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Evaluation of limestone rates and incorporation methods in a Latossol

Evaluación de dosis de caliza y métodos de incorporación en un Latossol

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Abstract

Practices such as liming, whether incorporated or not, can be beneficial for improving the productivity of agricultural crops. The objective of this study was to evaluate soil physical properties as a function of limestone rates and incorporation methods. The experimental design was strip-based, covering approximately 2.03 ha. The treatments consisted of four limestone rates: rate 1, with 5800 Mg ha^{-1}; rate 2, with 9600 Mg ha^{-1}; rate 3, with 13 400 Mg ha^{-1}; and rate 4, with 17 400 Mg ha^{-1}. These rates were incorporated in three ways: A, using a 36-inch disc harrow; B, using a moldboard plow; and C, using a subsoiler. The evaluated soil physical attributes were soil bulk density, gravimetric moisture, volumetric moisture, total porosity, macroporosity, microporosity, penetration resistance, and water-dispersible clay. The application of increasing limestone rates improved soil physical properties, with the rate of 17 400 Mg ha^{-1} providing the best results for the variables analyzed, except for soil bulk density. Among the incorporation methods, the use of a subsoiler was effective in enhancing soil physical properties.

Keywords: Disc harrow, moldboard plow, soil tillage system, subsoiler, *Zea mays*.

Resumen

Prácticas como el encalado, incorporadas o no, pueden ser beneficiosas para mejorar la productividad de los cultivos agrícolas. El objetivo de este estudio fue evaluar las propiedades físicas del suelo en función de las dosis de caliza y los métodos de incorporación. El diseño experimental fue en franjas, cubriendo aproximadamente 2.03 ha. Los tratamientos consistieron en cuatro dosis de caliza: tasa 1, con 5800 Mg ha^{-1}; tasa 2, con 9600 Mg ha^{-1}; tasa 3, con 13 400 Mg ha^{-1}; y tasa 4, con 17 400 Mg ha^{-1}. Estas dosis se incorporaron de tres maneras: A, con una grada de discos de 36 pulgadas; B, con un arado de vertedera; y C, con un subsolador. Los atributos físicos del suelo evaluados fueron densidad aparente, humedad gravimétrica, humedad volumétrica, porosidad total, macroporosidad, microporosidad, resistencia a la penetración y arcilla dispersable en agua. La aplicación de dosis crecientes de caliza mejoró las propiedades físicas del suelo, siendo la dosis de 17 400 Mg ha^{-1} la que mostró los mejores resultados para las variables analizadas, excepto para la densidad aparente. El método de incorporación con subsolador fue eficaz para mejorar las propiedades físicas del suelo.

Palabras clave: arado de vertedera, grada de discos, sistema de labranza del suelo, subsolador, *Zea mays*.

Introduction

Corn (*Zea mays* L.) is the most widely cultivated cereal worldwide, playing a crucial role in Brazilian agriculture, particularly in the Cerrado region, where technological advancements have enabled high productivity despite inherent soils limitations. In this context, Brazil has invested in research to improve cultivation practices, aiming to increase productivity in a sustainable manner. In the 2023/2024 crop season, the country achieved a production of 122 million tons over an area of 21.19 million hectares, according to data from CONAB (2025).

The state of Goiás, where this study was conducted, is a representative area of this expansion, characterized by flat to gently undulating topography, large-scale farming, and the adoption of integrated soil management practices. However, the intensive use of agricultural machinery and inadequate soil management have contributed to physical degradation, particularly compaction, which restricts root growth, water infiltration, and nutrient availability (Pedrão *et al.*, 2025).

Liming is one of the practices related to crop productivity. It is considered a routine soil preparation step in Brazilian farms, and its effects are associated with increased pH, higher exchangeable levels of calcium and magnesium (essential nutrients for corn development), greater cation exchange capacity, and reduced levels of toxic aluminium for plants (Carmo and Silva, 2016).

Limestone can be applied to the soil in various ways, both in no-till and conventional tillage systems. According to Caires *et al.* (2003), surface application of limestone corrects acidity and improves chemical attributes over time, creating a downward alkaline zone that reduces acidification in critical areas. In conventional tillage systems, an acceleration in organic matter degradation is commonly observed due to the disintegration of aggregates in the prepared layer.

Globally, it is estimated that between 30 % and 50 % of agricultural production is influenced by the use of commercial fertilizers (Alves Júnior *et al.*, 2024). Under the conditions of Brazilian soils, however, this estimate appears underestimated, as agriculture in soils not corrected for acidity often results in low productivity due to the limited availability of most nutrients (Silva *et al.*, 2021).

Deep plowing can assist in the incorporation of soil amendments and in improving the environment for root growth. Subsoiling promotes the rupture of compacted or dense layers, thereby facilitating root penetration and water infiltration into deeper soil layers (Cortes *et al.*, 2023).

Soil compaction not only hinders root development by creating mechanical barriers but also negatively affects essential processes, such as aeration, air and water conductivity, heat transfer, water infiltration, and redistribution, as well as chemical processes (Rodrigues *et al.*, 2023). The detection of compacted soil layers is commonly performed through the evaluation of soil penetration resistance, both in relation to root growth and cultivation tools. This assessment provides significant insights for identifying conditions that may limit plant root development (Gomes Junior *et al.*, 2023).

