

INCREASING FURROW OPENER DEPTH: AN ALTERNATIVE STRATEGY FOR SOIL COMPACTION MANAGEMENT UNDER NO-TILLAGE

16

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ABSTRACT: The effects of soil compaction are increasingly being observed in soils managed under no-tillage systems, potentially reducing crop yield. This study aimed to evaluate the effectiveness of increasing the depth of the fertilizer furrow at sowing in improving soil physical properties and its effects on maize and soybean yields. The experiment was conducted over three years with the following treatments: no-tillage with a sowing furrow operating at 0.07 m (NT7) and 0.11 m (NT11), and chiseling under minimum tillage (MT). Soil macroporosity, microporosity, total porosity, bulk density, penetration resistance, annual crop yield, and cumulative yield were evaluated. Macroporosity and total porosity were higher under MT in the three soil layers analyzed. Increasing the furrow opener depth began to show effects in the second year, increasing macroporosity and reducing soil penetration resistance. This resulted in increased soybean yield in the second and third years and higher cumulative yield. Although chiseling improved soil physical conditions, it did not increase crop yield. Increasing the operating depth of furrower shanks can improve soil physical conditions and may be an effective strategy for mitigating soil compaction under no-tillage systems.

Keywords: soil bulk density, penetration resistance, macroporosity, soybean, maize.

AUMENTO DA PROFUNDIDADE DO SULCADOR: UMA ESTRATÉGIA ALTERNATIVA PARA O MANEJO DA COMPACTAÇÃO DO SOLO NO SISTEMA DE PLANTIO DIRETO

RESUMO: Os efeitos da compactação do solo são cada vez mais observados em solos manejados sob sistemas de plantio direto, podendo reduzir a produtividade das culturas. Este estudo teve como objetivo avaliar a eficácia do aumento da profundidade do sulcador de fertilizantes na semeadura na melhoria das propriedades físicas do solo e seus efeitos sobre a produtividade das culturas de milho e soja. O experimento foi conduzido durante três anos, com os seguintes tratamentos: plantio direto com sulco de semeadura operando a 0,07 m (PD7) e 0,11 m (PD11), e escarificação sob cultivo mínimo (CM). Foram avaliadas a macroporosidade, microporosidade, porosidade total, densidade do solo, resistência do solo à penetração, produtividade anual das culturas e produtividade acumulada. A macroporosidade e a porosidade total foram maiores sob CM nas três camadas de solo analisadas. O aumento da profundidade de atuação do sulcador começou a apresentar efeitos no segundo ano, aumentando a macroporosidade e reduzindo a resistência do solo à penetração. Isso resultou em aumento da produtividade da soja no segundo e terceiro ano e maior produtividade acumulada. Embora a escarificação tenha melhorado as condições físicas do solo, não aumentou a produtividade. O aumento da profundidade de atuação dos sulcadores pode melhorar as condições físicas do solo e ser uma estratégia eficaz para mitigar a compactação em sistemas de plantio direto.

Palavras-chave: densidade do solo, resistência à penetração, macroporosidade, soja, milho.

INTRODUCTION

Soil compaction is a common process in agricultural soils managed under no-tillage systems. It is a factor that limits the productive potential of crops. Its effects include reduced water infiltration into the soil, increased soil penetration resistance, which can impair root growth, and increased soil bulk density, which reduces soil pore space, particularly macroporosity (NGO-CONG et al., 2021; SCOPEL et al., 2025).

Among the techniques used to mitigate soil compaction are chiseling and subsoiling, which disrupt compacted subsurface layers. However, their effects are short-lived (DAPPER et al., 2024), making them temporary rather than long-term solutions. Moreover, these practices can drastically reduce microbial activity (GU et al., 2025), which is essential for soil aggregation and organic matter decomposition.

These processes are particularly important in no-tillage systems, which minimize soil disturbance and rely on sowing into crop residues within crop rotation.

