Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission - Soil Physics

Short-term effects of *Urochloa* intercropped with corn on the structure properties of a soil under no-tillage

João de Andrade Bonetti[(1)*], Helio Henrique Soares Franco[(2)], Rachel Muylaert Locks Guimarães[(3)] and Cássio Antonio Tormena[(2)]

(1) Universidade Estadual Paulista, Departamento de Ciência Florestal, Solos e Ambiente, Botucatu, São Paulo, Brasil.
(2) Universidade Estadual de Maringá, Departamento de Agronomia, Maringá, Paraná, Brasil.
(3) Universidade Tecnológica Federal do Paraná, Departamento de Ciências Agrárias, Pato Branco, Paraná, Brasil.

ABSTRACT: The reduced crop diversity under no-tillage increases soil compaction and reduces soil quality. This study aimed to investigate whether intercropping corn and *Urochloa* has significant short-term effects on soil physical quality, as assessed by Visual Evaluation of Soil Structure (VESS), and its correlations with physical properties. Soil physical quality was assessed after corn and *Urochloa* intercropping and corn without *Urochloa*. The VESS, penetration resistance, bulk density, air-filled porosity, air permeability, pore continuity index, and water storage capacity were determined from 0.00 to 0.25 m depth in the Latossolo Vermelho Distroférrico. Intercropping of *Urochloa* and corn resulted in lower VESS values and favorable soil physical properties. For *Urochloa* and corn, the VESS score was improved (score 1 to 2.9). In the absence of the *Urochloa*, a moderate VESS score was observed (3 to 3.9). The results showed significant relationships between VESS scores and soil physical properties. Our findings suggest that the cultivation of *Urochloa* intercropped with corn improves the physical quality of Latossolo Vermelho Distroférrico, even in the short-term, 83 days after sowing, in a no-tillage system in a subtropical climate.

Keywords: crop diversification, soil physical, soil structure, soil visual assessment.

*** Corresponding author:**
E-mail: joao.bonetti@unesp.br

Received: February 23, 2024
Approved: February 11, 2025

How to cite: Bonetti JA, Franco HHS, Guimarães RML, Tormena CA. Short-term effects of *Urochloa* intercropped with corn on the structure properties of a soil under no-tillage in a subtropical climate of Brazil. Rev Bras Cienc Solo. 2025;49:e0240036.
https://doi.org/10.36783/18069657rbcs20240036

Editors: José Miguel Reichert and Milton César Costa Campos.

INTRODUCTION

Lower plant diversification under no-tillage increases soil compaction and reduces soil quality. The main difficulty in introducing diversity in production areas is related to the need to produce two cereal crops per year, aiming at higher profitability. However, the effects on the soil include structural degradation (Moraes et al., 2019) and increased compaction, such as higher bulk density and penetration resistance (Li et al., 2020).

In contrast, intercropping improves soil physical quality, such as higher aggregate stability, total porosity, and lower bulk density (Cagna et al., 2023). Therefore, it is essential to assess the physical quality of the soil, especially visual assessment, as physical assessment is difficult in production areas. Crop rotation improves the soil health and is fundamental for the sustainability of cereal production, especially in areas with frequent droughts during the rainy season. In this sense, crop diversification through intercropping under no-tillage could be a promising way to promote the physical, chemical, and biological properties of the soil (Stefan et al., 2021; Peng et al., 2023).

Urochloa, characterized by its high production of root and shoot biomass, has been grown intercropping with corn, for a more diversified and sustainable production system (Baptistella et al., 2020). The use of cover crops, such as *Urochloa* has shown benefits to subtropical soils in no-tillage production, like increasing organic matter (Silva et al., 2022; Crusciol et al., 2023), stabilising soil structure and improving nutrient cycling (Baptistella et al., 2020). Improvement of roots with positive effects on soil macroporosity and water infiltration (Santos et al., 2018a), increased water availability (Silva et al., 2020) and crop yield (Crusciol et al., 2023) are other benefits of *Urochloa*.

