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# Variation in soil penetration resistance as a function of soil moisture under crop management systems[1]

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**ABSTRACT** - The objective of this study was to monitor the temporal variation in penetration resistance (PR) after soil saturation under different management systems in three areas of the Cerrado biome: two in no-till systems (NT with 3 and 10 years of implementation) and one of crop-livestock integration (CL with 9 years of implementation) with soybean/forage succession. Four transects were delimited in each area. The delimited area was saturated and the PR measurements were performed daily for 11 days at 10 transect points, up to 0.40 m of depth. Soil moisture was determined with PR measurements, soil hydraulic conductivity, and organic carbon. PR values were more significant in the 0.10 - 0.20 m layer than in the 0.0 - 0.10 and 0.20 - 0.40 m layers. The NT-3 area showed a lower PR value (1.65 MPa) than the area under NT-10 and CL-9, with 2.48 and 2.69 MPa, respectively. Thus, critical soil moisture values, that is, soil moisture values most susceptible to soil compaction were determined. Thus, in the NT-3 area, the critical moisture was 0.20 kg kg$^{-1}$, in the NT-10, ranged from 0.19 - 0.20 kg kg$^{-1}$, and in the CL-9, between 0.23 and 0.20 kg kg$^{-1}$. Monitoring soil moisture can prevent management operations from restricting root growth.

**Key words**: No-tillage. Integrated crop-livestock. Hydraulic conductivity.

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## INTRODUCTION

Excessive machine traffic on wet soils, associated with low soil cover, increases the susceptibility of the soil to compaction (VIZIOLI *et al.*, 2021). In this context, farmers in the Cerrado biome region have opted for conservationist practices that give priority to the conservation of the straw on the soil surface after cultivation, as well as the quality of soil-plant system properties.

Soil physical quality should be constantly monitored before adopting management strategies to prevent or alleviate soil compaction, regardless of the cultivation system (LUZ *et al.*, 2019). One of the ways to monitor this is to measure soil penetration resistance (PR), which has proved to be effective in conjunction with water content measurement, in the prediction of soil compaction (BENEVENUTE *et al.*, 2020).

Resistance to penetration is related to soil moisture, directly influencing the development of crop root systems. As moisture contents decrease in the soil, its mechanical strength increases, thus impairing root growth (FAUSTINO; MARCIANO, 2021).

Critical penetration resistance values vary with soil type, consistency, and management, among other factors; some authors have adopted values of up to 2.0 MPa for Oxisols (MOURA *et al.*, 2021). However, other authors suggest higher values, as critical limits, in soils under a no-till farming system, arguing that the structural conditions are less restrictive due to the incorporation of plant mass, favoring root growth (MORAES *et al.*, 2014). According to Vizioli *et al.* (2021), in Oxisols, the limiting PR may vary with the crop species grown, with 2.0 MPa being a more conservative value to establish a standard critical penetration resistance.

No-till (NT) and integrated crop-livestock (CL) systems advocate the absence of soil disturbance, with a significant addition of straw, which is important in soil management and conservation. Soils managed under these systems are highly structured, showing more organic matter, improved aggregation index, and increased porosity, which provides good conditions for root development (PIAZZA *et al*., 2020; SILVA *et al*., 2021).

Still, soil physical properties in natural systems, such as native forests, have become a model in relation to soil structure, factors that interact for the consolidation of soil profile, such as soil organic carbon (OC), texture, and bulk density (Bd). Clay soils, for example, have a longer water drying time than sandy soil, which affects the relative dynamics of soil water content and influences plant root system growth (SOUZA *et al*., 2021).

Better evidence of changes in soil physical and chemical properties such as decompaction has been observed with crop diversification, such as the growth of the families Poaceae and Fabaceae, which has been related to the action of different root systems in the soil (FRANCZISKOWSKI *et al.*, 2019). This practice is expected to benefit the agricultural production environment, in addition to benefiting soil physical properties, providing soil protection against impacts from water droplets, increasing organic carbon, and decreasing weed emergence (BÜCHI *et al.*, 2018).

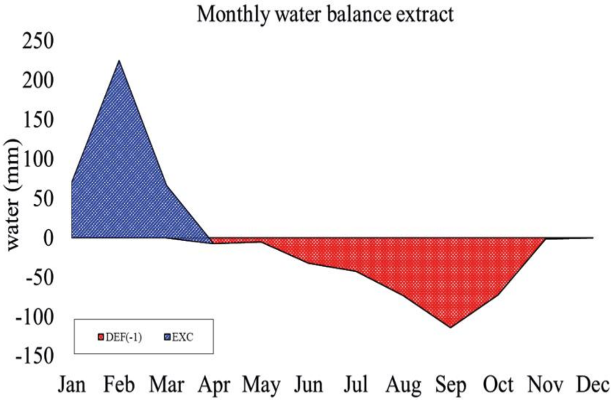
Based on such a perspective, this study aimed to monitor the temporal variation in penetration resistance (PR) after soil saturation and organic carbon contente under different production systems in the Cerrado biome.

## MATERIAL AND METHODS

The experiment was carried out at the Centro Tecnológico of cooperative COMIGO (CTC), in the municipality of Rio Verde, state of Goiás, Brazil. The local climate is classified as B4rB′4a′ (humid, small water deficit, mesothermal, and summer evapotranspiration lower than 48%), according to Köppen's classification. The areas used in the experiment are located at geographic coordinates 17°45′48″ S, 51°02′14″ W, and 832 m altitude. The local soil is classified as a dystrophic Red Latosol (Oxisol).

Climatological normal water balance (Figure 1) was estimated to demonstrate soil water storage during the evaluations, using the method proposed by Thornthwaite and Mather (1955) considering an available water capacity (AWC) of 100 mm.

**Figure 1** - Climatological normal water balance for the municipality of Rio Verde, state of Goiás, Brazil, 2020



Soil management involving liming and plastering is done periodically (every 3 or 4 years) following technical guidelines and annual monitoring by soil analysis. When there is a need for acidity amendment, the same has been done by broadcasting.