In no-tillage systems, compacted soil layers commonly occur at depths of 0.07–0.15 m (MIRZAKHANI et al., 2026). Increasing the furrow opener operating depth may improve soil physical conditions and alleviate compaction while reducing the need for intensive operations such as chiseling and subsoiling. However, its effectiveness remains insufficiently established and requires further investigation.

This study aimed to evaluate the effectiveness of increasing the depth of the fertilizer furrow at sowing in improving soil physical properties and its effects on maize and soybean yields.

MATERIAL AND METHODS

An experiment was conducted from 2012 to 2014 at the Federal Institute of Rio Grande do Sul (IFRS), Campus Sertão, Brazil (28°03'18" S, 52°14'53" W; 670 m a.s.l.), on a Red Nitosol. Soil fertility is presented in Table 1. The crop rotation included maize in 2012/2013, white oat in 2013, soybean in 2013/2014, forage turnip intercropped with common vetch in 2014, and soybean in 2014/2015.

Table 1. Soil fertility before the establishment of the experiment at depths of 0.00–0.10, 0.10–0.20, and 0.20–0.40 m.
Tabela 1. Fertilidade do solo antes da implantação do experimento nas profundidades de 0,00–0,10, 0,10–0,20 e 0,20–0,40 m.

Layer (m)	MO %	CTC		Al Cmolc dm ⁻³	Ca	Mg	H + Al	Saturation (%)	
		pH 7.0	Effective					Base	Al
		-----	-----					-----	-----
0.00–0.10	2.82	16.19	10.67	0.24	6.99	2.65	5.76	64.57	2.56
0.10–0.20	1.91	14.35	9.80	0.31	6.62	2.42	4.85	65.91	3.83
0.20–0.40	1.47	15.18	8.58	0.89	5.3	2.14	7.49	52.40	10.81
Layer (m)	Clay %	K	P	S mg dm ⁻³	Cu	Zn	Mn	pH	
								H ₂ O	SMP
								-----	-----
0.00–0.10	59.3	311.98	14.72	18.75	14.03	2.88	72.30	5.29	5.82
0.10–0.20	65.4	175.92	4.66	33.47	15.65	1.24	52.01	5.33	5.98
0.20–0.40	69.7	100.08	2.47	84.05	15.46	0.77	45.66	4.91	5.62

A randomized complete block design with eight replications and three treatments was used: no-tillage with the seeder furrow opener at 0.07 m (NT7); no-tillage at 0.11 m (NT11), as a soil physical improvement strategy; and minimum tillage (MT) using a subsoiler operating at 0.25 m depth, with shanks spaced 0.375 m apart. Subsoiling was performed only once, three months before maize sowing in the first experimental year.

Evaluations were performed at 3, 17, and 25 months after chiseling to determine macroporosity, total porosity, bulk density, and penetration resistance (PR), as well as annual and cumulative grain yield. Undisturbed soil samples were collected from 0.02–0.07, 0.07–0.12, and 0.15–0.20 m layers using 0.05×0.05 m stainless-steel cylinders and analyzed with a sand tension table. PR was measured along the seeding row to 0.30 m depth using a digital penetrometer (Falker®), with readings every 0.015 m and grouped into the same soil layers. Grain yield was determined from a 5 m² harvest area, with grain mass corrected to 13% moisture; cumulative yield was calculated as the sum of annual yields.

Residuals normality and variance homogeneity were assessed using the Shapiro–Wilk and Bartlett tests, respectively. Penetration resistance data were transformed as $(X + 1)^{0.5}$. After meeting the assumptions, ANOVA followed by Tukey's test ($p < 0.05$) was performed using Sisvar 5.6.

RESULTS

In the first year (Table 2), macroporosity was significantly higher under minimum tillage (MT) than under no-tillage at both furrow-opener depths (NT7, NT11) in all three layers evaluated. Microporosity differed significantly only in the 0.07–0.12 m layer, where MT was lower than NT7 and NT11. Total porosity was significantly higher under MT than under NT7 and NT11 in all layers. Bulk density did not differ significantly among treatments at any depth. Penetration resistance (PR) did not differ significantly among treatments in the two upper layers but was significantly lower under MT than under NT7 and NT11 in the 0.15–0.20 m layer.