Intercroping corn, which has a fibrous root system, intercropping with *Urochloa*, which has thinner and more abundant lateral roots (Galdos et al., 2020), has beneficial effects on the physical (Baptistella et al., 2020) and chemical (Crusciol et al., 2023) quality of the soil. However, the effectiveness of *Urochloa* intercropping with corn in improving the soil physical properties depends on climatic conditions, especially temperature and soil moisture. In this sense, little is known about the effects on soil physical quality when the *Urochloa* is cultivated for a few weeks between corn rows. Introducing *Urochloa* during the corn cycle may have a short-term effect, *i.e.,* between one commercial crop and another, similar to chisel plowing. However, the difference is that *Urochloa* is more economical and does not destroy the porosity created by no-tillage; it mitigates the effects of compaction, with the residual decompression effect lasting much longer than chisel plowing. The economic costs of scarifying the entire planting area are high (Pinheiro et al., 2021), affecting the farm sustainability.

Strategies for assessing the impact of crop management, such as intercropping, are based on laboratory analysis. However, visual methods can be used to provide important information about the soil condition. Visual evaluation of soil structure (VESS) is a qualitative method for soil health assessment, which farmers can use to investigate effective cultivation practices under different edaphoclimatic regions (Franco et al., 2019). Thus, the VESS uses objective criteria for rapid assessment and serves as an effective tool to illustrate the impact of management practices on soil properties and overall soil health.

The VESS has the potential to evaluate the effect of plant management and the relationship with soil physical properties, as observed by Paschoal et al. (2020) in intercropping corn + *Urochloa*, and by Tuchtenhagen et al. (2018) under different crop management systems in a typic eutrophic Albaqualf soil. The investigation of Paschoal et al. (2020) under clayey Oxisol showed that intercropping corn and forage grasses improves the soil structural quality, according to the VESS evaluation. Additionally, the linear regression between bulk densities and VESS scores showed that VESS is a useful tool for managing moderately compacted soils (Tuchtenhagen et al., 2018). Thus, the limiting values for some physical properties and VESS scores result from studies carried out in temperate soils and need to be carefully interpreted when applied to subtropical and tropical soils.

We hypothesized that the short-term intercropping of corn and *Urochloa* improves soil quality, and the visual assessment correlates with physical analytical properties, which remain understudied in commercial production systems. This study aimed to investigate whether intercropping corn and *Urochloa* has significant short-term effects on soil physical quality assessed by VESS and its correlations with physical properties.

MATERIALS AND METHODS

The study was carried out in an experimental area belonging to the *Unidade de Difusão de Tecnologias da Cocamar Cooperativa Agroindustrial* located in the city of Floresta, state of Paraná, southern Brazil (23° 35' 23" S and 52° 04' 27" W; Figure 1).

Climate of region is classified as mesothermal humid subtropical (Cfa), with hot summers and rare frosts, and with seasonal rainfall concentrated in summer, and no dry season (Peel et al., 2007). Mean annual temperature is 22 °C and the mean annual rainfall is 1,450 mm. No significant climatic changes, such as dry spells, were observed during this study. The soil in the area is classified as a Latossolo Vermelho Distroférrico, very clayey textural class (Santos et al., 2018b), like a Rhodic Ferralsol (IUSS Working Group WRB, 2022). Granulometric characterization and soil organic carbon (SOC) content in the 0.00-0.10 and 0.11-0.20 m layers are presented in table 1.

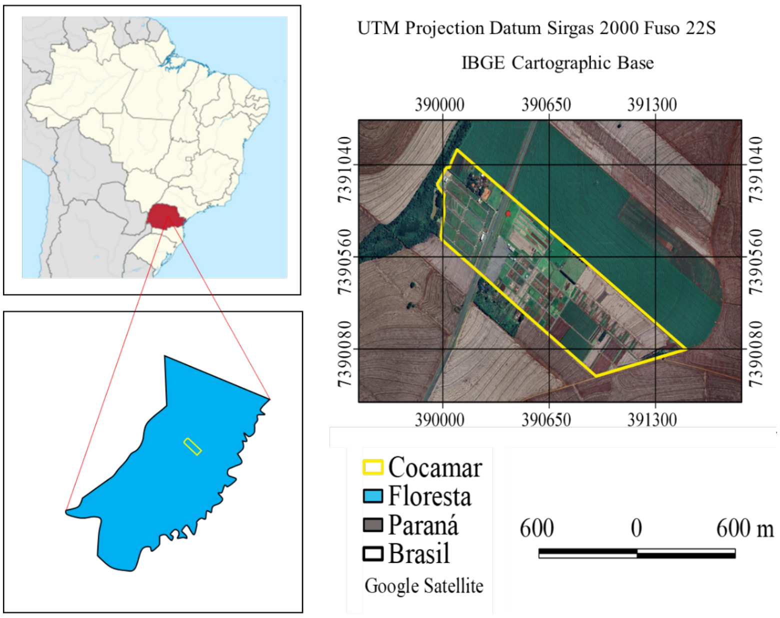

Figure 1. Geographic location of the study area at Cocamar Experimental Station, Floresta municipality, Paraná State, Brazil.