Among other factors, the application of liming at different rates has been shown to promote clay dispersion, which contributes, among other benefits, to straw decomposition (Diniz *et al.*, 2019). Based on this context, the hypothesis of this study is that both limestone rates and incorporation methods can positively influence the physical properties of a Latossol. Therefore, the objective of this study was to evaluate soil physical attributes as a function of limestone rates and incorporation methods in corn cultivation in Chapadão do Céu, Goiás, Brazil.

Material and methods

The experiment was conducted in the municipality of Chapadão do Céu, Goiás, Brazil, at Fazenda Alvorada, with coordinates 10º30’102.49’’ S, 52º43’11.20’’ W, at an altitude of 820 m. The regional climate is classified as Aw according to the Köppen-Geiger system, characterized as tropical with a dry winter. Chapadão do Céu has an average annual temperature of 22.8 °C.

During the crop season, the rainiest months were January, March, and April, with average rainfall of approximately 350 mm. The initial developmental stage of the crop coincides with a period of high water demand, considering that the total water requirement throughout the entire crop cycle is approximately 600 mm (Andrade *et al.*, 2006). In contrast, the months of July and August showed lower rainfall. The highest temperature (25.4 °C) was recorded at the end of October 2022, whereas the lowest (14.4 °C) occurred at the beginning of November 2022.

The soil in the region was classified as Latossol (Latossolo Vermelho distroférrico), with a clayey texture (Santos *et al.*, 2018). Table 1 presents the chemical analysis of the experimental area. All determinations were performed according to the methodology proposed by Teixeira *et al.* (2017).

Area history

This experiment has been conducted since September 2021, aiming to determine the most appropriate limestone rate and incorporation method for annual crop cultivation. The preceding crop was soybean (*Glycine max* (L.)), cultivar Aporé. Soybean sowing was carried out on October 25, 2022, with 11 seeds per meter, and harvesting took place on February 26, 2023.

Table 1. Chemical characterization (plot averages) and granulometric composition of the soil at a depth of 0 m – 0.2 m in the experimental area, Chapadão do Sul, MS, Brazil, 2023

Depth (m)	OM	pH	P	Ca	Mg	K	Al	H+Al	SB	CECe	CEC
	g dm^{-3}	$CaCl_2$	mg dm^{-3}	cmolc dm^{-3}							
0–0.20	34.39	5.37	36.03	3.91	1.30	0.35	0.06	4.14	5.56	5.62	9.70
Depth (m)	V	m	S	B	Cu	Fe	Mn	Zn	Clay	Silt	Sand
	%		mg dm^{-3}						%		
0–0.20	57.31	0.62	323.60	0.53	0.80	65.92	11.45	3.98	55.00	12.50	32.50

*OM: organic matter, pH: hydrogen potential, P: phosphorus, Ca: calcium, Mg: magnesium, K: potassium; Al: aluminum, H+Al: hydrogen + aluminum, SB: sum of bases, CECe: equivalent cation exchange capacity, CEC: cation exchange capacity, V%: base saturation, m%: aluminum saturation, S: sulfur, B: boron, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc.

Corn sowing was performed on March 8, 2023, using mechanical planting and the cultivar DKB360, with a distribution of 2.5 seeds per meter and a row spacing of 0.45 m. At sowing, base fertilization was applied using 0.030 Mg ha^{-1} of NPK in the formulation 10–46–00. Potassium topdressing was performed with 0.100 Mg ha^{-1} of KCl in the formulation 00–00–60, followed by nitrogen topdressing with 0.240 Mg ha^{-1} of N in the formulation 46–00–00.

Experimental design and treatments

The experimental design was a strip-plot arrangement in randomized blocks. Limestone rates (four levels) were assigned to the longer dimension of the strips (1500 m in length), while incorporation methods (three levels) were assigned to the shorter dimension (13.50 m in width). Each strip measured 1500 m x 13.50 m, corresponding to an area of 2.03 ha per strip.

The treatments consisted of four limestone rates: rate 1, 5800 Mg ha^{-1}; rate 2, 9600 Mg ha^{-1}; rate 3, 13 400 Mg ha^{-1}; and rate 4, 17 400 Mg ha^{-1}. These rates were incorporated using three different methods: A, a 36-inch disc harrow; B, a moldboard plow; and C, a subsoiler. The combination of these factors resulted in 12 treatments, described as follows:

- T1: 36-inch disc harrow + 5800 Mg ha^{-1} of limestone.
- T2: Moldboard plow + 5.800 Mg ha^{-1} of limestone.
- T3: Subsoiler + 5800 Mg ha^{-1} of limestone.
- T4: 36-inch disc harrow + 9600 Mg ha^{-1} of limestone.
- T5: Moldboard plow + 9600 Mg ha^{-1} of limestone.
- T6: Subsoiler + 9600 Mg ha^{-1} of limestone.
- T7: 36-inch disc harrow + 13 400 Mg ha^{-1} of limestone.
- T8: Moldboard plow + 13 400 Mg ha^{-1} of limestone.
- T9: Subsoiler + 13 400 Mg ha^{-1} of limestone.
- T10: 36-inch disc harrow + 17 400 Mg ha^{-1} of limestone.
- T11: Moldboard plow + 17 400 Mg ha^{-1} of limestone.
- T12: Subsoiler + 17 400 Mg ha^{-1} of limestone.

