ARCOVERDE, S. N. S.; KURIHARA, C. H.; OLIVEIRA, G. B. A.; NAGAHAMA, H. J.; OLSZEVSKI, N.; SILVA, C. J. Physical quality of sandy soil under management systems and chiseling of sugarcane ratoons. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 13, n. 1, e9580, 2026. ISSN 2358-6303.

Physical quality of sandy soil under management systems and chiseling of sugarcane ratoons

Sálvio Napoleão Soares Arcoverde[1], Carlos Hissao Kurihara[2], Graciela Benites Acunha de Oliveira[2], Hideo de Jesus Nagahama[3], Nelci Olszevski[3], Cesar José da Silva[2]

[1] Universidade Federal da Grande Dourados, Dourados, Mato Grosso do Sul, Brasil. E-mail: salvionapoleao@gmail.com
[2] Embrapa Agropecuária Oeste. Email: cesar.silva@embrapa.br, carlos.kurihara@embrapa.br, gracibenites@gmail.com
[3] Universidade Federal do Vale do São Francisco. Email: hideo.agro@gmail.com, nelci.olszevski@univasf.edu.br

Received: 14/05/2025; Accepted: 27/11/2025.

ABSTRACT

The adoption of soil management practices in sugarcane production areas must ensure both economic and environmental sustainability. This study evaluated the effects of different management systems (conventional tillage – CT, reduced tillage – RT, and no-tillage – NT) and sugarcane ratoon field chiseling on soil physical quality indicators. The experiment was conducted in a randomized block design, with split-plots and three replications. The plots consisted of the management systems, and the subplots corresponded to treatments without and with chiseling (WoC and WiC, respectively). In the fourth ratoon cycle (five years after planting), the following soil physical attributes were evaluated at depths of 0.00–0.10 m, 0.10–0.20 m, and 0.20–0.30 m: soil bulk density, macroporosity and microporosity, total porosity, and soil penetration resistance. Data were subjected to multivariate factor analysis, with factor extraction using the principal component analysis method. The results indicated that CT was effective in maintaining soil physical quality (bulk density values ranged from 1.56 ± 0.05 to 1.64 ± 0.03 Mg m^{-3}), keeping bulk density below the critical limit in the 0.00–0.30 m layer (1.70 Mg m^{-3}) after five years of sugarcane cultivation. Mechanical chiseling proved beneficial in NT areas, reducing penetration resistance in sandy soils, but showed no significant effects in the CT and RT systems. Among the evaluated attributes, penetration resistance was the most sensitive to variations in mechanical chiseling methods across the management systems. Chiseling is recommended for NT systems, while CT proved more effective in preserving soil physical quality in the long-term.

Keywords: Soil degradation, Mechanical intervention, Soil tillage, Land use.

Qualidade física do solo arenoso sob sistemas de manejo e escarificação de soqueiras de cana-de-açúcar

RESUMO

A adoção de práticas de manejo do solo nas áreas de produção de cana-de-açúcar deve assegurar à sustentabilidade econômica e ambiental. Este estudo avaliou os efeitos de diferentes sistemas de manejo (preparo convencional – SPC, preparo reduzido – SPR e plantio direto – SPD) e escarificação de soqueiras de cana sobre os indicadores de qualidade física de solo. O experimento foi conduzido em delineamento experimental de blocos casualizados, com parcelas subdivididas e três repetições. As parcelas consistiram nos sistemas de manejo e as subparcelas corresponderam aos tratamentos sem e com escarificação (SE e CE, respectivamente). Na quarta soqueira (05 anos após o plantio) avaliou-se os seguintes atributos físicos do solo nas camadas de 0,00-0,10 m, 0,10-0,20 m e 0,20-0,30 m: densidade, macro e microporosidade, porosidade total, resistência do solo à penetração. Os dados foram submetidos à análise fatorial multivariada, com extração de fatores pelo método de componentes principais. Os resultados indicaram que o preparo convencional do solo (CT) foi eficaz na manutenção da qualidade física do solo (com valores de densidade variando de 1,56 ± 0,05 a 1,64 ± 0,03 Mg m^{-3}), mantendo abaixo do limite crítico na camada de 0,00–0,30 m (1,70 Mg m^{-3}) após cinco anos de cultivo de cana-de-açúcar. A escarificação mecânica mostrou-se benéfica em áreas sob SPD, reduzindo a resistência à penetração em solos arenosos, mas não apresentou efeitos significativos nos sistemas SPC e SPR. Dentre os atributos avaliados, a resistência à penetração foi o mais sensível às variações nos métodos de escarificação mecânica para os sistemas de manejo. A escarificação é recomendada em SPD, enquanto o SPC mostrou maior eficácia na preservação da qualidade física do solo em longo prazo.

Palavras-chave: Degradação do solo, Intervenção mecânica, Preparo do solo, Uso do solo.

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the main crops produced worldwide, cultivated in more than 100 countries. It is among the most economically important crops in Brazil, which stands out as the world's largest producer, with a yield of 713.2 million tons in the 2023/2024 season, occupying approximately 8.3 million hectares (CONAB, 2024).

Although sugarcane is considered one of the most sustainable crops for biofuel production, the expansion of its cultivated area, combined with current soil and crop management practices, has raised controversial issues regarding its sustainability (Baquero et al., 2012; Arcoverde et al., 2019a; Cherubin et al., 2021). This is mainly due to critical changes in the structural quality of the soil, which compromise its physical functions and, consequently, affect the growth, development, and productivity of sugarcane (Baquero et al., 2012; Barbosa et al., 2019; Arcoverde et al., 2023).