Table 1. Clay, silt, sand and soil organic carbon (SOC) contents of the 0.00 to 0.10 and 0.11 to 0.20 m layers of the Latossolo Vermelho Distroférrico

Layer	Clay	Silt	Sand	SOC
m	g kg^{-1}			
0.00 to 0.10	785	75	140	1.79
0.11 to 0.20	760	65	175	1.08

No-tillage has been used in the area since 2011 involving soybean (*Glycine max* (L.) Merrill), wheat (*Triticum* ssp.) and corn (*Zea mays* L.) (Figure 2). The experimental design was a randomized block, with four replications. The plots contained 12 rows of corn, 6 m long, spaced 0.9 m, and an intercropping treatment of *Urochloa* between the rows. The treatments evaluated were: a) corn crop without *Urochloa* (control - NTC) and b) intercropping corn and *Urochloa* (NTUr). Corn and intercropping corn, and *Urochloa* (sown simultaneously) were established on February 6, 2016, after the soybean harvest (Figure 2).

Seeder was equipped with furrow rods for fertilizer application at a depth of 0.10 m (340 kg ha^{-1} of an NPK 13-09-09 formulation) and cutting discs for opening the furrow and depositing the corn seeds at a depth of 0.05 m. *Urochloa* was sown in the central part of the inner rows of the corn crop at a depth of 0.03 m, using cutting discs to open the sowing furrow for the *Urochloa*, no fertilizer was added.

Evaluations and sampling were carried out 83 days after corn and *Urochloa* sowing, when the soil water content was close to field capacity. In the field, the soil structural quality score (Sq) through the Visual Evaluation of Soil Structure (VESS) was carried out according to Guimarães et al. (2011), with four samples for each treatment. After the VESS evaluation, 12 undisturbed samples from each treatment (four blocks × three subsamples) were removed at 0 to 0.05 and 0.10 to 0.15 m. Undisturbed samples were collected using cylinders (0.07 m in diameter × 0.05 m in height ~192 cm^3 cm^{-3}). The dimensions of the samples were adjusted to the dimensions of the cylinders and kept at the temperature of 5 °C until they were used in the analyses.

