual effects of the tillage, which agree with data reported in [19]. Among the different soil tillage, NT showed values over 2 MPa in the 0.10-0.20 m soil layer, agreeing with the data found in [40,41]. The treatments with chiseling, from the 0.10 m soil layer onwards, presented lower PR, due to the characteristics of this operation that is an efficient soil decompaction technique, which reduces PR for increasing aeration and porosity [41].

In 2022 crop season (Figure 3B), NTCa showed the lowest PR values, possibly due to the fact that the equipment used was adjusted with smaller space between shanks. The other treatments presented gradual increase in the PR and this might be ascribed to the chiseling effect reduction. We also observed that NTCt and NT presented values over the critical limit regarding root growth [38], which might be related to the lower soil gravimetric moisture during the PR measurement.

In the 0.05-0.10 m soil layer (Table 2), we observed that NTCa and NTMTa showed a similar PR in the mix. This might have occurred due to the high root activity observed in the associated species. However, in the remaining treatments, PR was lower in NTCa when compared to NTMTa, possibly due to the space between shanks, which was smaller in the equipment used in NTCa, thus resulting in greater soil surface mobilization, and also due to the increased chiseling interval, which became two years.

In NTCa, PR was lower in radish than in NTMTa due to the greater soil mobilization, which allows better development of the radish root and consequent reduction in PR values. For the oats, NTMTt obtained the lower PR than NTCt. This might have occurred due to the fact that the Terrus equipment provides lower mulch mobilization on the surface as reported in [50]. This provides longer moisture time and, consequently, greater root development and biological activity, reducing PR values.

In the 0.20-0.30 m soil layer (Table 2), the higher RP in NT with oats and with vetch might have occurred due to the lower influence of these species root system, since they might find difficulties in going beyond the 0.20 m depth, which in NT usually present higher PR. We also observed that in NTCa with oats and vetch had lower PR than NTMTa, possibly due to the space between shanks, which was smaller in the equipment used in NTCa. And, for the NTMTa, in this soil layer, there was no effect of the different cover crops.

During the evaluation period of the experiment, there were two distinct crop seasons in relation to rainfall. The 2021/22 crop season presented rainfall below 400 mm throughout the crop cycle and with great water shortage in December (Figure 1), only 2 mm, with a drought period that lasted over 30 days and coincided with the maize reproductive period, which resulted in a significant yield reduction (Table 3). In the 2022/23 crop season, with homogenous rainfall, the yield was within the expectations. In the 2021/22 there was a a reduction of over 85% in yield compared to to the 2022/23 crop (Table 3). Occurred because maize requires around 600 mm to complete the cycle. In the reproductive period, which occurs around 9 weeks after emergence, a 1-week period of water shortage during the bolting phase might compromise around 50% of the yield [51].

The mean maize yield in the 2021/22 crop season (Table 3), agreed with the results in [42], which had similar grain yield to reported in this study when maize was subjected to water deficit from R1 onwards. However, [52] found the 1.5 Mg ha^{-1} grain yield in succession of oats with water shortage at the beginning of the reproductive phase, agreeing to our study results (Table 3).

In the 2022/23 crop season, when the rainfall was well distributed along the whole maize cycle and was over 1.000 mm (Figure 1), the maize grain yield when in succession of mix confirmed the yield reported by [52]. However, the absence of differences in maize yield regarding winter cover crops agreed with [14,38], but it differed from the data verified in [46], which obtained higher maize yield in the succession of vetch and radish due to the high biomass production that enabled good nitrogen biological fixation provided by the legume and the good nutrient cycling provided by the crucifer. Unlike our study, in which low DM production was observed (Table 1), mainly for vetch in both years. The influence of cover crops in the crop grain yield can also be related to the weather conditions and soil management practices [53].

Maize grain yield in NT in succession of vetch (Table 3) was similar to the grain yield reported in [33]. In NTCa and NTMTa, the mean maize yield was close to that obtained in [17], due to an increase in soil porosity and root development after chiseling. However, the absence of differences observed in maize yield in relation to the soil tillage, agrees with studies developed in previous years and reported in [17,46]. Regarding chiseled areas, [38] did not find increased yield for the soybean and wheat crops when grown in such areas under continuous NT, reinforcing that the physical qualities of NT soil remain stable providing good crop development conditions.

Regardless of the crop season (2021/22 or 2022/23) the occurrence of a drought period or not, the maize yield did not present differences among the different soil tillage (Table 3), which evidenced that a well-consolidated NT, with crop rotation and soil cover, is an efficient way of managing the soil and producing food, with consequent reduction in carbon gas emissions from the fuel used in the chiseling operation. Chiseling increases water infiltration and reduces penetration resistance; however, its operational cost is high due to the power required. Thus, thorough studies are still required to establish need and cost/benefit of this operation since its effects usually last only a year [54].

CONCLUSION

Soil chiseling did not provide maize productivity gains, despite reducing PR. NT proved to be the most efficient soil management, even though it had a higher PR, especially in the 0.10-20 m layer, without causing any productivity losses in the system. These results reinforce the significant importance of NT in the pursuit of a more sustainable agriculture. Associated with the NT, the use of cover crops, despite not influencing maize productivity, provided a reduction in PR, especially for radish and mix crops.

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