Regarding phytosanitary management of pests, diseases, and invasive plants, chemical control is carried out in different periods following management recommendations for the region. After the implementation of the systems, a soil-turning operation was carried out in the planting row during sowing.

Sowing fertilization was similar for all systems and in the furrow by applying 400 kg ha$^{-1}$ of the formulated fertilizer 0 - 20 - 18, which is equivalent to 32, 80, and 72 kg ha$^{-1}$ of nitrogen, phosphorus, and potassium, respectively. The plots had 2,930 m$^2$ and received topdressing fertilization on March 20, 2020, with 200 kg ha$^{-1}$ of the formulated fertilizer 20-00-20, which is equivalent to 40 and 72 kg ha$^{-1}$ of nitrogen and potassium, respectively.

Treatments consisted of areas under different agricultural production systems, namely: two areas under a no-till system (NT) with soybeans (*Glycine max*)/ corn (*Zea mays*) succession established in 2010 and 2018 (NT-3 and NT-10 respectively), an area under an integrated crop-livestock system (CL) with soybeans/ forage (*Urochloa hibrida* cv. Mavuno) succession established in 2011 (CL-9), and an area under native Cerrado vegetation (NV). Table 1 lists the soil textural characterization for each area studied, as well as their sand, silt, and clay contents.

Evaluations started before soybean sowing in the 2020/2021 season and after planting corn hybrid AG 8061 PRO 2 (2019/2020 growing season) in NT-3, and corn hybrid AG 8088 PRO 2 in NT-10. Forage of the *Urochloa hibrida* cv. Mavuno was used in CL-9, with grazing rotated between 7 and 14 days with 20 Nellore calves (average weight of 260.4 kg) in each paddock of 2,930 m$^2$. Grazing started 85 days after forage sowing (May 26, 2020).

Four transects measuring 2 m × 0.25 m were delimited within each area, totaling 16 experimental units + 1 transect in the native vegetation area. These areas were saturated with water contents above the total available water capacity (AWC). According to Albuquerque (2010), the addition of 52 liters of water in an area of 0.30 m$^2$ is sufficient to saturate the soil to a depth of 0.40 m in soils like that studied here.

However, a higher value (160 liters) was adopted due to runoff losses and differences between the studied soil and the soil in which the AWC was estimated. After saturating the delimited areas, PR was measured daily from September 19, 2020, using a Falker® electronic penetrometer to a depth of 0.40 m. PR was measured for 11 consecutive days, always at the same time (9 - 11 am). The areas were covered after measurement to minimize evaporation.

**Table 1** - Particle-size distribution of a dystrophic Red Latosol (Oxisol) in different production systems in the municipality of Rio Verde, state of Goiás, Brazil

| System | Sand (%) | Clay (%) | Silt (%) | Texture class |
|---|---|---|---|---|
| | | 0.00 - 0.10 m | | |
| NT 3 | 44.83 | 46.41 | 8.76 | Clay |
| NT 10 | 59.30 | 35.18 | 5.53 | Clay |
| CL 9 | 57.43 | 35.24 | 7.32 | Clay |
| NV | 64.91 | 29.48 | 5.62 | Medium |
| | | 0.10 - 0.20 m | | |
| NT 3 | 46.21 | 43.26 | 10.53 | Clay |
| NT 10 | 57.41 | 36.22 | 6.38 | Clay |
| CL 9 | 57.06 | 33.78 | 9.71 | Medium |
| NV | 63.42 | 29.71 | 6.88 | Medium |
| | | 0.20 - 0.40 m | | |
| NT 3 | 46.30 | 43.99 | 9.71 | Clay |
| NT 10 | 56.12 | 37.19 | 6.70 | Clay |
| CL 9 | 57.72 | 34.71 | 7.58 | Medium |
| NV | 60.86 | 25.71 | 13.43 | Medium |

NT-3: No-till system with 3 years of implementation; NT-10: No-till system with 10 years of implementation; CL-9: crop-livestock system with 9 years of implementation; NV: native vegetation area

Temporal variation in PR was used to identify at which soil moisture conditions this variable becomes critical and whether it is similar among the agricultural production systems studied. Simultaneously, soil moisture was determined for the depths of 0.00 - 0.10, 0.10 - 0.20, and 0.20 - 0.40 m, using the gravimetric method (TEIXEIRA *et al.*, 2017).

Soil organic carbon (OC) was determined according to the method by Sims and Haby (1971), whose principle is the oxidation of organic matter in a moist pathway with potassium dichromate in a strongly acidic medium ($H_2SO_4$). The results were calculated using a standard curve with 7% sucrose solution.

Dry matter analysis was also carried out by collecting plant material on the soil after the corn crop cycle in the NT and *Urochloa* disposed in the CL. For this, a square of 0.25 $m^2$ was randomly thrown in the plots. The material inside the square was collected and dried in a greenhouse at 140 °C for 72 h to obtain the dry mass. The amount of mass obtained by the square area was expressed as Mg $ha^{-1}$.

Afterward, on November 10, 2020, after 36 mm precipitation, saturated soil hydraulic conductivity (Ksat), a property linked to dynamic processes in the soil, was determined at the sampling points. For this reason, the proposed field method by Bagarello, Iovino and Elrick (2004) was used to assess the impact of management systems on Ksat, known as soil-saturated hydraulic conductivity. For this effect, PVC cylinders (0.10 m in diameter and 0.25 m in height) were inserted into the soil at a depth of 5 cm. The technique consists of applying a small water volume (V) onto the surface of a soil confined by a cylinder (with cross-sectional area A) inserted into the soil and measuring the time (ta) from water application until the moment when the surface is no longer covered by water. Saturated hydraulic conductivity was calculated using Equation (1):

$$K_{sat} = \frac{\Delta\theta}{(1-\Delta\theta)t_{\alpha}}\left[\frac{D}{\Delta\theta} - \frac{D+\left(\frac{1}{\alpha^{*}}\right)}{\Delta\theta} In\left(1+\frac{(1-\Delta\theta)D}{\Delta\theta\left(D+\frac{1}{\alpha^{*}}\right)}\right)\right] \quad (1)$$

Wherein: $\Delta\theta$ is the difference between the water content of saturated soil (or total porosity) and the initial water content, $t_{\alpha}$ is the infiltration time, D is the water depth height (m) at the beginning of the measurement, and α* is the relationship between Ksat and matric potential flow.