Sugarcane cultivation in Brazil has expanded into degraded pastures and sandy soils. Field renewal is carried out after five or more harvest cycles, using conventional tillage, followed by sugarcane planting or the cultivation of soybeans or a cover crop (Moraes et al., 2022). For sugarcane planting, conventional soil tillage is performed through successive plowing and harrowing, which disturbs the soil and alters its structure (Arcoverde et al., 2019b; Farhate et al., 2022). This system involves soil preparation through plowing, harrowing, and subsoiling operations aimed at reducing soil compaction, incorporating lime and fertilizers, controlling pests, and leveling the terrain (Barbosa, 2013). However, recent studies indicate that soil management can negatively affect physical properties related to soil structure, such as bulk density, penetration resistance, and porosity (Silva Junior et al., 2013; Marasca et al., 2015; Arcoverde et al., 2019b). These changes directly impact soil conditions, as well as root growth and development, productivity, quality, and longevity of sugarcane (Melo et al., 2020).

The potential and limitations of each soil type must be considered when choosing the tillage system in sugarcane production environments, where there is intense machinery traffic throughout the cycle (Arcoverde et al., 2023). Machinery traffic during the sugarcane cycle is the main factor responsible for soil compaction near the planting row, where root concentration is highest in the surface layers (up to 40 cm) and close to the stools, up to 30 cm deep (Sá et al., 2016). Since sugarcane root growth is concentrated near the planting row center, tillage operations carried out between the rows tend to be as effective in mobilizing the soil for growth and development as operations done across the entire area (Melo et al., 2025). Thus, the practice of mechanical chiseling between the rows of ratoon sugarcane has potential to mitigate soil compaction and improve soil physical-hydraulic attributes and nutrient availability to plants. However, the use of this technique has been controversial regarding its feasibility based on sugarcane yield results (Sá et al., 2016), and even its effectiveness in mitigating soil compaction has been questioned, as the effects are typically temporary (Melo et al., 2025).

Several studies emphasize the importance of monitoring soil physical quality throughout the sugarcane cultivation cycle, either through a general soil physical quality index (Cherubin et al., 2016) or by evaluating individual changes in physical properties (Castioni et al., 2019; Barbosa et al., 2019; Awe et al., 2020). Soil bulk density, porosity, and penetration resistance are physical properties that are sensitive to changes induced by management practices and are often used to characterize soil compaction in agricultural areas (Arcoverde et al., 2019b; Arcoverde et al., 2025). Additionally, soil bulk density can indirectly reflect soil aeration, resistance, and its water storage and transmission capacity (Reynolds et al., 2009). Regarding pore size distributions, macroporosity is related, although indirectly, to the soil's ability to quickly drain excess water and facilitate root proliferation (Reynolds et al., 2009). In addition to being used as a compaction measure, soil penetration resistance also serves as an indicator of root penetration and growth capacity (Valadão et al., 2015; Sá et al., 2016; Barbosa et al., 2019). Soil structure regulates water retention and infiltration, gas exchange, organic matter and nutrient dynamics, root penetration, and erosion susceptibility, which makes it a key indicator of soil physical quality (Rabot et al., 2018).

To meet the global demand for biofuels and support national public policies and international agreements aimed at reducing greenhouse gas emissions through the use of biofuels, sugarcane production areas are expected to expand significantly in the coming years. Therefore, it is essential to use conservation strategies that allow soil management practices without compromising soil physical quality. Thus, quantifying and monitoring the agronomic and environmental impacts of different management systems in sugarcane crops over the long term is fundamental to identifying the system that contributes the most to sustainable sugarcane production (Martíni et al., 2023).

Thus, the objective was to evaluate the influence of management systems and annual mechanical chiseling between rows of ratoon sugarcane on the physical quality of the soil during one cultivation cycle.

2. Material and Methods

The experiment was conducted at Amélia Farm, in the expansion area of the sugarcane field of the Adecoagro Vale do Ivinhema Mill (22º03'64" S, 54º04'62" W), located in the Ipezal district, in Angélica, MS, Brazil (Figure 1). Soil in the experimental area is classified as a Latossolo Vermelho distrófico psamítico, according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to Oxisol in Soil Taxonomy (Soil Survey Staff, 2014). The climate of the region, according to Köppen’s classification, is Cwa, humid mesothermal, with hot summers and dry winters (Fietz et al., 2017). The clay, sand, and silt contents were determined according to Teixeira et al. (2017), and the particle size distribution is presented in Table 1.

The experimental design was a randomized block design in a split-plot scheme with three replications. The main plots consisted of management systems: conventional tillage (CT), reduced tillage (RT), and no-tillage (NT). The subplots were defined by treatments with (WiC) and without (WoC) mechanical chiseling (Figure 2). Each experimental unit consisted of six sugarcane rows spaced 1.50 meters apart and 15 meters in length.

The experimental area had been cultivated with sugarcane. In the implementation of the conventional tillage system (CT), field renewal was carried out in November 2017 with the application of 2.0 Mg ha^{-1} of dolomitic limestone, 1.2 Mg ha^{-1} of agricultural gypsum, and 1.5 Mg ha^{-1} of Agroffos 100 phosphate (containing 10% total P_2O_5 and 4% P_2O_5 soluble in neutral ammonium citrate + water), incorporated using a disc harrow and intermediate harrow, followed by an additional 2.0 Mg ha^{-1} of dolomitic limestone and leveling with a leveling harrow. Subsequently, sunn hemp (*Crotalaria juncea L.*) was sown.