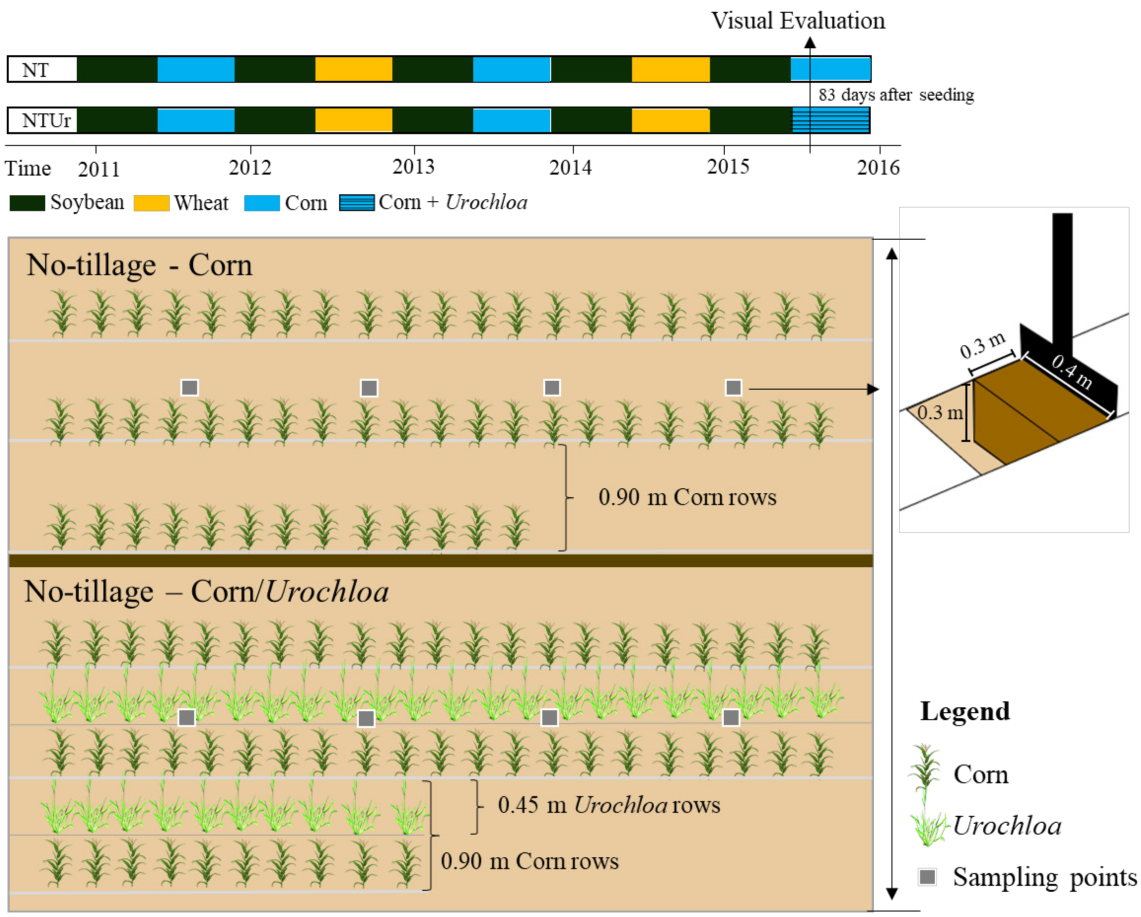

Figure 2. Land use history under no-tillage and sampling positions of the evaluated study areas. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*.

To determine the VESS Sq, small trenches were opened, from which soil samples (0.25 × 0.10 × 0.20 m) were taken using a straight spade. After the samples were taken, soil aggregates were revealed manually at their fracture points, and their color, size, shape, and resistance to rupture, as well as the presence of inter and/or intra-aggregate roots and visible porosity were evaluated (Guimarães et al., 2011). The VESS Sq score was attributed to each layer, according to the VESS chart (Guimarães et al., 2011). Contrasting layers of the structure were identified (0 to 0.03 and 0.04 to 0.25 m to intercropping, and 0 to 0.10 m and 0.11 to 0.25 m to *corn*). The first layer was called the top layer, and the second was the bottom layer. The VESS Sq scores range from 1 to 5, allowing intermediate numbers. Scores varying from 1 to 2.9 have good structural quality, requiring no changes in soil management; from 3 to 3.9 requires long-term changes in management (not immediate) to reduce further structural degradation; and 4 to 5 correspond to a poor structural quality, requiring an immediate change in management to support adequate plant production (Ball et al., 2017). For each block, a weighted average was calculated according to equation 1.

$$Ev = \sum \left[(Evi\ Ei) / ET \right] \qquad \text{Eq. 1}$$

in which: Ev is the average score of the sample (dimensionless); Evi (dimensionless) and Ei (m) are the score and depth of each layer, respectively; ET is the sum of the depth of the individual layers of each sample.

Undisturbed samples were placed in trays for gradual saturation with water for a week. After saturation, the samples were weighed and subjected to a matric with the potential of -6 kPa (Deeks et al., 2004) in a tension table (Ball and Hunter, 1988). After the soil equilibrium, the samples were weighed again. Then, they were placed back on the tension table and subjected to a matric potential of -10 kPa, according to Reynolds et al. (2002). After equilibrium, at this potential, the permeability of the soil to the air was determined using a constant head permeameter (Figueiredo, 2010). Permeability of the soil to air (Ka) was estimated according to equation 2.

$$Ka = (Q / As) \times (z / P) \qquad \text{Eq. 2}$$

in which: Ka is the permeability of the soil to air (μm^2); *Q* is the mass flow rate ($m^3\ s^{-1}$); η is the air viscosity at 20 °C (1.8×10^{-5} $N\ s^{-1}\ m^{-2}$); *As* is the area perpendicular to the air movement (m^2); *z* is the soil column (m) and *P* the differential air pressure (Pa).