The method is suggested by Elrick and Reynolds (1992), defined by a constant value based on soil texture and structure. All measurements were taken using the constant volume of 0.00033 $m^3$, as proposed by Keller *et al.* (2012).

The difference between saturated soil moisture and initial soil moisture was determined from volumetric moisture (TEIXEIRA *et al.*, 2017). A value of $\alpha^* = 12\ m^{-1}$ was used based on the soil texture and structure observed for the conditions in which the experiment was conducted, as indicated by Elrick and Reynolds (1992) and Bagarello, Iovino and Elrick (2004).

Data were interpreted by standard deviation analysis separately for each soil depth. Additionally, daily averages were plotted for each treatment and soil layer, and a linear correlation analysis was performed between the analyzed variables, using the Sigmaplot software.

## RESULTS AND DISCUSSION

Soil moisture in the surface layer (0.00 - 0.10 m) showed a difference ($p < 0.05$) on almost all days evaluated, with the soil under NT-3 showing higher (0.13 - 0.24 g $Kg^{-1}$) values than the other production systems (Figure 2A).

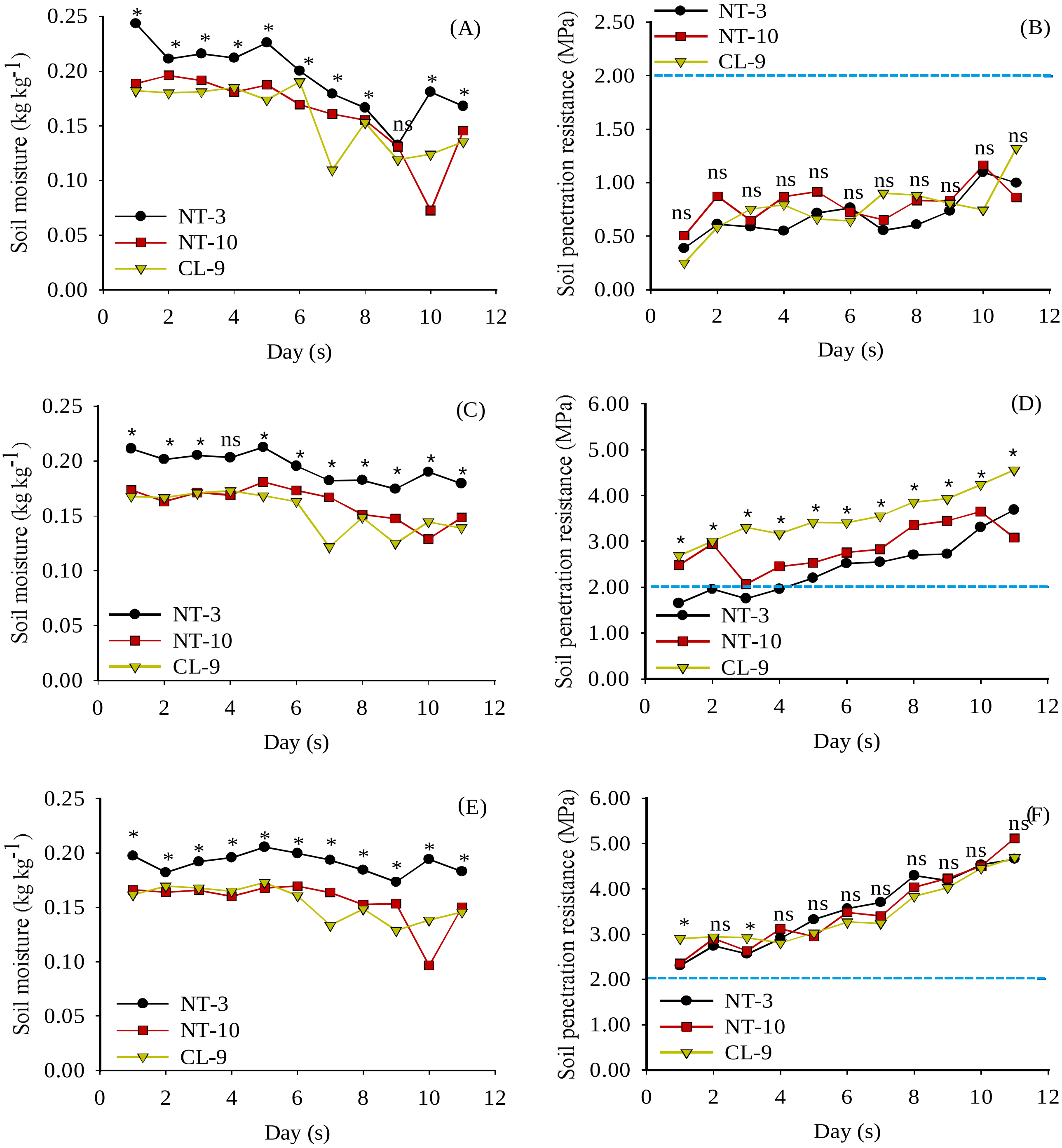
This effect may be related to the higher clay content in the soil under NT-3 (Table 1), favoring a higher soil water storage. In the same soil layer, PR was non-significant ($p > 0.05$), with values ranging from 0.25 to 1.32 MPa between production systems (Figure 2B). This layer does not represent a physical barrier to plant growth considering the ideal maximum critical limit of 2.0 MPa (MOURA *et al.*, 2021), because it is a region of change, especially during sowing, when there is minimal soil disturbance.

In the 0.00 - 0.10 m soil depth, the sowing standardization did not allow the detection of PR differences between the systems. This occurs because sowing operations change soil dynamics and porous geometry of the soil, improving or deteriorating soil porosity (GALDOS *et al.*, 2020).