The implements were operated at their typical working depths: the 36-inch disc harrow at 20 cm – 25 cm, the moldboard plow at 20 cm – 30 cm, and the subsoiler at 30 cm – 50 cm, in accordance with regional practices for soil preparation and compaction mitigation.

The limestone used in the experiment was dolomitic, containing 18 % MgO, 30 % CaO, and a Relative Neutralizing Value (RNV) of 85 %, and was applied by broadcasting. For the collection of soil physical samples, trenches measuring 0.50 m in width, 0.50 m in length, and 0.40 m in depth were opened. Samples were collected at depths of 0 m – 0.10 m and 0.10 m – 0.20 m.

The soil physical attributes analyzed were soil bulk density (BD), total porosity (TP), macroporosity (MACRO), microporosity (MICRO), penetration resistance (PR), gravimetric moisture (GM), and volumetric moisture (VM). Soil samples for BD, TP, MACRO, MICRO, GM, and VM were collected in May 2023, approximately two months after limestone application, incorporation, and corn sowing, allowing for initial soil-amendment interaction. Penetration resistance (PR) was evaluated on May 15, 2023. All determinations were performed according to the methodology proposed by Teixeira *et al.* (2017).

Soil bulk density (BD) was calculated using the volumetric ring method, and total porosity (TP) was calculated according to Equation 1, as described by Teixeira *et al*. (2017):

$$TP=[(a-b)-(c-d)]/e \qquad \textbf{(Eq. 1)}$$

Where TP is the total porosity (m^3 m^{-3}); *a* is the mass of the saturated sample-ring-cloth-tie set (kg); *b* is the mass of the sample-ring-cloth-tie set dried at 105 °C (kg); *c* is the mass of the saturated ring-cloth-tie set (kg); *d* is the mass of the ring-cloth-tie set dried at 105 °C (kg); and *e* is the total volume of the sample (m^3). In this case, the total volume of the sample was assumed to be equal to the volume of the cylinder.

Microporosity was determined using the tension table method, in which samples were subjected to a 0.60 m water column. Macroporosity was calculated as the difference between microporosity and total porosity.

Penetration resistance (PR), referring to the mean resistance along the soil profile from 0 m to 0.60 m depth, was measured using a Falker PenetroLOG-PLG 1020 digital penetrometer. The equipment was configured to record readings at 5 mm intervals, with a constant penetration speed and results expressed in MPa. Measurements were performed on May 15, 2023, with three sampling points collected per treatment and their replicates.

Subsequently, disturbed soil samples were collected for the determination of gravimetric moisture (GM), expressed as percentage (g of water per 100 g of dry soil), using a Dutch auger. The samples were transported to the Soil Laboratory at the Federal University of Mato Grosso do Sul (UFMS), where they were weighed to obtain wet mass. Samples were then dried in a forced-air circulation oven at 105 °C until constant weight was achieved and weighed again after cooling in a desiccator.

Gravimetric moisture was calculated using Equation 2:

$$GM=mw/ms \qquad \textbf{(Eq. 2)}$$

Where GM is the gravimetric moisture (%); *mw* is the mass of water (g); and *ms* is the mass of dry soil (g).

Volumetric moisture (VM), expressed as a percentage (cm^3 of water per 100 cm^3 of soil), represents the volume of water contained within a given volume of soil and was calculated after determining GM, using Equation 3:

$$VM = GM.BD \qquad \textbf{(Eq. 3)}$$

Where VM is the volumetric moisture (%); GM is the gravimetric moisture (%); and BD is the soil bulk density (cm^3).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) using a randomized block design. Mean comparison for soil depths and incorporation methods were performed using Tukey's test at a significance level of $p \leq 0.05$. Polynomial regression analysis was applied to evaluate the effects of limestone rates, using the Sisvar software (Ferreira, 2019).

Results and discussion

The analysis of variance indicated that the variables soil bulk density (BD), gravimetric moisture (GM), volumetric moisture (VM), total porosity (TP), microporosity (MICRO), and macroporosity (MACRO) were significantly affected by limestone rates and incorporation methods (Table 2). In contrast, the interaction between limestone rates and incorporation methods was significant for BD, TP, MICRO, and MACRO.

According to the analysis of variance (Table 2), both limestone rates and incorporation methods significantly influenced soil macroporosity and microporosity ($p \leq 0.05$). In addition, a significant interaction between these factors was observed for both porosity variables, indicating that the effect of the incorporation method depended on the limestone rate applied. This result highlights the importance of appropriate limestone incorporation to optimize soil pore space distribution. Crop growth is directly and positively related to soil porosity, as it influences air exchange, water retention, and root exploration (Oliveira *et al*., 2023).

Soil bulk density was significantly influenced by the incorporation methods evaluated. Figures 1 and 2 illustrate the interaction between soil bulk density and limestone rates under different incorporation methods. At limestone rates of 5800 Mg ha^{-1} and 17 400 Mg ha^{-1}, the subsoiler showed the best results, statistically differing from the 36-inch disc harrow and the moldboard plow. At the rate of 9600 Mg ha^{-1}, the moldboard plow and the subsoiler showed better results but did not differ statistically from the 36-inch disc harrow. At the rate of 13 400 Mg ha^{-1}, the subsoiler showed the best performance, differing statistically from the 36-inch disc harrow but not from the moldboard plow.