At the time of sugarcane field renewal, part of the area was managed under a no-tillage system (NT), with chemical desiccation of regrowth from the last ratoon crop and the sunn hemp plants. To implement the reduced tillage system (RT), mechanical chiseling was carried out between the sugarcane rows in part of the no-tillage area, 30 days after mechanized planting.

On May 16, 2018, sugarcane (cultivar CTC 9001) was planted mechanically in 1.5-meter row spacing. At planting, 500 kg ha^{-1} of 12-30-10 NPK fertilizer was applied, along with 6 L ha^{-1} of zinc sulfate, 2 L ha^{-1} of boric acid, 0.33 L ha^{-1} of the insecticide Fipronil (600 g L^{-1}), 0.25 L ha^{-1} of the fungicide combination Azoxystrobin (200 g L^{-1}) + Cyproconazole (80 g L^{-1}), 0.20 kg ha^{-1} of the nematicide based on *Bacillus subtilis* (200 g kg^{-1}) + *Bacillus licheniformis* (200 g kg^{-1}), and 0.50 L ha^{-1} of the rooting agent Ethephon (240 g L^{-1}).

A few days after sugarcane planting, the sunn hemp plants (68 days old) were desiccated with 4.0 L ha^{-1} of glyphosate herbicide. After performing ridge-breaking (leveling of the interrow area), an additional 500 kg ha^{-1} of 25-00-25 fertilizer was applied. After the harvest of the plant cane in July 2019, 100% of the crop residue (mulch) was retained on the soil surface across all plots.

Ratoon crop chiseling was carried out using a DMB® brand subsoiler, Novo São Francisco model, equipped with straw-cutting discs and double shanks, operating at an approximate depth of 0.35 meters, positioned at the center of the sugarcane interrow. In all subplots, under the previously mentioned levels of straw mulch, part of the area was subjected to annual chiseling, while in the other part, no periodic chiseling was performed throughout the cultivation cycle.

Following the mechanized harvest of the fourth ratoon crop in July 2023, soil samples were collected from a total of 36 soil pits. These pits were positioned between the crop rows. Undisturbed soil samples were collected using metal cylinders (0.0557 m in diameter and 0.0441 m in height) at the wheel track position (0.75 m from the planting furrow), in the 0.00–0.10 m, 0.10–0.20 m, and 0.20–0.30 m soil layers. Soil bulk density (Bd) and porosity (total, macroporosity, and microporosity) were determined in samples with preserved structure, according to the methodologies described in Teixeira et al. (2017).

In September 2023, soil penetration resistance (PR) was evaluated in each experimental unit using the PenetroLOG-PLG 2040 field penetrometer, with electronic data acquisition capabilities (ASABE, 2006). The average penetration resistance was determined, stratified in the 0.00–0.10 m, 0.10–0.20 m, and 0.20–0.30 m soil layers. PR measurements consisted of nine sampling points, located at the wheel track position (furrow). In each experimental unit, disturbed soil samples were collected at three points in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers, located at the wheel track position (furrow). The gravimetric moisture of the samples was determined according to the methodologies described in Teixeira et al. (2017).

A qualitative analysis was also conducted to graphically depict the transverse PR profile under soil moisture conditions near field capacity, which, among the evaluated conditions, was regarded as the moisture level most favorable for root growth.

Table 1. Averages of the clay, sand, and silt contents, and the sand grain size fraction in the soil layers of 0.00-0.10, 0.10-0.20, and 0.20-0.40 m.

Layers	Clay	Sil	Sand T[1]	VC[2]	C[3]	MS[4]	F[5]	VF[6]	Textural class
m	------------	------------	------------	g kg^{-1}	------------	------------	------------	------------	
Conventional tillage – CT									
0.00-0.10	94.0	37.2	868.8	0.0	1.0	226.6	578.4	62.8	Loamy-sand
0.10-0.20	94.0	39.0	867.0	0.0	1.2	211.4	589.0	65.4	Loamy-sand
0.20-0.40	111.0	48.6	840.4	0.0	1.2	223.6	552.0	63.6	Loamy-sand
Reduced tillage – RT									
0.00-0.10	94.0	56.0	850.0	0.0	2.2	226.8	557.6	63.4	Loamy-sand
0.10-0.20	111.0	31.8	857.2	0.0	1.2	279.8	520.2	56.0	Loamy-sand
0.20-0.40	128.0	46.2	825.8	0.0	0.0	257.6	499.6	68.6	Sandy-loam
No-tillage – NT									
0.00-0.10	111.0	51.2	837.8	0.0	1.60	288.6	485.4	62.2	Loamy-sand
0.10-0.20	111.0	51.2	837.8	0.0	0.80	262.0	511.0	64.0	Loamy-sand
0.20-0.40	128.0	45.4	826.6	0.0	1.20	245.4	508.0	72.0	Sandy-loam

(1)Total sand: 2-0.05 mm; (2)Very coarse sand: 2-1 mm; (3)Coarse sand: 1-0.5 mm; (4)Medium sand: 0.5-0.25 mm; (5)Fine sand: 0.25-0.125 mm; (6)Very fine sand: 0.125-0.05 mm.

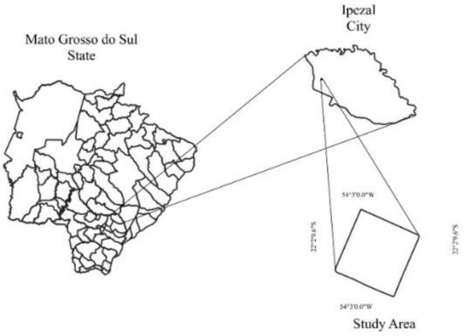

Figure 1. Experimental area located in the state of Mato Grosso do Sul, Brazil.