The breakdown of aggregates and exposure of soil organic matter that is readily available to soil microorganisms, increases mineralization and decreases their concentration in the soil profile, increases the mechanical resistance of the soil to root penetration in the surface layer, and reduces water availability, gas exchange, and biological activity with depth, negatively affecting crop growth and yield (KUNDE *et al.*, 2018).

These effects were observed here with a negative correlation between PR and OC (-0.61), RP and Kfs (-0.58), and a positive correlation between OC and Kfs (0.86), indicating that in the 0.00 - 0.10 m layer, in addition to the mechanical actions of soil tillage, the OC content in this soil depth helped to reduce PR values and improved water infiltration into the soil (Table 2).

**Figure 2** - Temporal variation in soil moisture and penetration resistance in agricultural areas under no-till systems with 3 and 10 years of implementation (NT-3 and NT-10, respectively) and integrated crop-livestock system with 9 years of implementation (CL-9) at the depths of 0.00 - 0.10 (A and B), 0.10 - 0.20 (C and D), and 0.20 - 0.40 m (E and F)



* : significant ($p < 0.05$), ns: non-significant ($p > 0.05$). Dashed lines indicate the maximum desirable soil PR limit

The 0.10 - 0.20 m layer showed different soil moisture and PR values. The soil moisture contents ranged from 0.21 to 0.17 g kg$^{-1}$ in NT-3 and was significantly higher than the moisture in the areas NT-10 and CL-9 with values varying from 0.17 to 0.12 g kg$^{-1}$ (Figure 2 C). About the PR, only NT-3 showed values below the critical limit until the fourth day of evaluation, while all areas showed values above 2.0 MPa on the other days evaluated (Figure 2 D).

According to Nunes *et al.* (2015), the highest compaction is observed up to 0.20 m depth in no-till systems. At this layer, the lowest PR (1.65 MPa) was found in NT-3 area, while in NT-10 and CL- 9, the values were 2.48 and 2.69 MPa, respectively (Figure 2D). Low PR in NT-3 up to the 0.20 m depth is associated with higher soil moisture, with which PR was significantly and negatively correlated (0.76) ($p < 0.01$) (Figure 4A); the disturbance in this system is the most recent. However, these relationships were significant only when the systems were evaluated separately (Figure 4).

The 0.20 - 0.40 m layer showed no significant difference ($p > 0.05$) in PR between the evaluated areas. However, all areas showed PR values higher than 2.0 MPa, indicating harmful densification (Figure 2F).

In general, when comparing the soil depths for each system, the 0.00 - 0.10 m layer showed lower PR values than the other layers (0.10 - 0.20 and 0.20 - 0.40 m) (Figure 3), possibly due to the higher CO content in this layer than other soil depths (Figure 5). The comparison between NT-3 and NT-10 showed a higher PR distinction among the layers (Figure 4B and C), whereas in CL-9, the layers 0.10 - 0.20 and 0.20 - 0.40 m had a more homogeneous effect (Figure 3F), possibly due to the good development of roots in the CL, promoting greater soil aeration in depth, which can be beneficial from the point of view of standardizing water infiltration in the soil profile in this environment.

According to Galdos *et al.* (2020), growing of the *Urochloa hibrida* cv. Mavuno under a CL system provides a well-structured fine-root network, increasing soil macroporosity, as well as improving porosity complexity and connectivity, which may be positive for soil structure uniformity.

**Dashed lines indicate the maximum desirable soil PR limit.**

PR showed a significant correlation ($p < 0.05$) with soil moisture in all areas when evaluating the systems separately. In NT-3, this relationship was observed in the 0.10 - 0.20 m layer. The relationship was significant in all layers for NT-10 (Figure 4 B) and in layers 0.10 - 0.20 and 0.20 - 0.40 m for CL-9 (Figure 4 C). In parallel, for the area with native vegetation, the relationship between the two properties was significant for the 0.20 - 0.40 m layer (Figure 4 D).

In NT-3, PR showed values in the 0.10 - 0.20 m layer ranging from 1.65 to 3.69 MPa. Furthermore, the maximum PR (3.69 MPa) was observed when soil moisture was 0.18 g $kg^{-1}$ (Figure 4 A). According to Peixoto *et al.* (2019), a PR > 2.0 MPa in Oxisols under NT may be critical for crop development, restricting root elongation by 60%, and even reaching 95% with values of 3.6 MPa.

Considering the upper limit for good plant growth a PR of 2.0 MPa, the soil moisture would be 0.20 g $kg^{-1}$ in NT-3 for the 0.10 - 0.20 m layer. In another approach, this moisture value can indicate optimum moisture conditions for machine traffic based on Atterberg limits, which define soil consistency on hardness scales (< 0.20 kg $kg^{-1}$), friability (0.20 - 0.34 kg $kg^{-1}$), and plasticity (0.34 - 0.42 kg $kg^{-1}$). Thus, moisture of 0.20 g $kg^{-1}$ at the limit of 2.0 MPa would have a friable consistency, whose condition presents better trafficability conditions, with higher soil resistance to compaction (WEBER *et al.*, 2021).