Table 2. Macroporosity (Ma), microporosity (Mi), total porosity (Tp), bulk density (Bd), and soil penetration resistance (PR) under different mechanical strategies for improving soil physical conditions at depths of 0.02–0.07, 0.07–0.12, and 0.15–0.20 m in the first year.

Tabela 2. Macroporosidade (Ma), microporosidade (Mi), porosidade total (Pt), densidade do solo (Ds) e resistência do solo à penetração (RP) sob diferentes estratégias mecânicas para a melhoria das condições físicas do solo, nas profundidades de 0,02–0,07, 0,07–0,12 e 0,15–0,20 m, no primeiro ano.

Layers (m)	Management	Ma		Mi		Tp		Bd		PR	
		m ³ m ⁻³						Mg m ⁻³	MPa		
0.02–0.07	NT7	0.185	b ¹	0.387	a	0.572	b	1.12	a	1.27	a
	NT11	0.156	b	0.397	a	0.553	b	1.16	a	1.31	a
	MT	0.262	a	0.388	a	0.651	a	1.05	a	1.15	a
	CV (%)	22.57		11.69		7.92		10.49		21.94	
0.07–0.12	NT7	0.099	b	0.459	a	0.559	b	1.22	a	2.81	a
	NT11	0.094	b	0.466	a	0.548	b	1.32	a	2.81	a
	MT	0.169	a	0.439	b	0.605	a	1.22	a	2.05	a
	CV (%)	38.49		6.70		5.46		7.97		15.92	
0.15–0.20	NT7	0.074	b	0.488	a	0.563	b	1.33	a	3.19	a
	NT11	0.066	b	0.495	a	0.561	b	1.36	a	3.25	a
	MT	0.131	a	0.477	a	0.609	a	1.30	a	2.20	b
	CV (%)	18.42		5.34		5.79		10.32		7.18	

¹Means followed by different letters within the same column differ at the 5% significance level according to Tukey's test. CV: coefficient of variation.

In the second year (Table 3), macroporosity was significantly higher under MT than under NT7 in the 0.02–0.07 m layer (NT11 not differing from either); both NT11 and MT exceeded NT7 in the 0.07–0.12 m layer; and MT exceeded both NT7 and NT11 in the 0.15–0.20 m layer. Microporosity differed significantly only in the 0.07–0.12 m layer, where MT was lower than NT7 and NT11. Total porosity did not differ significantly among treatments in the 0.02–0.07 m layer, was significantly higher under MT than NT7 and NT11 in the 0.07–0.12 m layer, and was significantly higher under MT than NT11 in the 0.15–0.20 m layer (NT7 not differing from either). Bulk density showed no significant differences among treatments at any depth. PR did not differ significantly among treatments in the 0.02–0.07 m layer; in the 0.07–0.12 m layer it was significantly lower under MT than under NT7 and NT11; and in the 0.15–0.20 m layer it was significantly lower under MT than under NT7 (NT11 not differing from either).

Table 3. Macroporosity (Ma), microporosity (Mi), total porosity (Tp), bulk density (Bd), and soil penetration resistance (PR) under different mechanical strategies for improving soil physical conditions at depths of 0.02–0.07, 0.07–0.12, and 0.15–0.20 m in the second year.

Tabela 3. Macroporosidade (Ma), microporosidade (Mi), porosidade total (Pt), densidade do solo (Ds) e resistência do solo à penetração (RP) sob diferentes estratégias mecânicas para a melhoria das condições físicas do solo, nas profundidades de 0,02–0,07, 0,07–0,12 e 0,15–0,20 m, no segundo ano.