After determining the air permeability of the soil, the samples were again saturated and subjected to progressive air drying in the laboratory at a controlled temperature of 25 °C to determine the penetration resistance. For drying, the samples were placed on a wire mesh device with an approximate height of 0.05 m to allow water loss through both ends of the sample. Five penetration resistance measurements were made for each sample over the drying period, resulting in observations from five different water contents, starting from close to saturation. The penetration resistance was determined using a bench penetrometer equipped with a metal rod with a conical tip, with a basal diameter of 0.0038 m and an angle of 30°. The mass of each sample was obtained before each measurement of penetration resistance for the subsequent determination of the soil water content. After the last determination of resistance, the samples were dried in an oven at 105 °C for 48 h to obtain the mass of soil solids and thus allow the calculation of the soil bulk density and water contents at different times of soil drying according to Moreira et al. (2014).

Values of penetration resistance were adjusted with the soil water content using the model proposed by Busscher (1990), described in equation 3.

$$PR = a \times \Theta \times b \qquad \text{Eq. 3}$$

in which: PR is penetration resistance (MPa); Θ is the water content of the soil ($m^3\ m^{-3}$); *a* and *b* are the parameters for fitting the model to the data. Soil water content for the PR is 3.5 MPa, the PR value suggested by Moraes et al. (2014) as critical for crops grown in soils under NT, it was calculated according to equation 4.

$$\Theta_{PR} = (3.5/a)^{(1/b)} \qquad \text{Eq. 4}$$

The pore continuity index was estimated through the ratio between the permeability of the soil to air and the air-filled porosity at a potential of -10 kPa, as proposed by Groenevelt et al. (1984) - equation 5.

$$K1 = Ka/Par \qquad \text{Eq. 5}$$

in which: *K1* is the soil pore continuity index (dimensionless); *Ka* is the permeability of the soil to air (μm^2); Par is the air-filled porosity ($m^3\ m^{-3}$) at the potential of -10 kPa. *Par* was determined by the difference between the water content of the saturated soil and the water content at the potential of -10 kPa, according to Reynolds et al. (2002).

Soil bulk density was determined by the ratio between the mass of solids and the volume of the core (Teixeira et al., 2017); the total porosity was considered the water content of the saturated soil (θs) and the macroporosity was obtained by the difference between θs and θ under the potential -6 kPa (field capacity), according to Ball and Hunter (1988).

Soil water storage capacity (SWSC) was calculated using the ratio between soil water content at -10 kPa, taken as the field capacity (FC), and the total porosity (TP) (Reynolds et al., 2002), according to equation 6.

$$SWSC = FC/TP \qquad \text{Eq. 6}$$

in which: SWSC is the water storage capacity (dimensionless); FC is the soil water content or volume of pores occupied with water at the potential of -10 kPa ($m^3\ m^{-3}$); TP is the total porosity ($m^3\ m^{-3}$).

For the layers identified through the VESS assessment of each sample, an aliquot of soil, aggregates were collected and used to determine the SOC. Soil aggregates were air-dried, ground, and sieved at a 2 mm mesh opening, and the SOC was determined in triplicate using oxidation with potassium dichromate and titration with ammonium ferrous sulfate (Teixeira et al., 2017).

Critical limits to soil physical quality were according to: VESS Sq score of <3.0 (Ball et al., 2017); soil density of 1.21 Mg m^{-3} (Ferreira et al., 2020), total porosity of 0.50 $m^3\ m^{-3}$ (Kiehl, 1979) and macroporosity of 0.10 $m^3\ m^{-3}$ (Baquero et al., 2012); water stock capacity of 0.66 $m^3\ m^{-3}$ (Reynolds et al., 2002); total organic carbon of 1.1 dag kg^{-1} (Pawar et al., 2017); air-filled porosity of 0.09 $m^3\ m^{-3}$ (Reynolds et al., 2015); soil air permeability of 1 μm^2 (McQueen and Shepherd, 2002) and water content at PR equal to 3.5 MPa (Moraes et al., 2014).