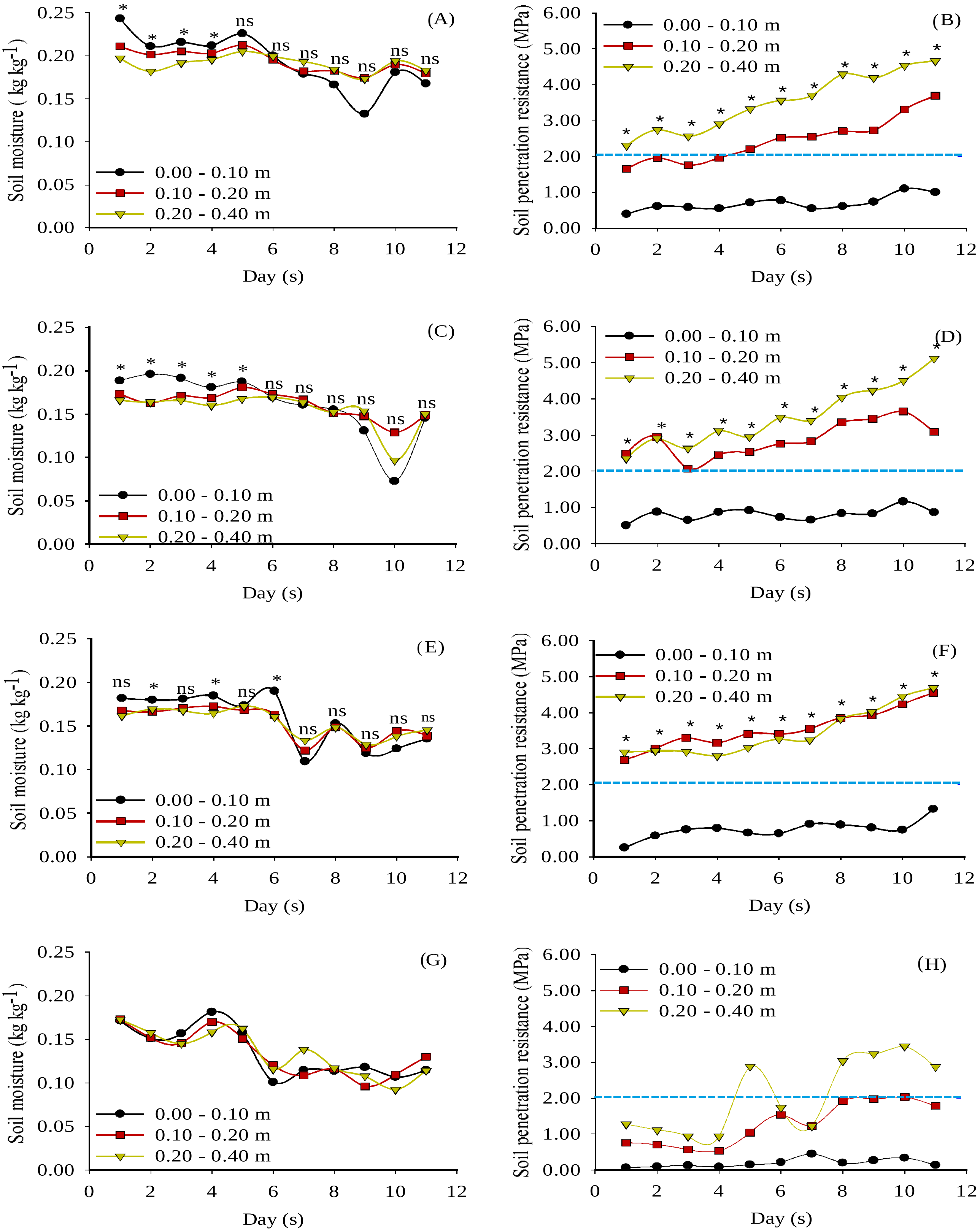
Despite the significant correlation between PR and moisture in the 0.00 - 0.10 m layer, PR was lower than 2.0 MPa under NT-10 (Figure 4 B), which does not represent harmful soil densification. However,

**Table 2** - Correlation analysis of soil physical properties at different soil depths

| | Sm (0 - 10) | OC (0 - 10) | Dm | Kfs | PR (10 - 20) | Sm (10 - 20) | OC (10 - 20) | PR (20 - 40) | Sm (20 - 40) | OC (20 - 40) |
|---|---|---|---|---|---|---|---|---|---|---|
| PR (0 - 10) | 0.07 | 0.61* | -0.02 | -0.58* | 0.66* | 0.13 | -0.64* | 0.81** | -0.06 | -0.63* |
| Sm (0 - 10) | - | 0.58* | 0.28 | -0.67* | -0.33 | 0.64* | -0.53 | 0.46 | 0.81** | -0.49 |
| OC (0 - 10) | | - | 0.02 | 0.86** | -0.50 | -0.33 | 0.98** | -0.81** | -0.43 | 0.98** |
| Dm | | | - | -0.30 | -0.44 | 0.32 | -0.03 | 0.08 | 0.42 | 0.02 |
| Kfs | | | | - | -0.21 | -0.29 | 0.89** | -0.82** | -0.60* | 0.83** |
| PR (10 - 20) | | | | | - | -023 | -0.51 | 0.53 | 0.53 | -0.55* |
| Sm (10 - 20) | | | | | | - | -0.28 | 0.27 | 0.39 | -0.25 |
| OC (10 - 20) | | | | | | | - | -0.81** | -0.41 | 0.97** |
| PR (20 - 40) | | | | | | | | - | 0.34 | -0.79** |
| Sm (20 - 40) | | | | | | | | | - | -0.32 |

PR: soil penetration resistance; Sm; soil moisture; OC: Organic carbon; Dm: Dry mass; Kfs: saturated hydraulic conductivity; 0 - 10: 0.00 - 0.10 m; 10 - 20: 0.10 - 0.20 m; 20 - 40 : 0.20 - 0.40 m. * significant ($p < 0.05$) ** significant ($p < 0.01$)

**Figure 3** - Comparative effect of soil layers on soil moisture and soil penetration resistance in different production systems, 3 years no-till systems (A and B) (NT-3), 10 years (C and D) (NT-10), 9 years livestock-crop integration (E and F) (CL-9) and Native vegetation (G and H) (NV). *: Significant ($p < 0.05$), ns: non-significant ($p > 0.05$)



moisture for soil management in NT-10 considering PR of 2 MPa would be 0.19 kg kg$^{-1}$ for 0.10 - 0.20 m, and 0.21 kg kg$^{-1}$ for 0.20 - 0.40 m (Figure 4 B). For CL-9 in the 0.10 - 0.20 m layer, moisture based on a PR of 2 MPa would be 0.23 kg kg$^{-1}$ (Figure 4 C). According to Cecagno *et al.* (2016), soil compaction problems in CL systems, if any, are usually restricted to the 0.05 - 0.10 m soil layer.