Soil bulk density was significantly influenced by the interaction between limestone rates and incorporation methods ($p < 0.05$). At the limestone rate of 5800 Mg ha^{-1}, the 36-inch disk harrow showed the lowest bulk density value (1.16 g cm^{-3}), differing significantly from the moldboard plow and the subsoiler. Similarly, at the rate of 17 400 Mg ha^{-1}, the 36-inch disk harrow showed the lowest bulk density (1.14 g cm^{-3}), also differing from the moldboard plow and the subsoiler. At intermediate limestone rates (9600 Mg ha^{-1} and 13 400 Mg ha^{-1}), no significant differences were observed among the methods.

In clayey soils, Reinert *et al.* (2006) reported soil bulk density values ranging from 0.9 g cm^{-3} to 1.7 g cm^{-3}. Thus, the values obtained in the present study fall within the range reported in the literature, which generally varies. Similarly, Bortoluzzi *et al.* (2008) observed no significant variation in soil bulk density as a function of limestone rates and application methods in the 0.0 m – 0.5 m soil layer.

In this study, soil bulk density was significantly influenced by the interaction between limestone rates and incorporation methods (Table 2). For example, at the lowest limestone rate (5800 Mg ha^{-1}), the subsoiler resulted in the lowest bulk density value (1.16 g cm^{-3}), differing significantly from the disc harrow and moldboard plow (Figure 1). This inverse relationship was also evident for porosity-related variables, as treatments with higher bulk density

Table 2. Summary of the analysis of variance for soil depths of 0.0 m – 0.10 m and 0.10 m – 0.20 m as a function of limestone rates and incorporation methods

SV	DF	BD	GM	VM	TP	MICRO	MACRO
Block	2	0.006*	25185.9*	382.7*	0.032*	0.029*	0.01*
Doses (D)	3	0.0696*	487977.0*	23043.8*	2.454*	2.452*	0.736*
Incorporation (I)	2	0.0636*	49906.8*	4047.4*	0.299*	0.279*	0.093*
Depth (P)	1	0.0054 ns	345.9 ns	145.4 ns	0.002 ns	0.003 ns	0.000 ns
D x I	6	0.0565*	10001.8 ns	343.1 ns	0.015*	0.016*	0.010*
D x P	3	0.0035 ns	478.1 ns	177.8 ns	0.002 ns	0.005 ns	0.001 ns
I x P	2	0.0000 ns	2395.1 ns	43.0 ns	0.003 ns	0.005 ns	0.000 ns
D x I x P	6	0.0032 ns	2633.1 ns	278.8 ns	0.004 ns	0.005 ns	0.002 ns
Error	46	0.0060	6616.2	173.5	0.005	0.004	0.003
CV (%)		6.16	43.89	15.16	7.42	7.64	11.29
Media		1.26	185.33	86.92	0.97	0.91	0.51

*ns and *: not significant and significant at the 5 % probability level by the F-test, respectively. SV: sources of variation, DF: degrees of freedom, CV: coefficient of variation, BD: soil bulk density, TP: total porosity, MACRO: macroporosity, MICRO: microporosity, PR: penetration resistance, GM: gravimetric moisture, and VM: volumetric moisture.

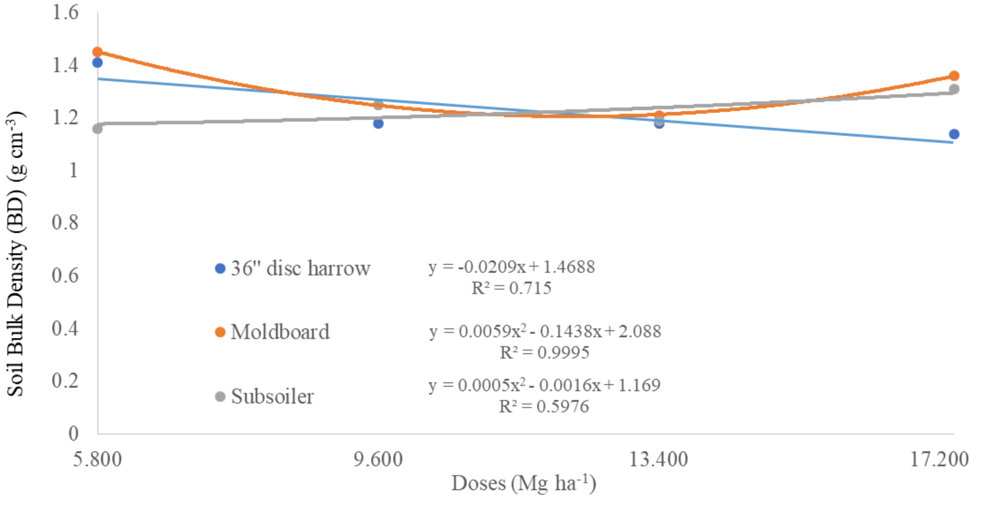

Figure 1. Soil bulk density (g cm^{-3}) as a function of limestone rates and incorporation methods.