Conventional tillage withouth mechanical chiseling

Conventional tillage with mechanical chiseling

No - tillage withouth mechanical chiseling

No - tillage with mechanical chiseling

Reduced tillage withouth mechanical chiseling

Reduced tillage with mechanical chiseling

Figure 2. Management systems with and without annual chiseling during the third ratoon (August 27, 2022), immediately before mechanical chiseling.

This representation aimed to highlight the possible effects of annual mechanical intervention through chiseling on PR in that management system more sensitive to such practices.

Based on the six soil physical attributes (PR, Bd, macroporosity, microporosity, total porosity) determined in the sampled layers of the soil under both conditions, multivariate factor analysis was conducted to examine the intercorrelation structure between the physical attributes and the clusters formed by these attributes, influenced by chiseling management. Multivariate factor analysis was carried out using principal component extraction, with varimax normalized rotation to investigate the correlation structure between the variables (soil physical attributes), which defines a set of common latent dimensions called factors.

The rotation method aims to redistribute the variance of the first factors to the others until a simple significant factor pattern is achieved, making the result easier to interpret while preserving its statistical properties (Hair-Jr et al., 2009). The extracted factors were selected based on Kaiser's criterion, which suggests that only factors with eigenvalues greater than 1.00 should be retained.

After this procedure, the factor loading matrix, communalities, and rotated factor scores were obtained, which represent the estimated contributions of the various factors at each original observation, in addition to being used for sample classification (Landim, 2011). Multivariate factor analysis was conducted using Statistica 7.0® software (STATSOFT, 2005).

The effects of management systems and chiseling treatments on the factor scores of the extracted coefficients (latent variables) from multivariate factor analysis in the sampled layers, after the sugarcane cultivation cycle, were subjected to analysis of variance. When the F-values were significant, the mean factor scores for each extracted factor were compared using the Tukey test with $p < 0.05$. Analysis of variance and the Tukey test were performed using the statistical software AgroEstat (Barbosa and Maldonado Júnior, 2015).

3. Results and Discussion

In the evaluated management systems, a greater variation was observed in the mean values of PR (Table 2). With chiseling, there were reductions in the absolute values of PR in the 0.00 to 0.10 m layer in the conventional tillage system (CT) and in the reduced tillage system (RT), as well as in the 0.00 to 0.10 m, 0.10 to 0.20 m, and 0.20 to 0.30 m layers in the no-tillage system (NT). This suggests that PR was more sensitive in detecting variations related to mechanical chiseling, in agreement with Nagahama et al. (2016).

However, in the surface layer (0.00 to 0.20 m), it was observed that PR values were high for sandy soils cultivated with sugarcane. According to Barbosa et al. (2018), values > 1.5 MPa are considered critical, as they cause severe restrictions to the root growth of sugarcane. Furthermore, a value of 2 MPa for PR is widely recognized as detrimental to plant root development.

In the CT, except for the 0.20 to 0.30 m layer, Bd values ranged from 1.61 ± 0.04 to 1.64 ± 0.03 Mg m^{-3}; in the NT, they ranged from 1.76 ± 0.10 to 1.87 ± 0.06 Mg m^{-3}, and in the RT, from 1.72 ± 0.14 to 1.82 ± 0.02 Mg m^{-3}. Tavares Filho et al. (2010), when evaluating physical quality indicators of a sandy-textured dystrophic Red Latosol (Oxisol) cultivated with sugarcane, recorded a maximum density of 1.61 Mg m^{-3} in the 0.00 to 0.20 m layer.

The authors highlighted that these values did not indicate excessive compaction, meaning they did not pose risks to root development, water infiltration, soil aeration, or biological activity. However, Viana et al. (2023) warned that soil bulk densities ranging from 1.60 to 1.70 Mg m^{-3} are already at the critical limit for crop root growth. Furthermore, Barbosa et al. (2018) observed that, in sandy soils, bulk densities above 1.70 Mg m^{-3} severely restrict the sugarcane root system. Thus, after five cuts of sugarcane, the CT proved efficient in maintaining the physical quality of the soil for sugarcane cultivation, with Bd values below the critical limit (1.70 Mg m^{-3}) in the 0.00 to 0.30 m layer (Barbosa et al., 2018).

Regarding macroporosity values, the following variation was observed: in the CT, values ranged from 0.09 ± 0.03 to 0.15 ± 0.03 m^3 m^{-3}; in the NT, from 0.11 ± 0.04 to 0.15 ± 0.05 m^3 m^{-3}; and in the RT, from 0.13 ± 0.05 to 0.16 ± 0.03 m^3 m^{-3}. In general, Ma values were > 0.10 m^3 m^{-3}, a limit associated with aeration problems and reduced productivity (Arcoverde et al., 2019a). This likely occurred because values below this threshold can result in insufficient root aeration and a decrease in water content within the soil's optimal water-holding range.

Microporosity showed slight variation between management systems and between WoC and WiC - ranging from 0.19 ± 0.02 to 0.24 ± 0.04 m^3 m^{-3} (Table 2). These results are consistent with those obtained by Melo et al. (2025), who, when studying the effects of soil chiseling in the sugarcane inter-rows, observed microporosity values between 0.23 and 0.28 m^3 m^{-3} in sandy loam soil. On the other hand, Moraes et al. (2022), when evaluating different management systems (conventional tillage + sugarcane; conventional tillage + soybean; conventional tillage + cover crop) in renewal areas, found microporosity values between 0.30 and 0.35 m^3 m^{-3} up to a depth of 0.40 m after 36 months.