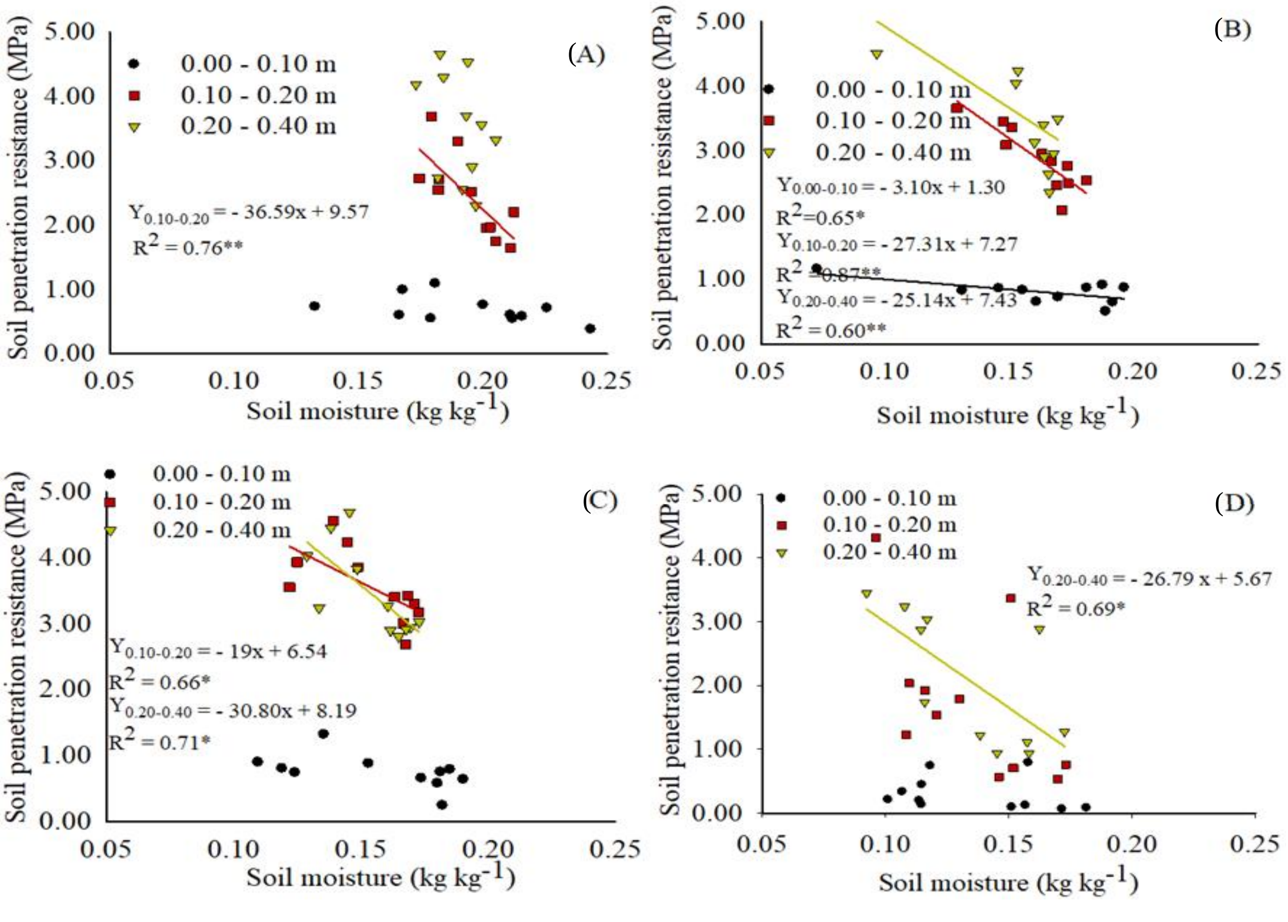
However, according to Reis, Armindo and Pires (2019), annual grain crops reach a greater root development within the 0.10 - 0.20 m soil layer, which must be monitored for critical PR level so that management operations are not limited and/or root growth restricted. In contrast, the ideal moisture in the 0.20 - 0.40 m soil layer for machinery traffic would be 0.20 kg kg$^{-1}$.

Hydraulic conductivity data (Figure 5 A) showed differences between systems (NT-10 and CL-9), with higher values under CL-9. Balbinot Junior *et al.* (2017) advocated that *Urochloa* forages in an CL system can effectively stimulate soil profile structuring, especially in tropical and subtropical regions where NT is predominantly used.

Salton *et al.* (2014) compared production systems in terms of soil physical properties and found improved aggregate stability in soil under cattle grazing (CL). This system showed a weighted average diameter of aggregates significantly higher (about 20%) than NT, resulting in higher drainage for the soil under CL, thus increasing hydraulic conductivity.

Organic matter plays a key role in improving soil structure. In this sense, the amount of total carbon (OC) in the soil showed a significant difference in the 0.00 - 0.10 m layer, with higher values in the native vegetation area with 28.73 g kg$^{-1}$ than in agricultural areas with a variation of 18.77 - 19.68 g kg$^{-1}$ (Figure 5 C), whose result can be related to the effect of converting natural to agricultural systems, which alters the soil structure, exposing OC to higher mineralization by soil microorganisms and,

**Figure 4** - Correlation analysis between soil penetration resistance under different production systems in the Cerrado biome with 3 and 10 years of implementation (A and B, respectively), integrated crop-livestock system with 9 years of implementation (C), and native vegetation (D)