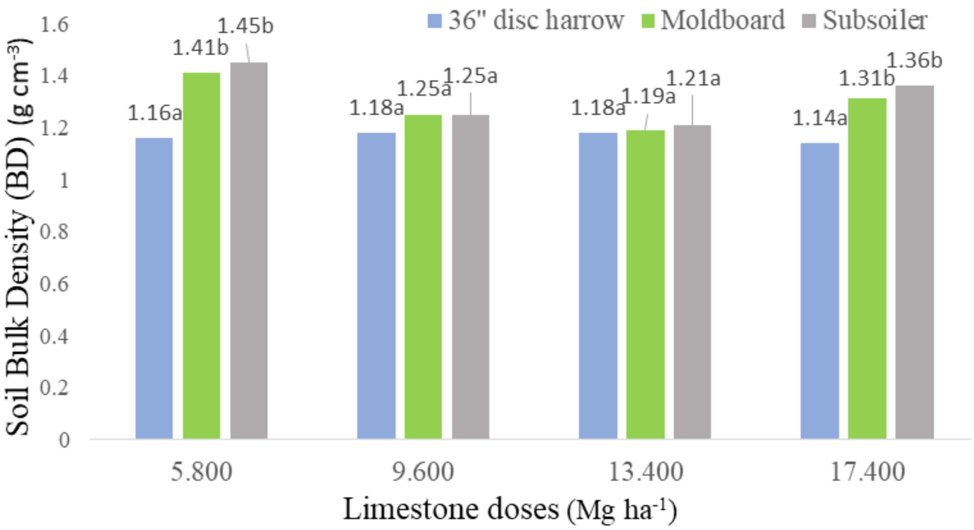

Figure 2. Soil bulk density as a function of limestone rates and three soil incorporation methods. Different lowercase letters above the bars indicate significant differences among incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

values—such as the disc harrow at 5800 Mg ha^{-1} (1.41 g cm^{-3})—were associated with lower total porosity and macroporosity (Table 2). These results indicate that the choice of incorporation method can substantially alter soil compaction status, with subsoiling promoting a less dense and more porous structure, particularly at lower limestone rates. Some compaction states are known to induce changes in soil structure, leading to increased soil bulk density and penetration resistance (Oliveira *et al.*, 2020).

Gravimetric moisture as a function of limestone rates showed that soil moisture increased with increasing limestone application (Figure 3). This response can be attributed to improvements in soil structure promoted by liming, which enhance aggregation and porosity and, consequently, increase the soil's water retention capacity. Furthermore, the reduction in exchangeable aluminium and the increased availability of calcium and magnesium favor root development, allowing greater water uptake and storage in the soil profile.

Bortoluzzi *et al.* (2008) reported an increase of up to 90 % in gravimetric moisture with increasing limestone rates. At the limestone rate of 13 400 Mg ha^{-1}, the subsoiler and moldboard plow showed better results compared to the 36-inch disc harrow, likely due to the deeper soil disturbance caused by the subsoiler, which enhances water infiltration and reduces surface runoff. However, at the rate of 17 400 Mg ha^{-1}, no significant differences were observed among incorporation methods, suggesting that under high limestone doses, improvements in soil physical conditions are sufficient to maintain moisture regardless of the incorporation method used.

Figure 4 shows the relationship between volumetric moisture and limestone rates under different incorporation methods. An increase in soil volumetric moisture was observed at rates of 5800 Mg ha^{-1}, 9600 Mg ha^{-1}, and 13 400 Mg ha^{-1} as the application rate increased. At the rate of 17 400 Mg ha^{-1}, the subsoiler resulted in the highest volumetric moisture values, differing statistically from the other incorporation methods.

Figure 5 illustrates the interaction between total soil porosity and limestone rates under different incorporation methods. The analysis of variance revealed a significant interaction ($p \leq 0.05$) between limestone rates and incorporation methods for total porosity (Table 2), indicating that the effect of the incorporation method depends on the limestone rate applied. Individually, both factors significantly influenced total porosity: increasing limestone rates generally enhanced porosity, and among the incorporation methods, the subsoiler tended to promote higher porosity values, particularly at lower limestone rates.

At limestone rates of 5800 Mg ha^{-1} and 9600 Mg ha^{-1}, the subsoiler showed the best results, differing significantly from the other incorporation methods. At rates of 13 400 Mg ha^{-1} and 17 400 Mg ha^{-1}, both the moldboard plow and the subsoiler showed better results compared to the 36-inch disc harrow for this variable. Total soil porosity represents the sum of macro- and micropores; therefore, an increase in one pore class may result in a proportional reduction in the other.