Layers (m)	Management	Ma		Mi		Tp		Bd		PR	
		----- m ³ m ⁻³ -----		----- m ³ m ⁻³ -----		----- m ³ m ⁻³ -----		Mg m ⁻³		MPa	
0.02–0.07	NT7	0.222	b ¹	0.431	a	0.681	a	1.10	a	0.56	a
	NT11	0.241	ab	0.426	a	0.666	a	1.10	a	0.39	a
	MT	0.300	a	0.385	a	0.722	a	1.01	a	0.23	a
	CV (%)	11.02		10.88		5.33		2.19		13.73	
0.07–0.12	NT7	0.141	b	0.474	a	0.614	b	1.20	a	2.18	a
	NT11	0.230	a	0.444	a	0.629	b	1.29	a	1.21	a
	MT	0.282	a	0.403	b	0.707	a	1.06	a	0.86	b
	CV (%)	13.51		2.99		1.73		7.88		12.55	
0.15–0.20	NT7	0.148	b	0.479	a	0.624	ab	1.35	a	2.79	a
	NT11	0.147	b	0.445	a	0.578	b	1.42	a	2.16	ab
	MT	0.237	a	0.456	a	0.692	a	1.27	a	1.78	b
	CV (%)	17.32		10.71		7.08		4.43		12.39	

¹Means followed by different letters within the same column differ at the 5% significance level according to Tukey's test. CV: coefficient of variation.

In the third year (Table 4), no significant differences among treatments were found for macroporosity, microporosity, total porosity, or bulk density in the 0.02–0.07 and 0.15–0.20 m layers. In the 0.07–0.12 m layer, macroporosity was significantly lower under NT7 than under NT11 and MT, while microporosity, total porosity, and bulk density did not differ significantly among treatments. PR did not differ significantly among treatments in the 0.02–0.07 m layer; in the 0.07–0.12 m layer it was significantly higher under NT7 than under MT (NT11 not differing from either); and in the 0.15–0.20 m layer it was significantly lower under MT than under both NT7 and NT11.

Table 4. Macroporosity (Ma), microporosity (Mi), total porosity (Tp), bulk density (Bd), and soil penetration resistance (PR) under different mechanical strategies for improving soil physical conditions at depths of 0.02–0.07, 0.07–0.12, and 0.15–0.20 m in the third year.

Tabela 4. Macroporosidade (Ma), microporosidade (Mi), porosidade total (Pt), densidade do solo (Ds) e resistência do solo à penetração (RP) sob diferentes estratégias mecânicas para a melhoria das condições físicas do solo, nas profundidades de 0,02–0,07, 0,07–0,12 e 0,15–0,20 m, no terceiro ano.

Layers (m)	Management	Ma		Mi		Tp		Bd		PR	
		-----		m ³ m ⁻³	-----			Mg m ⁻³		MPa	
0.02–0.07	NT7	0.185	a ¹	0.411	a	0.596	a	1.21	a	0.78	a
	NT11	0.215	a	0.362	a	0.578	a	1.08	a	0.47	a
	MT	0.211	a	0.379	a	0.590	a	1.10	a	0.41	a
	CV (%)	28.24		14.39		10.87		14.22		12.89	
0.07–0.12	NT7	0.113	b	0.440	a	0.554	a	1.38	a	1.85	a
	NT11	0.132	a	0.418	a	0.550	a	1.34	a	1.21	ab
	MT	0.130	a	0.433	a	0.564	a	1.36	a	0.99	b
	CV (%)	10.12		8.13		5.23		5.70		10.14	
0.15–0.20	NT7	0.112	a	0.449	a	0.561	a	1.39	a	2.08	a
	NT11	0.140	a	0.409	a	0.550	a	1.41	a	1.98	a
	MT	0.136	a	0.414	a	0.551	a	1.39	a	1.31	b
	CV (%)	17.32		9.29		7.08		5.29		6.15	

¹Means followed by different letters within the same column differ at the 5% significance level according to Tukey's test. CV: coefficient of variation.

PR increased with depth under all treatments in the three years evaluated (Figure 1). In the first and second years, PR under NT7 and NT11 exceeded the 2.5 MPa limiting threshold within approximately the 0.08–0.20 m depth range, whereas values under MT remained consistently lower throughout the profile. In the third year, PR values remained below 2.5 MPa under all three treatments across the entire evaluated profile.