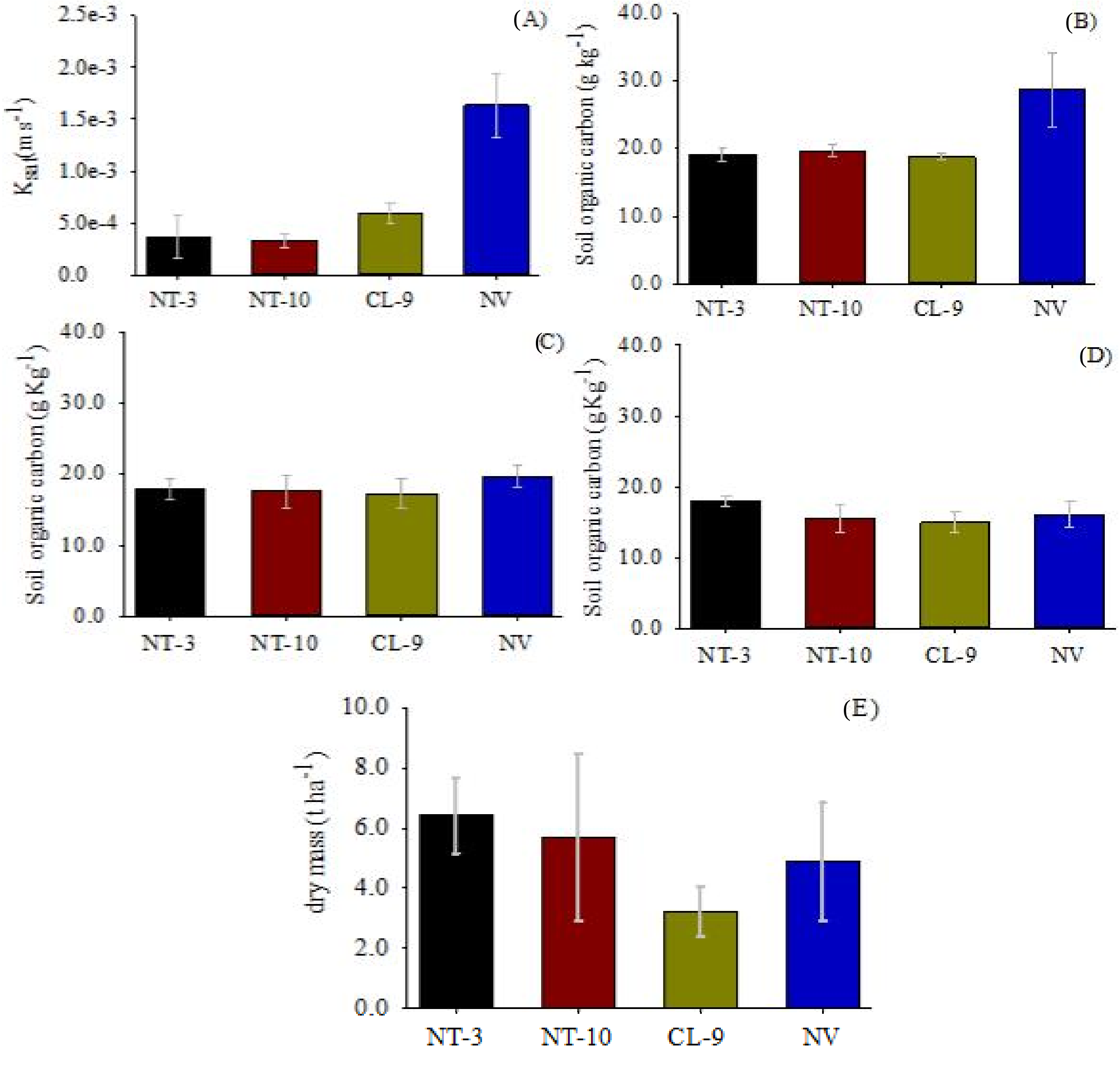
as a consequence, the decrease of carbon in the soil (BRAIDA; REICHERT, 2014).

In general, changes in OC resulting from use and management are detectable in the superficial layer (0.00 - 0.05 or 0.00 - 0.10 m) (BRAGA; BRAGA; VENTURIN, 2022). At greater depths, a dilution effect occurs, especially in more labile organic matter fractions.

The native vegetation soil presented higher values of hydraulic conductivity than the other systems (Figure 5 A). This behavior possibly develops due to the provision of greater profile uniformity, with macro and micropores in balance, additionally, its root system is deep, exerting greater physical interaction in deeper soil layers (SOARES *et al.*, 2021).

The main source of organic matter in the soil in agricultural systems comes from plant residues left on the soil. However, no significant correlation was detected between organic matter, represented by OC, and dry mass (Table 2).

**Figure 5** - Hydraulic conductivity (A), soil organic carbon at the depths of 0.00 - 0.10 (B), 0.10 - 0.20 (C), 0.20 - 0.40 m (D) and dry mass (E) in agricultural areas under no-tillage systems with 3 and 10 years of establishment (NT-3 and NT-10, respectively), integrated crop-livestock system with 9 years of implementation (CL-9) and Native vegetation (NV)



The NT-3 area showed a higher surface dry mass content (6.43 t $ha^{-1}$) compared to the CL-9 area (3.22 t $ha^{-1}$), while the NT-10 and Native vegetation areas showed average values of 5.69 and 4.86 t $ha^{-1}$, respectively. The dry mass was collected at the end of the off-season in NT-3 and 10 and the end of grazing in CL-9, which resulted in a greater amount of dry mass in the NT-3 area because, in NT-10, the remaining straw presents a higher degree of decomposition. In turn, in CL-9, the end of grazing leaves less amount of green mass on the ground.

## CONCLUSION

1. After three years under no-till, the lowest soil penetration resistance is reached compared to no-till for 10 years and crop-livestock for 9 years with 2.48 and 2.69 MPa, respectively. The low values of soil resistance to penetration in no-till for 3 years, in the 0.10 - 0.20 m layer, are associated with higher soil moisture;
2. When a critical soil penetration resistance of 2.0 MPa is established, all systems show values below this limit, allowing suitable conditions for plant development, that is, no-till and crop-livestock management systems are practices that tend to keep the soil in good physical condition.

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## REFERENCES

ALBUQUERQUE, P. E. P. **Estratégias de Manejo de Irrigação: Exemplos de Cálculo**. Circular técnica, Ministério de agricultura pecuária e abastecimento. Circular técnica 136. Sete Lagoas, MG, 25 p. 2010

BAGARELLO, V.; IOVINO, M.; ELRICK, D. A simplified falling-head technique for rapid determination of field saturated hydraulic conductivity. **Soil Science Society of America Journal**, v. 68, n. 1, p. 66-73, 2004.