The interaction between soil microporosity and limestone rates under different incorporation methods indicates that, at limestone rates of

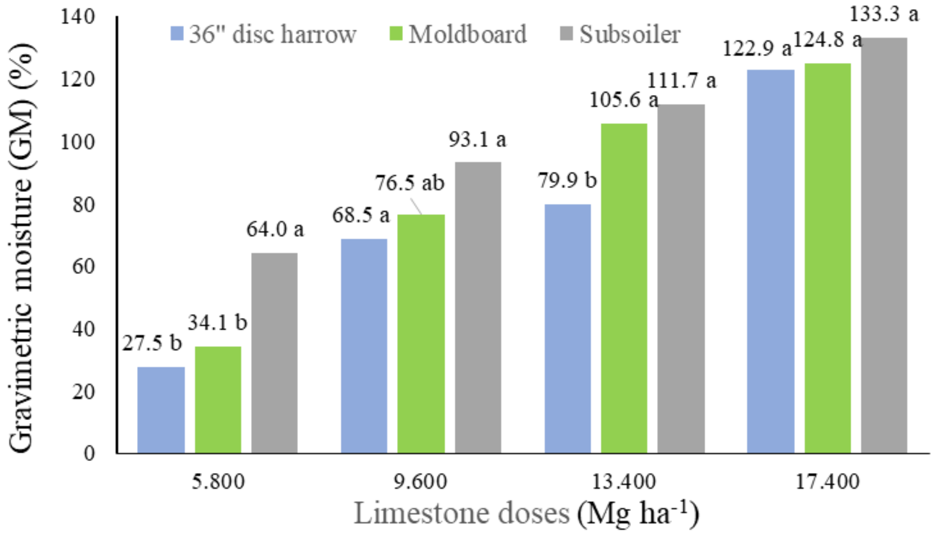

Figure 3. Gravimetric moisture as a function of limestone rates and three soil incorporation methods. Different lowercase letters above the bars indicate significant differences among incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

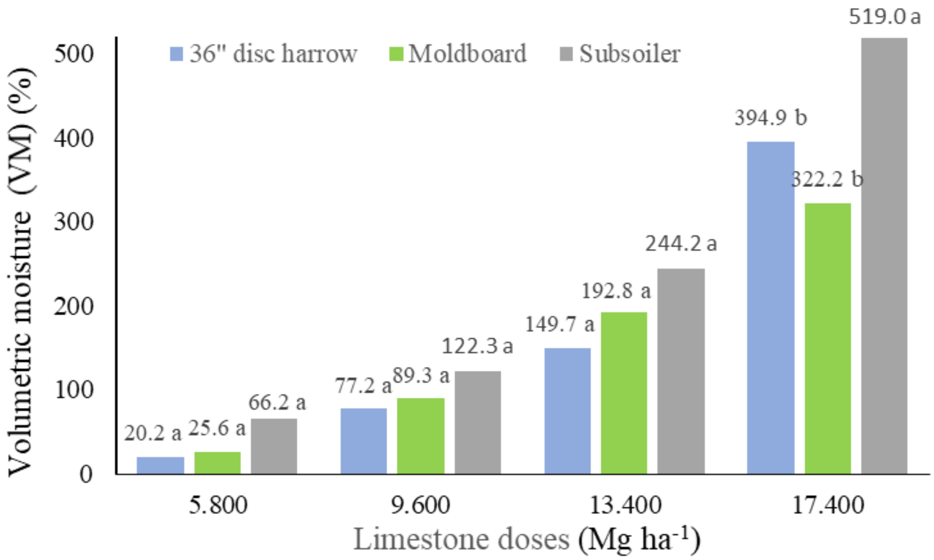

Figure 4. Volumetric moisture as a function of limestone rates and three soil incorporation methods. Different lowercase letters above the bars indicate significant differences among incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

5800 Mg ha^{-1} and 9600 Mg ha^{-1}, the subsoiler presented the best results (Figure 6). At rates of 13 400 Mg ha^{-1} and 17 400 Mg ha^{-1}, both the moldboard plow and the subsoiler showed better performance regarding soil microporosity. Clay content, which is directly associated with soil microporosity, is strongly influenced by several soil-forming factors, including geological and pedological processes, climatic and weathering conditions, and topography (Oliveira *et al*., 2025).

At limestone rates of 9600 Mg ha^{-1} and 13 400 Mg ha^{-1}, the subsoiler resulted in higher microporosity values compared to the 36-inch disc harrow and the moldboard plow (Figure 7). The rate of 13 400 Mg ha^{-1} showed the best result with the subsoiler, differing from the moldboard plow and the 36-inch disc harrow. In contrast, no significant differences among incorporation methods were observed at the highest limestone rate (17 400 Mg ha^{-1}). These findings are consistent with those reported by Nogueira *et al.* (2016), who observed that total porosity ($p < 0.01$), macroporosity ($p < 0.05$), and microporosity ($p < 0.01$) were significantly affected by the interaction between soil management practices and the application of limestone and agricultural gypsum at a soil depth of 0.10 m – 0.20 m.