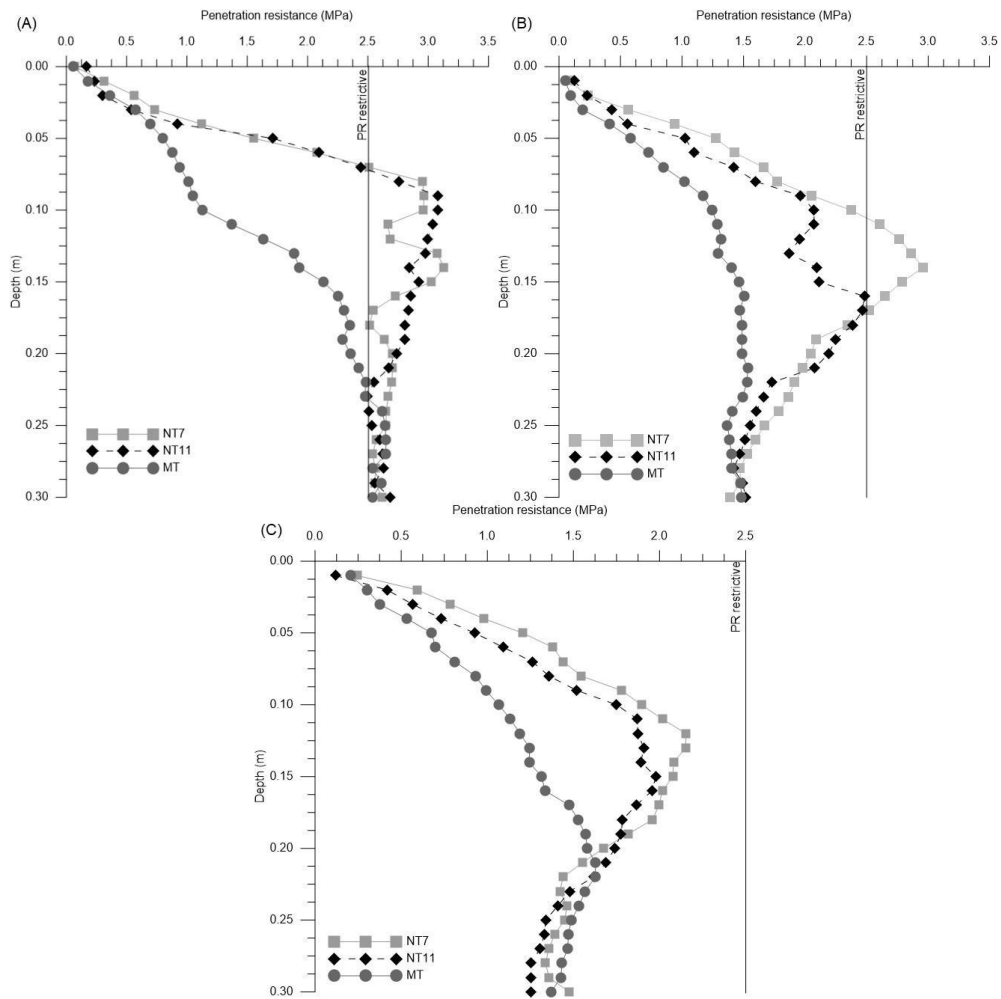


Figure 1. Soil penetration resistance (PR) evaluated to a depth of 0.30 m in 2012/2013 (A), 2013/2014 (B), and 2014/2015 (C) under minimum tillage (MT) and no-tillage with fertilizer furrow openers operating at 0.07 m (NT7) and 0.11 m (NT11).

Figura 1. Resistência do solo à penetração (RP) avaliada até a profundidade de 0,30 m nos anos de 2012/2013 (A), 2013/2014 (B) e 2014/2015 (C), sob preparo mínimo do solo (MT) e sistema plantio direto, com os sulcadores de fertilizantes operando a 0,07 m (NT7) e 0,11 m (NT11).