Table 2. Mean and standard deviation of the physical attributes: soil penetration resistance (PR), bulk density (Bd), macroporosity, microporosity, and total porosity, in the 0.00 to 0.10 m, 0.10 to 0.20 m, and 0.20 to 0.30 m layers, in the soil management systems subjected to mechanical chiseling (WiC) and without chiseling (WoC).

Layer	Chiseling	PR	Bd	Macroporosity	Microporosity	Total porosity
m		MPa	Mg m^{-3}	-------------------	m^3 m^{-3}	-------------------
Conventional tillage - CT						
0.00-0.10	WoC	1.38 ± 0.58	1.61 ± 0.04	0.13 ± 0.03	0.21 ± 0.02	0.34 ± 0.02
	WiC	0.94 ± 0.41	1.64 ± 0.03	0.09 ± 0.03	0.24 ± 0.02	0.33 ± 0.01
0.10-0.20	WoC	2.66 ± 0.51	1.61 ± 0.03	0.14 ± 0.04	0.19 ± 0.02	0.33 ± 0.03
	WiC	2.77 ± 0.30	1.62 ± 0.02	0.12 ± 0.02	0.24 ± 0.03	0.35 ± 0.02
0.20-0.30	WoC	3.35 ± 0.51	1.59 ± 0.05	0.13 ± 0.04	0.21 ± 0.02	0.34 ± 0.03
	WiC	3.50 ± 0.66	1.56 ± 0.05	0.15 ± 0.03	0.20 ± 0.02	0.35 ± 0.02
No tillage - NT						
0.00-0.10	WoC	1.51 ± 0.53	1.76 ± 0.10	0.11 ± 0.04	0.22 ± 0.03	0.33 ± 0.03
	WiC	1.06 ± 0.64	1.80 ± 0.08	0.13 ± 0.04	0.22 ± 0.03	0.35 ± 0.03
0.10-0.20	WoC	3.58 ± 0.90	1.79 ± 0.04	0.12 ± 0.01	0.22 ± 0.01	0.33 ± 0.01
	WiC	2.43 ± 0.32	1.87 ± 0.06	0.11 ± 0.04	0.23 ± 0.03	0.34 ± 0.02
0.20-0.30	WoC	4.28 ± 0.66	1.78 ± 0.04	0.11 ± 0.03	0.22 ± 0.02	0.33 ± 0.03
	WiC	3.18 ± 0.51	1.79 ± 0.08	0.15 ± 0.05	0.21 ± 0.03	0.36 ± 0.02
Reduced tillage - RT						
0.00-0.10	WoC	1.45 ± 0.61	1.75 ± 0.06	0.14 ± 0.03	0.25 ± 0.02	0.39 ± 0.03
	WiC	1.17 ± 0.58	1.81 ± 0.09	0.13 ± 0.05	0.24 ± 0.04	0.37 ± 0.03
0.10-0.20	WoC	2.68 ± 0.96	1.72 ± 0.14	0.16 ± 0.03	0,20 ± 0,01	0.36 ± 0.03
	WiC	2.67 ± 0.47	1.76 ± 0.08	0.14 ± 0.03	0.22 ± 0.03	0.36 ± 0.02
	WoC	3.12 ± 0.91	1.76 ± 0.06	0.14 ± 0.03	0.21 ± 0.02	0.35 ± 0.03
	WiC	3.51 ± 0.65	1.82 ± 0.02	0.14 ± 0.02	0.21 ± 0.03	0.35 ± 0.02

(±): standard deviation.

However, the authors recorded critical Ma values below 0.06 m³ m^{-3}, which could partially explain the high microporosity values. This scenario suggests a potential trend of soil physical degradation due to compaction, indicating that the soil structure in this study may be at an earlier stage of physical degradation compared to the soil in their study.

When analyzing the transverse PR profile (Figure 3) between sugarcane rows to demonstrate the effects of chiseling, it is noteworthy that in the no-tillage, subsoiling significantly reduced the compaction profile.

This is evidenced by the fact that, in the 0.10 to 0.20 m layer, PR values exceeded 3 MPa, and in the 0.20 to 0.30 m layer, values surpassed 4 MPa in the treatment without mechanical chiseling (WoC).

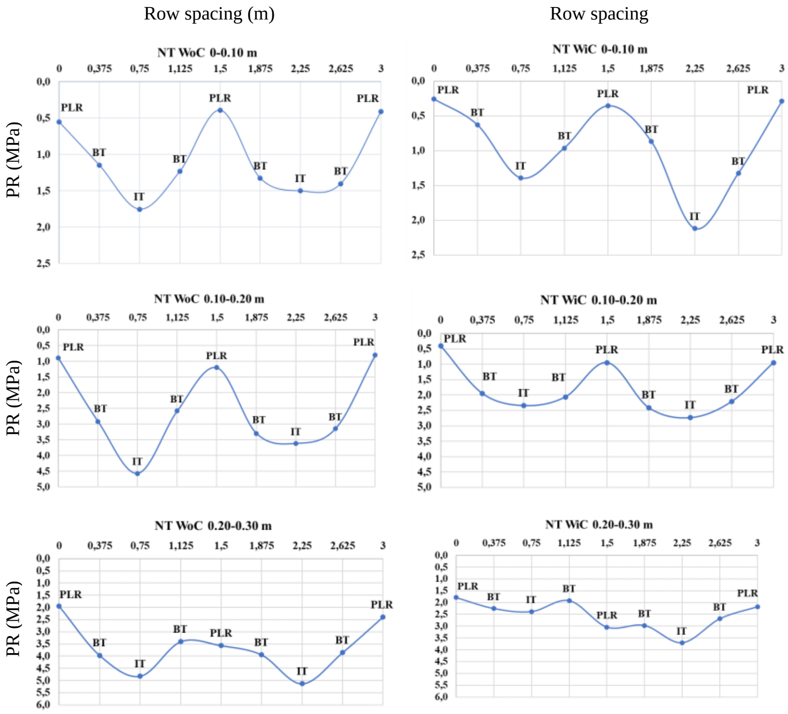

Figure 3. PR profile under no-tillage, under treatments without chiseling (WoC) and with chiseling (WiC). PLR: Planting row; BT: Between track; IT: In track.