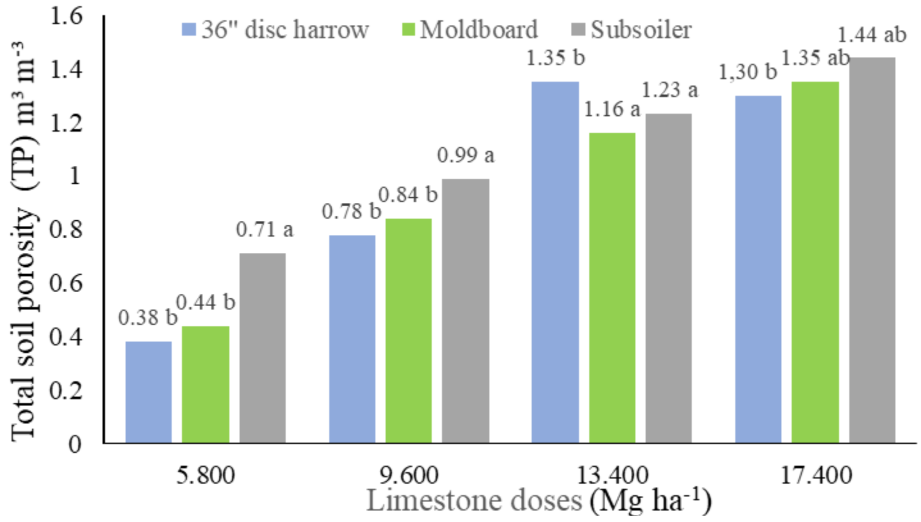

Figure 5. Total soil porosity as a function of limestone rates and three soil incorporation methods. Different lowercase letters above the bars indicate significant differences among incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

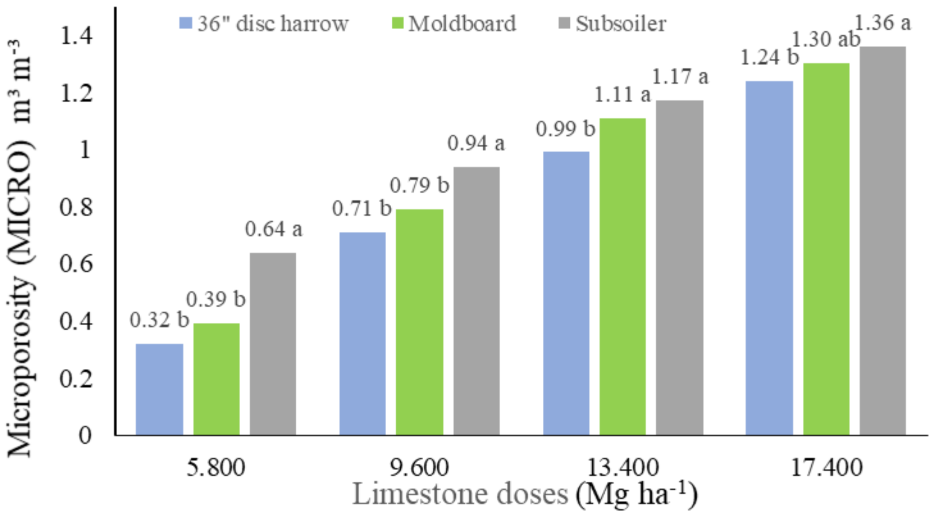

Figure 6. Soil microporosity in relation to limestone rates and soil incorporation methods. Different lowercase letters above the bars indicate significant differences between incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

Figure 8 presents the penetration resistance values observed across treatments. The least compacted layer was recorded at 0.10 m depth for treatment T3 (subsoiler combined with 5800 Mg ha^{-1} of limestone). In contrast, treatments T1, T4, T5, T7, T9, T10, and T11 exhibited compacted soil layers, with penetration resistance values exceeding 2 MPa, as shown in Figure 8. Among these, treatment 4 showed the highest degree of soil compaction, with penetration resistance values of approximately 2.8 MPa. This treatment exhibited a compacted layer extending from 0.15 m to 0.55 m depth, with the highest penetration resistance observed at 0.30 m depth.

*Treatments were defined as follows: T1, 36-inch disc harrow + 5800 Mg ha^{-1} of limestone; T2, moldboard plow + 5800 Mg ha^{-1}; T3, subsoiler + 5800 Mg ha^{-1}; T4, 36-inch disc harrow + 9600 Mg ha^{-1}`; T5, moldboard plow + 9600 Mg ha^{-1}; T6, subsoiler + 9600 Mg ha^{-1}; T7, 36-inch disc harrow + 13 400 Mg ha^{-1}; T8, moldboard plow + 13 400 Mg ha^{-1}; T9, subsoiler + 13 400 Mg ha^{-1}; T10, 36-inch disc harrow + 17 400 Mg ha^{-1}; T11, moldboard plow + 17 400 Mg ha^{-1}; and T12, subsoiler + 17 400 Mg ha^{-1}.

The treatment showing the highest degree of soil compaction was T4 (36-inch disc harrow combined with 9600 Mg ha^{-1}), with penetration resistance values