Maize yield (2012/2013) did not differ significantly among treatments. Soybean yield in 2013/2014 was significantly higher under NT7 and NT11 than under MT. In 2014/2015, soybean yield was significantly higher under NT11 than under MT, with NT7 not differing significantly from either treatment. Cumulative grain yield was significantly higher under NT11 than under MT, while NT7 did not differ significantly from either treatment.

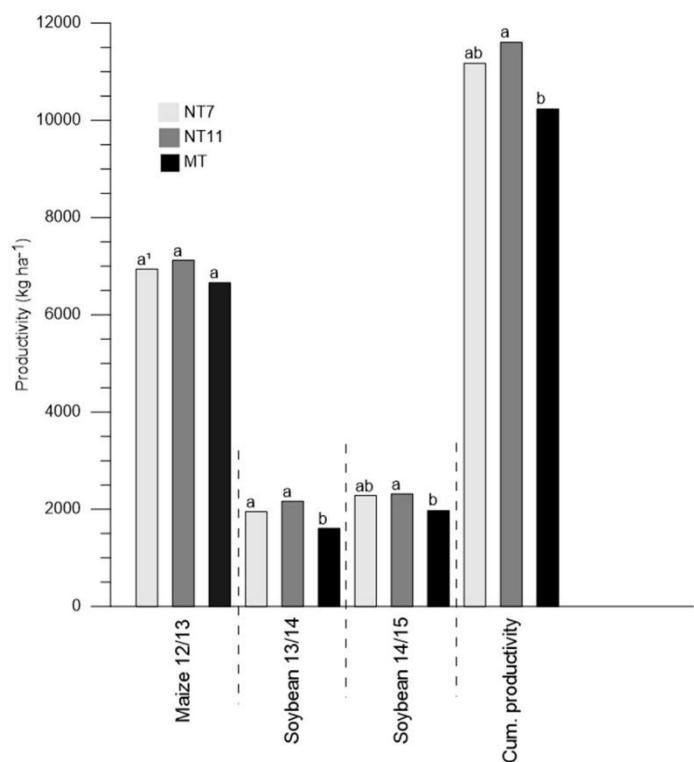


Figure 2. Grain yield of maize (2012/2013), soybean (2013/2014 and 2014/2015), and cumulative grain yield (Cum.) under minimum tillage (MT) and no-tillage with fertilizer furrow openers operating at 0.07 m (NT7) and 0.11 m (NT11). ¹Means followed by different letters within the same column differ significantly at the 5% level according to Tukey's test.

Figura 2. Produtividade de grãos de milho (2012/2013), soja (2013/2014 e 2014/2015) e produtividade de grãos acumulada (Cum.) sob preparo mínimo do solo (MT) e sistema plantio direto, com os sulcadores de fertilizantes operando a 0,07 m (NT7) e 0,11 m (NT11). ¹Médias seguidas por letras diferentes na mesma coluna diferem significativamente ao nível de 5%, de acordo com o teste de Tukey.

DISCUSSION

Increasing the furrow opener operating depth from 0.07 to 0.11 m proved effective in improving soil physical conditions under no-tillage, although the benefit only became evident from the second year onward and was concentrated in the 0.07–0.12 m layer directly reached by the seeding shank. This pattern supports the use of a deeper furrow opener as an alternative to chiseling for alleviating soil compaction while preserving the no-tillage system, since compacted layers in Brazilian soils under no-

tillage typically occur within this same 0.07–0.15 m range (SUZUKI et al., 2022). Thus, the furrow opener can reach the compacted zone while restricting soil disturbance to the sowing row rather than the entire field surface.

Chiseling, by contrast, is a more invasive intervention that can reduce microbial biomass, phosphatase activity, and soil carbon and nitrogen contents relative to no-tillage (SILVA et al., 2025). Because it compromises biological and chemical, in addition to physical, soil attributes, chiseling should be reserved for situations of severe compaction in which biological mitigation through cover crops (HASKEL et al., 2025) or localized loosening at sowing (DRESCHER et al., 2017) proves insufficient.