PR is an important indicator used to classify the degree of soil compaction, a process that strongly influences soil structure and its intended functions (Celik et al., 2010). In this study, the high PR observed under NT without periodic (annual) mechanical chiseling, in the surface layer (0.00 to 0.30 m) of the sugarcane inter-row, suggests the presence of additional compaction (Reichert et al., 2021). Mechanical chiseling has been widely studied as a strategy to mitigate the effects of soil compaction by promoting improvements in physical attributes such as Bd, porosity, and PR (Sá et al., 2016; Drescher et al., 2016), as well as by increasing water infiltration rates and reducing surface runoff and PR (Santos et al., 2019). However, its effectiveness is variable and often temporary (Barbosa et al., 2019), depending on edaphoclimatic conditions and the agricultural management practices adopted. Recent studies indicate that reductions in PR may be sustained for up to 18 months (Drescher et al., 2016). In the CT, two factors were extracted using multivariate factor analysis, which together explained 76% of the data variance (Table 3).

Table 3. Explained variance, communalities, and factor loadings extracted from the physical attributes of the soil, five years after sugarcane planting, in management systems with and without chiseling.

Variably	Factor 1	Factor 2	Communality
Conventional tillage - CT			
Bd	0.65	-0.48	0.66
Macroporosity	-0.73	0.61	0.90
Microporosity	0.97	0.08	0.95
Total porosity	0.07	0.97	0.94
PR	-0.38	0.44	0.34
Explained variance (%)	41	35	
No tillage - NT			
Bd	-0.79	0.005	0.63
Macroporosity	0.88	-0.41	0.94
Microporosity	-0.84	-0.12	0.71
Total porosity	0.45	-0.71	0.70
PR	0.18	0.76	0.61
Explained variance (%)	47	25	
Reduced tillage - RT			
Bd	0.92	0.12	0.87
Macroporosity	-0.95	-0.002	0.91
Microporosity	0.57	-0.69	0.80
Total porosity	-0.33	-0.74	0.65
PR	-0.02	0.77	0.59
Explained variance (%)	44	33	

Bd: bulk density; PR: penetration resistance. Factor loadings above 0.60 are considered to show a high correlation with the extracted factors.

This percentage indicates that the factors (Factor 1 and Factor 2) generated contain a significant amount of information from the original variables. Factor 1 was composed of the attributes Bd, macroporosity, and microporosity, with Bd and microporosity showing a joint variation, while Ma exhibited an opposite behavior. On the other hand, the attributes macroporosity and total porosity showed a positive correlation, being determinants in the formation of Factor 2 (Table 3). These relationships were verified by Arcoverde et al. (2015) in studies on sandy soils, where they found positive correlations between sand and Bd and between clay, macroporosity, and total porosity.

In the NT, multivariate factor analysis allowed the extraction of two factors, which together explained 73% of the data variance (Table 3). Factor 1 was composed of the attributes Bd (bulk density), macroporosity, and microporosity, with Bd and microporosity showing joint variation, while Ma exhibited an opposite behavior. Factor 2 was formed by the attributes total porosity and PR, which varied in a correlated manner. These results highlight the relevance of chiseling in the NT to mitigate soil compaction in sandy soils, especially in the 0.00 to 0.30 m depth layer (Table 3).

In the RT, multivariate factor analysis allowed the extraction of two factors, which together explained 77% of the data variance (Table 3). Factor 1 (compaction) was composed of the attributes Bd and macroporosity, which showed variation in opposite directions. Factor 2 was formed by the attributes total porosity and microporosity, which varied together and in the opposite direction to PR (Table 3).

Factor 1 reflects soil compaction resulting from chiseling practices associated with machine traffic in the sugarcane inter-rows. On the other hand, Factor 2 demonstrates a possible relationship between total porosity and microporosity influencing PR. Considering that total porosity is composed of macroporosity and microporosity, alterations in the microporosity/macroporosity ratio greater than 2:1 (Hillel, 1980) can modify the relationship between macroporosity and Bd, indirectly influencing PR.

In the evaluated management systems, the extracted factors (Factor 1 and Factor 2) were not influenced ($p < 0.05$) by the interaction between management and chiseling, as determined by the analysis of variance (Table 4), except for Factor 1 in the 0.10 to 0.20 m depth layer. According to the data in Table 4, it was found that after the chiseling management of the ratoon crops during the harvest cycle (five cuts), similar physical conditions were provided for the development of the sugarcane root system. This result can be explained by soil reconsolidation, influenced by natural factors such as rainfall and wetting and drying cycles, or by the mechanical pressure exerted by machine traffic (Reichert et al., 2017). The variations identified in the 0.10 to 0.20 m layer may be associated with the cumulative effect of machine traffic in the sugarcane inter-row, as the soil has different load-bearing capacities in this layer.

Table 4. Decomposition of the interaction between management and chiseling for the factorial scores of the extracted factors in the 0.00-0.10 m, 0.10-0.20 m, and 0.20-0.30 m layers, five years after sugarcane planting.