BALBINOT JUNIOR, A. A. *et al.* Contribuição de raízes e parte aérea de espécies de brachiaria no desempenho em sucessão da soja. **Pesquisa Agropecuária Brasileira**, v. 52, n. 8, p. 592-598, 2017.

BENEVENUTE, P. A. N. *et al.* Penetration resistance: an effective indicator for monitoring soil compaction in pastures. **Ecological Indicators**, v. 117, n. 1, e106647, 2020.

BRAGA, R. M.; BRAGA, F. A.; VENTURIN, N. Carbono orgânico no solo sob mata nativa e florestas plantadas em longo prazo. **Pesquisa Florestal Brasileira**, v. 42, e202002121, p. 1-10, 2022.

BRAIDA, J. A.; REICHERT, J. M. Matéria orgânica e comportamento mecânico para fins de manejo de solo. *In*: LEITE, L. F. C.; MACIEL, G. A.; ARAÚJO S. F. **Agricultura conservacionista no Brasil**. Brasília: Embrapa, 2014. p. 309-361.

BÜCHI, L. *et al*. Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. **Agriculture, Ecosystems and Environment**, v. 256, n. 1, p. 92-104, 2018.

CECAGNO, D. *et al.* Least limiting water range and soybean yield in a long-term, no-till, integrated crop-livestock system under different grazing intensities. **Soil and Tillage Research**, v. 156, n. 1, p. 54-62, 2016.

ELRICK, D.; REYNOLDS, W. Methods for analyzing constant-head well permeameter data. **Soil Science Society of America Journal**, v. 56, n. 1, p. 320-323, 1992.

FAUSTINO, L. L.; MARCIANO, C. R. Least limiting water range and critical bulk density values as recovery indicators of soil under forest and pasture systems. **Ciência Florestal**, v. 31, n. 2, p. 658-682, 2021.

FRANCZISKOWSKI, M. A. *et al.* Propriedades físicas do solo no sistema de plantio direto e preparo reduzido, cultivado com plantas de cobertura. **Engenharia na Agricultura**, v. 27, n. 6, p. 556-564, 2019.

GALDOS, M. V. *et al*. Brachiaria species infuence nitrate transport in soil by modifying soil structure with their root system. **Scientific Reports**, v. 10, n. 1, e5072, 2020.

KUNDE, R. J. *et al.* Tensile strength, friability, aggregation, and soil organic matter physical fractions of an Oxisol cultivated with sugarcane. **Pesquisa Agropecuária Brasileira**, v. 53, n. 4, p. 487-494, 2018.

KELLER, T. *et al.* Using field measurement of saturated soil hydraulic conductivity to detect low-yielding zones in three Swedish fields. **Soil and Tillage Research**, v. 124, n. 1, p. 68-77, 2012.

LUZ, F. B. *et al*. Monitoring soil quality changes in diversified agricultural cropping systems by the Soil Management Assessment Framework (SMAF) in southern Brazil. **Agriculture, Ecosystems e Environment**, v. 281, n. 1, p. 100-110, 2019.

MORAES, M. T. *et al.* Critical limits of soil penetration resistance in a rhodic Eutrudox. **Revista Brasileira de Ciência do Solo**, v. 38, n. 1, p. 288-298, 2014.

MOURA, M. S. *et al*. Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. **Agricultural Water Management**, v. 243, n. 1, e106523, 2021.

NUNES, M. R. *et al*. Mitigation of clayey soil compaction managed under no-tillage. **Soil and Tillage Research**, v. 148, n. 1, p. 119-126, 2015.

PEIXOTO, D. S. *et al*. A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. **Soil and Tillage Research**, v. 194, n. 1, e104307, 2019.

PIAZZA, G. *et al*. Long-term conservation tillage and nitrogen fertilization effects on soil aggregate distribution, nutrient stocks, and enzymatic activities in bulk soil and occluded microaggregates. **Soil and Tillage Research**, v. 196, n. 1, e104482, 2020.

REIS, A. M. H.; ARMINDO, R.; PIRES, L. Physical assessment of a Haplohumox soil under integrated crop-livestock system. **Soil and Tillage Research**, v. 194, n. 1, e104294, 2019.

SALTON, J. C. *et al*. Integrated crop-livestock system in tropical Brazil: toward a sustainable production system. **Agriculture, Ecosystems and Environment**, v. 190, n. 1, p. 70-79, 2014.

SILVA, M. F. *et al*. Contribution of tillage systems and crop succession to soil structuring. **Soil and Tillage Research**, v. 209, n. 1, e104924, 2021.

SIMS, J. R.; HABY, V. A. Simplified colorimetric determination of soil organic matter. **Soil Science**, v. 112, p. 137-141, 1971.

SOARES, M. D. R. *et al*. Mudança no uso da terra e seu impacto nas propriedades físicas e mecânicas da Terra Negra Arqueológica na Floresta Amazônica. **Catena**, v. 202, n. 1, e105266, 2021.

SOUZA, R. *et al*. Dynamics of soil penetration resistance in water-controlled environments. **Soil and Tillage Research**, v. 205, n. 1, e104768, 2021.

TEIXEIRA, P. C. *et al*. Manual de métodos de análise de solos. 3. ed. Brasília: Embrapa, 2017.

THORNTHWAITE, C. W.; MATHER, J. R. **The water balance**: publications in climatology. New Jersey: Drexel Institute of Technology, 1955. 104 p.

VIZIOLI, B. *et al*. Effects of long-term tillage systems on soil physical quality and crop yield in a Brazilian Ferralsol. **Soil and Tillage Research**, v. 209, n. 1, e104935, 2021.

WEBER, L. L. *et al*. Impact of self-propelled sprayer trafc on Ferralsol physical properties in Southern Brazil. **Journal of Soil Science and Plant Nutrition**, v. 21, n. 4, p. 2957-2966, 2021.