The mitigation of penetration resistance achieved with the deeper furrow opener and with chiseling is consistent with reports that deeper-acting soil-engaging components alleviate compaction more effectively than shallower ones. In an Oxisol under no-tillage, a furrow opener operating at 0.15 m reduced penetration resistance and increased porosity relative to shanks set at 0.10 or 0.07 m (DRESCHER et al., 2017), and depths of up to 0.17 m sustained compaction mitigation for 12 months in the same soil type. Part of the lower resistance recorded in the superficial layer can also be attributed to organic matter accumulated from decomposing crop residues across successive years of rotation (JAT et al., 2024), together with the disturbance produced by the seeder's soil-engaging components themselves, whose mobilized soil volume scales with operating depth (MIRZAEI et al., 2021). Since higher penetration resistance restricts root elongation and access to water and nutrients while raising the plant's metabolic costs (KASIRAJAN et al., 2024), these mechanisms are consistent with the higher yield recorded under the deeper furrow opener in this study.

This depth effect nonetheless has a practical ceiling. As the compacted layer generally lies within the 0.07–0.15 m depth range (MACENA et al., 2021), operating the furrow opener beyond this depth may increase energy requirements without addressing additional compaction. Moreover, as with chiseling, greater operating depths increase tractor draft and wheel slip, thereby increasing fuel consumption and potentially discouraging producers from adopting deeper settings (ALE et al., 2023).

Bulk density, unlike porosity and penetration resistance, was not altered by any of the three strategies, contrasting with Stédile et al. (2026), who observed lower bulk density as the intensity of soil disturbance increased across tillage systems, and with Suzuki et al. (2022), who reported a similar reduction six months after chiseling in an Oxisol. Values in the present study nevertheless remained mostly below the 1.30–1.40 Mg m⁻³ critical range established for clayey soils (SUZUKI et al., 2022), exceeding it only under NT11 in the 0.15–0.20 m layer, a depth not reached by the furrow opener. This isolated exceedance is therefore more plausibly related to machinery traffic than to the treatments themselves, consistent with reports that wheel-transmitted stresses can raise penetration resistance and bulk density to depths of up to 0.45 m (WANG et al., 2022; BOTTA et al., 2022).

The persistence of chiseling effects through the third year, 25 months after the operation, compares favorably with the six-month duration reported by Drescher et al. (2016) in an Oxisol and is more consistent with the outcome described by Ren et al. (2022) in Planosols, where chiseling disrupted compacted layers without inverting the soil profile, thereby preserving the surface residue associated with conservation-oriented management. Such variation in persistence across studies is likely related to differences in soil moisture at the time of the operation and to the design and adjustment of the implement, since commercially available chisels differ widely in chassis configuration, angle of attack, tip and shank type, and row spacing, all of which affect the extent of soil mobilization (SALAR et al., 2021; VANDERHASSELT et al., 2023; CHEN et al., 2023).

Yield responses lagged behind the physical improvements, becoming evident only once soil physical conditions had consolidated over more than one growing season. A comparable lag was reported in an Oxisol under annual chiseling, where physical changes did not translate into maize or soybean yield gains (MOURA et al., 2021; VANDERHASSELT et al., 2024), whereas a yield penalty emerged 12 months after chiseling in an Ultisol cultivated with maize (FERREIRA et al., 2023). The higher cumulative yield achieved under the deeper furrow opener relative to chiseling reinforces the value of evaluating soil management from a long-term perspective, since

yield responses to physical interventions can take several seasons to manifest and may also be modulated by climatic conditions: in an Oxisol under 16 years of no-tillage, chiseling combined with deep fertilizer placement (0.13 m) did not alter soybean yield, an outcome the original authors attributed to favorable conditions throughout the crop cycle that limited the expression of compaction effects (FERREIRA et al., 2026).

CONCLUSIONS

Increasing the operating depth of the furrow opener improved soil physical conditions by increasing macroporosity and total porosity and reducing soil penetration resistance from the second year onward, resulting in increased crop yield. Chiseling provided the greatest improvement in soil physical conditions, with higher macroporosity and total porosity and lower soil penetration resistance throughout the soil profile. However, despite improving soil physical conditions, chiseling reduced crop yield.

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