Management	Chiseling	Factor 1	Factor 2
		0.00 – 0.10 m	
CT	WoC	-0.25	0.08
	WiC	-0.09	0.75
NT	WoC	-0.73	0.07
	WiC	-1.12	0.09
RT	WoC	-0.22	1.28
	WiC	-0.99	0.24
	F Value	1.00^{ns}	0.94^{ns}
		0.10 – 0.20 m	
CT	WoC	0.07	-0.53
	WiC	0.50	-1.00
NT	WoC	1.05	-0.11
	WiC	0.43	-1.34
RT	WoC	0.09	-1.17
	WiC	0.12	-1.08
	F Value	7.64^{**}	0.17^{ns}
		0.20 – 0.30 m	
CT	WoC	-0.21	-0.04
	WiC	-0.75	-0.76
NT	WoC	-1.23	-0.06
	WiC	-0.94	0.32
RT	WoC	-0.50	0.67
	WiC	-0.55	0.45
	F Value	0.08^{ns}	1.43^{ns}

ns: not significant. **: significant ($p < 0.01$).

According to Drescher et al. (2016), soil management practices can alter the mass-to-volume ratio due to the rearrangement of soil particles after mechanical interventions such as chiseling. This operation, according to Melo et al. (2025), promotes an increase in macroporosity and, consequently, a reduction in Bd and PR, demonstrating an inverse correlation between macroporosity, Bd, and PR. In other words, higher volumes of macropores result in lower values of Bd and PR. On the other hand, the increase in PR and Bd, associated with a decrease in macroporosity, can be attributed to the compaction of soil particles. This phenomenon can result from both natural processes, such as reconsolidation, and pressures induced by machine traffic. According to Oliveira et al. (2013), in both scenarios, the rearrangement of particles reduces macropores and increases Bd and PR.

4. Conclusions

After five sugarcane cuts, the conventional tillage system (CT) maintained favorable soil physical quality for cultivation, with soil bulk density values in the 0.00 to 0.30 m layer remaining below the critical limit.

After a sugarcane cultivation cycle (five cuts), mechanical chiseling in the sugarcane inter-rows is recommended in areas under the no-tillage system (NT) due to its efficiency in maintaining appropriate penetration resistance (PR) values for sandy soils cultivated with sugarcane. On the other hand, chiseling was not effective in reducing soil compaction in areas with CT and reduced tillage system (RT), indicating the need for other management practices to maintain soil physical quality.

Among the physical attributes evaluated, PR showed greater sensitivity in detecting variations resulting from mechanical chiseling across the different management systems.

Authors' Contribution

Sálvio Napoleão Soares Arcoverde performed the data collection, analyses, writing, and text editing. Carlos Hissao Kurihara and Cesar José da Silva conducted the experiments and contributed to the revision. Graciela Benites Acunha de Oliveira conducted the experiments and data collection. Hideo de Jesus Nagahama contributed to the writing and revision. Nelci Olszevski contributed to the revision.

Acknowledgments

Raízen/Polo MS and Embrapa are gratefully acknowledged for the financial support of this work through the project FAPED/CPAO/RAÍZEN 30.21.90.028.00.00.

Bibliographic References

Arcoverde, S.N.S., Kurihara, C.H., Silva, C.J., Oliveira, G.B.A. 2025. Physical soil quality under management systems in sugarcane field renewal. Engenharia agrícola, 45 (e20240214). http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v45e20240214/2025

Arcoverde, S.N.S., Kurihara, C.H., Staut, L.A., Tomazi, M., Pires, A.M.M., da Silva, C.J. 2023. Soil fertility, nutritional status, and sugarcane yield under two systems of soil management, levels of remaining straw and chiseling of ratoons. Revista Brasileira de Ciência do Solo, 47:e0220138. https://doi.org/10.36783/18069657rbcs20220138

Arcoverde, S.N.S., Salviano, A.M., Olszevski, N., Melo, S.B., Cunha, T.J.F., Giongo, V., Pereira, J.S. 2015. Qualidade física de solos em uso agrícola na região semiárida do estado da bahia. Revista Brasileira de Ciência do Solo, 39(5), 1473-1482. https://doi.org/10.1590/01000683rbcs20140282

Arcoverde, S.N.S., Souza, C.M.A., Cortez, J.W., Maciak, P.A.G., Suárez, A.H.T. 2019a. Soil physical attributes and production components of sugarcane cultivars in conservationist tillage systems. Revista Engenharia Agrícola, 39(2), 216-224. https://doi.org/10.1590/1809-4430-eng.agric.v39n2p216-224/2019

Arcoverde, S.N.S., Souza, C.M.A., Suarez, A.H.T., Colman, B.A., Nagahama, H.J. 2019b. Atributos físicos do solo cultivado com cana-de-açúcar em função do preparo e época de amostragem. Revista de Agricultura Neotropical, 6(1), 41-47. http://dx.doi.org/10.32404/rean.v6i1.2761

ASABE. American Society of Agricultural and Biological Engineers. 2006. Soil cone penetrometer. ASABE, p902-904. (ASABE standard: ASAE S313.3 FEB04).