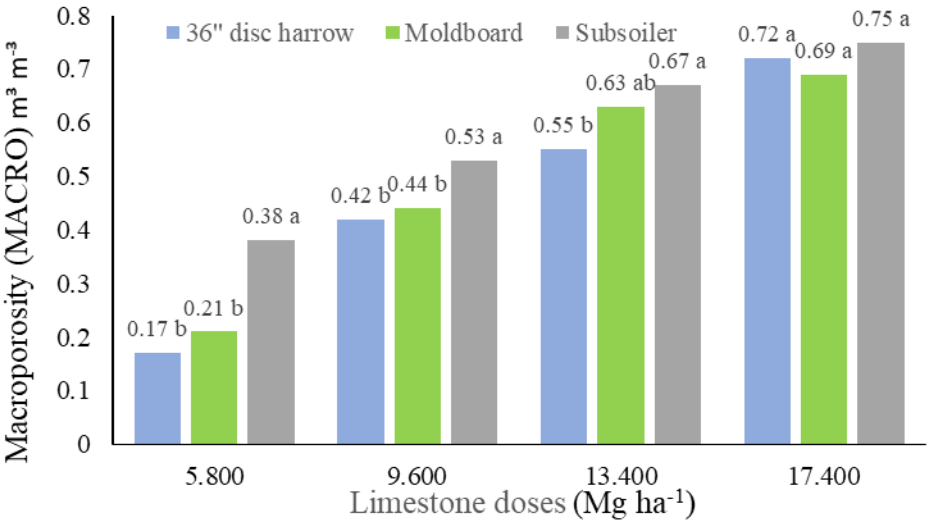

Figure 7. Soil macroporosity as a function of limestone rates and three incorporation methods. Different lowercase letters above the bars indicate significant differences among incorporation methods within each limestone rate (Tukey's test, $p \leq 0.05$). Error bars represent the standard deviation.

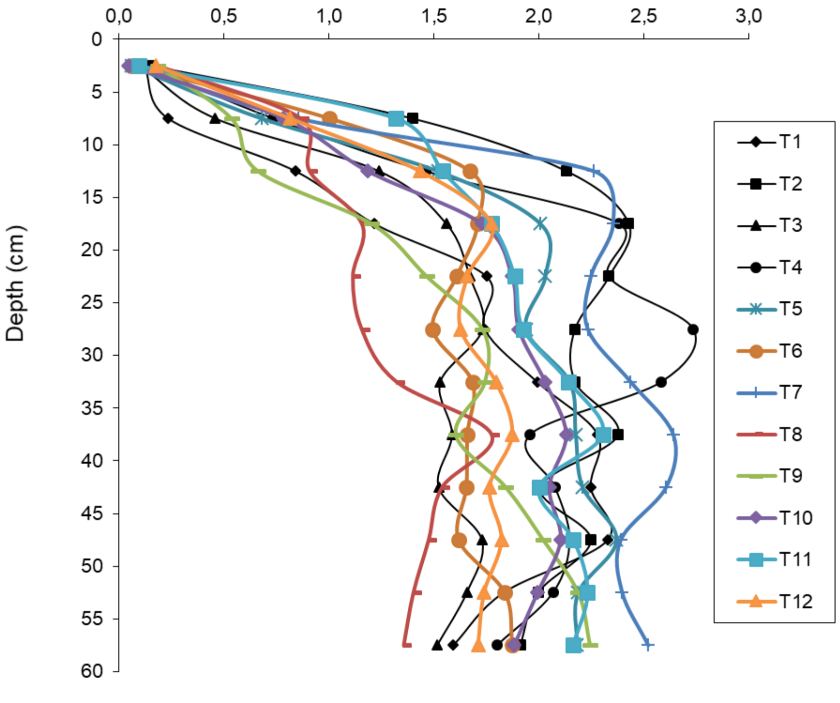

Figure 8. Soil penetration resistance (PR) in relation to limestone rates and three soil incorporation methods.

of approximately 2.8 MPa. This treatment exhibited a compacted layer between 0.15 m and 0.55 m depth, with the highest penetration resistance observed around 0.30 m depth. These results indicate that, among the incorporation methods evaluated, the disc harrow generally promoted greater soil compaction, particularly when combined with intermediate limestone rates. In contrast, the subsoiler resulted in the least compacted conditions, as evidenced by treatment T3 (subsoiler with 5800 Mg ha^{-1}), which showed the lowest penetration resistance values.

However, Tavares Filho *et al*. (2001) demonstrated that penetration resistance values above 3.5 MPa did not limit corn root development or grain yield, affecting only its morphology. As reported by Gavande (1972), increasing soil compaction is typically characterized by higher soil bulk density and reduced total porosity, with a relative increase in the proportion of smaller pores at the expense of larger ones.

Figure 8 shows the penetration resistance values obtained in the field. The highest RP values in relation to the treatments were found in the 0.10 m – 0.40 m soil layer, reaching approximately 2.5 MPa, exceeding the recommended levels. From a depth of 0.10 m onward, several treatments exhibited penetration resistance values above 2.0 MPa, indicating the presence of soil compaction. According to Lal (2000), mechanical penetration resistance values ranging from 2.0 MPa to 4.0 MPa can restrict or even inhibit root growth and development. Based on this criterion, treatments T2, T7, and T4 showed soil compaction at the 0.10 m depth, whereas treatments T5, T10, T11, and T12 exhibited compaction below 0.30 m depth. The remaining treatments presented penetration resistance values below the recommended limit.

Conclusion

The application of increasing limestone rates promoted improvements in soil physical attributes, with the highest rate (17 400 Mg ha^{-1}) providing the most favorable results for the variables evaluated, except for soil bulk density. Among the incorporation methods, the use of a subsoiler proved to be the most effective, particularly in reducing soil compaction and increasing porosity. Moreover, the significant interaction observed between limestone rates and incorporation methods indicates that the response of soil physical properties depends on the limestone rate applied. These findings underscore the importance of jointly considering limestone rates and incorporation methods in the management of Latossols to optimize soil physical quality and support sustainable corn production.

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