Awe, G.O., Reichert, J.M., Fontanela, E.F. 2020. Sugarcane production in the subtropics: Seasonal changes in soil properties and crop yield in no-tillage, inverting and minimum tillage. Soil & Tillage Research, 196: 104447. https://doi.org/10.1016/j.still.2019.104447

Baquero, J.E., Ralisch, R., Conti, M., Tavares Filho, C., Guimarães, M.F. 2012. Soil physical properties and sugarcane root growth in a red oxisol. Revista Brasileira de Ciência do Solo, 36(1), 63-70. https://doi.org/10.1590/S0100-06832012000100007

Barbosa, J.C., Maldonado Junior, W. 2015. AgroEstat – sistema para análises estatísticas de ensaios agronômicos. Jaboticabal: FCAV/UNESP, 396p

Barbosa, L.C., Magalhães, P.S.G., Bordonal, R.O., Cherubin, M.R., Castioni, G.A.F., Tenelli, S., Franco, H.C.J., Carvalho, J.L.N. 2019. Soil physical quality associated with tillage practices during sugarcane planting in south-central Brazil. Soil & Tillage Research, 195: 104383. https://doi.org/10.1016/j.still.2019.104383

Barbosa, L.C., Souza, Z.M., Franco, H.C.J., Otto, R., Rossi Neto, J., Garside, A.L., Carvalho, J.L.N. 2018. Soil texture affects root penetration in Oxisols under sugarcane in Brazil. Geoderma Regional, 13, 15-25. https://doi.org/10.1016/j.geodrs.2018.03.002

Barbosa, V.F.A.M. 2013. Sistemas de Plantio, in: Santos, F., Borém, A. (Eds.), Cana-de-Açúcar: Do Plantio à Colheita. Editora UFV, Viçosa/MG, p. 27-48

Castioni, G.A.F., Cherubin, M.R., Bordonal, R.O., Barbosa, L.C., Menandro, L.M.S., Carvalho, J.L.N. 2019. Straw Removal Affects Soil Physical Quality and Sugarcane Yield in Brazil. BioEnergy Research, 12:789–800. https://doi.org/10.1007/s12155-019-10000-1

Celik, I., Gunal, H., Budak, M., Akpinar, C. 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semiarid Mediterranean soil conditions. Geoderma, 160(2), 236-43. https://doi.org/10.1016/j.geoderma.2010.09.028

Cherubin, M.R., Carvalho, J.L.N., Cerri, C.E.P., Nogueira, L.A.H., Souza, G.M., Cantarella, H. 2021. Land use and management effects on sustainable sugarcane-derived bioenergy. Land, 10(1):72. https://doi.org/10.3390/land10010072

Cherubin, M.R., Karlen, D.L., Franco, A.L., Tormena, C.A., Cerri, C.E., Davies, C.A., Cerri, C.C. 2016. Soil physical quality response to sugarcane expansion in Brazil. Geoderma, 267: 156-168. https://doi.org/10.1016/j.geoderma.2016.01.004

CONAB. Companhia Nacional de Abastecimento. Safra Brasileira de Cana-de-Açúcar. 2024. Produção de cana-de-açúcar na safra 2023/24 chega a 713,2 milhões de toneladas, a maior da série histórica. Available at: https://www.conab.gov.br/info-agro/safras/cana.

Drescher, M.S., Reinert, D.J., Denardin, J.E., Gubiani, P.I., Faganello, A., Drescher, G.L. 2016. Duração das alterações em propriedades físico-hídricas de latossolo argiloso decorrentes da escarificação mecânica. Pesquisa Agropecuária Brasileira, 51(02), 159-168. https://doi.org/10.1590/S0100-204X2016000200008

Farhate, C.V.V., Souza, Z.M., Cherubin, M.R., Lovera, L.H., Oliveira, I.N., Guimarães Júnnyor, W.S., Scala Junior, N.L. 2022. Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage. Revista Brasileira de Ciência do Solo, 46:e0210123. https://doi.org/10.36783/18069657rbcs20210123

Fietz, C.R., Fisch, G.F., Comunello, E., Flumignan, D.L. 2017. O clima da região de Dourados, MS. Dourados, Embrapa Agropecuária Oeste. Dourados, MS: Embrapa (Série Documentos, 138).

Hair-JR, J.F., Black, A.C., Babin, B.J., Anderson, R.E., Tatham, R.L. 2009. Análise multivariada de dados. 6. ed. Porto Alegre, RS: Bookman, 688 p.

Hillel, D. 1980. Fundamentals of soil physics. New York: Academic, 413 p.

Landim, P.M.B. 2011. Análise estatística de dados geológicos multivariados. 1. ed. São Paulo, SP: Oficina de textos, 208 p

Marasca, I., Lemos, S.V., Silva, R.B., Guerra, S.P.S., Lanças, K.P. 2015. Soil Compaction Curve of an Oxisol under Sugarcane Planted after In-Row Deep Tillage. Revista Brasileira de Ciência do Solo, 39(5),1490-1497. https://doi.org/10.1590/01000683rbcs20140559

Martíni, A., Valani, G., Silva, L.F.S., Paula, S., Bolonhezi, D., Cooper, M. 2023. Soil physical quality response to management systems in a long-term sugarcane trial. Land Degradation & Development, 35(4), 1-15. https://doi.org/10.1002/ldr.4988

Melo, N.C., Fernandes, C., Pinheiro, D.P. 2025. Impact of scarification on soil physical quality and sugarcane production in southeastern Brazil. Rev. Caatinga, 38: e12734. https://doi.org/10.1590/1983-21252025v3812734rc

Melo, P.L.A., Cherubin, M.R., Gomes, T.C.A., Lisboa, I.P., Satiro, L.S., Cerri, C.E.P., Siqueira-Neto, M. 2020. Straw removal effects on sugarcane root system and stalk yield. Agronomy, 10: e1048. https://doi.org/10.3390/agronomy10071048

Moraes, L.A.S., Tavares Filho, J., Melo, T.R., Moraes, L.A.A., Tavares Filho, J., Melo, T.R. 2022. Different managements in conventional sugarcane reform in sandy soils: effects on physical properties and soil organic carbon. Revista Brasileira de Ciência do Solo, 46:e0220017. https://doi.org/10.36783/18069657rbcs20220017