Differences in soil physical properties and SOC between the studied managements (intercropping corn-*Uroclhoa* and without intercropping) were analyzed using ANOVA. A Shapiro-Wilk normality test was applied to the residuals of the ANOVA models to check for the assumption of normality and homogeneity of variance (p-values <0.05 were significant at 5 %, linear model residuals can be considered normal). In this study, both assumptions of the tests (normality and homogeneity) were met, and the data were submitted to a Tukey test (α = 0.05), which was done separately for each soil type and layer (top and bottom layer). Statistical analyses were performed according to Ferreira (2011). Regression analyses were performed using the Sigma Plot software. Principal component analysis was performed for the different soil properties, following the normalization of the data in *score Z*, as suggested by Gotelli and Ellison (2011) and based on the correlation matrix of these variables using the Paleontological Statistics software, 3.0 (Hammer, 2001).

RESULTS

The VESS showed different layers (thickness) between the treatments (Figure 3). For the NTC treatment, the average VESS Sq score was 3.1 (top layer) and 3.6 (bottom layer) (Figure 3a). For the NTUr treatment, an average VESS Sq score of 1.9 (top layer) and 2.8 (bottom layer) (Figure 3a). The mean values for the VESS Sq scores differed ($p<0.05$) between NTC and NTUr in the top layer (Figure 3b). For the bottom layer, no significant difference ($p>0.05$) was observed between NTC and NTUr. Although the average score shows that they belong to different quality classes: NTUr good and NT moderate (Ball et al., 2017) (Figure 3b). These results, with distinct VESS Sq, and layer depth for NTC and NTUr, are due to aggregates of different shapes and sizes, with differences in fracture resistance, visible pores and the presence or absence of roots in the sampled profile.

The average values for soil bulk density, total porosity, macroporosity, SOC, penetration resistance and water content at PR equal to 3.5 MPa are shown in figure 4. There was a reduction in soil bulk density, penetration resistance, and water content at PR equal to 3.5 MPa, and an increase in total porosity and macroporosity for the NTUr top layer compared to NTC (Figure 4). There were no differences in SOC between the NTC and NTUr in the individual layers (Figure 4d).

Compared to NTC, NTUr increased (top layer), soil air porosity at ψ -10 kPa by 52 %; air permeability by 98 %, and pore continuity index by 94 % (Figure 5). No significant differences between the management treatments were observed in the bottom layer ($p<0.05$).

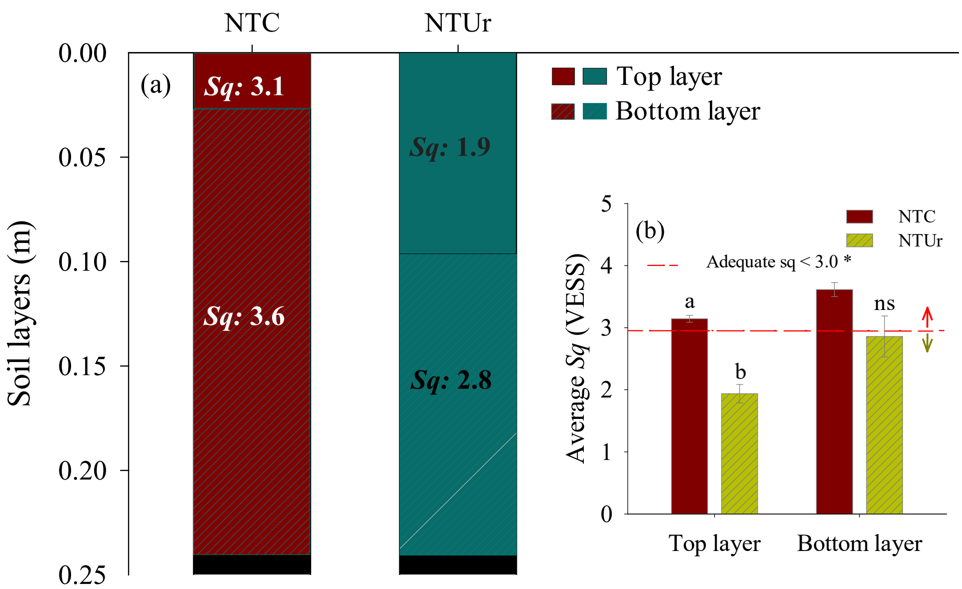

Figure 3. Mean depth of the different soil layers with their respective VESS Sq scores (a) and the mean VESS Sq score of the soil layers (b) in the treatments studied. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*. Bars: standard errors. Different lowercase letters indicate significant differences between systems by t-test $p<0.05$. ns: not significant. * <3.0 following Ball et al. (2017)

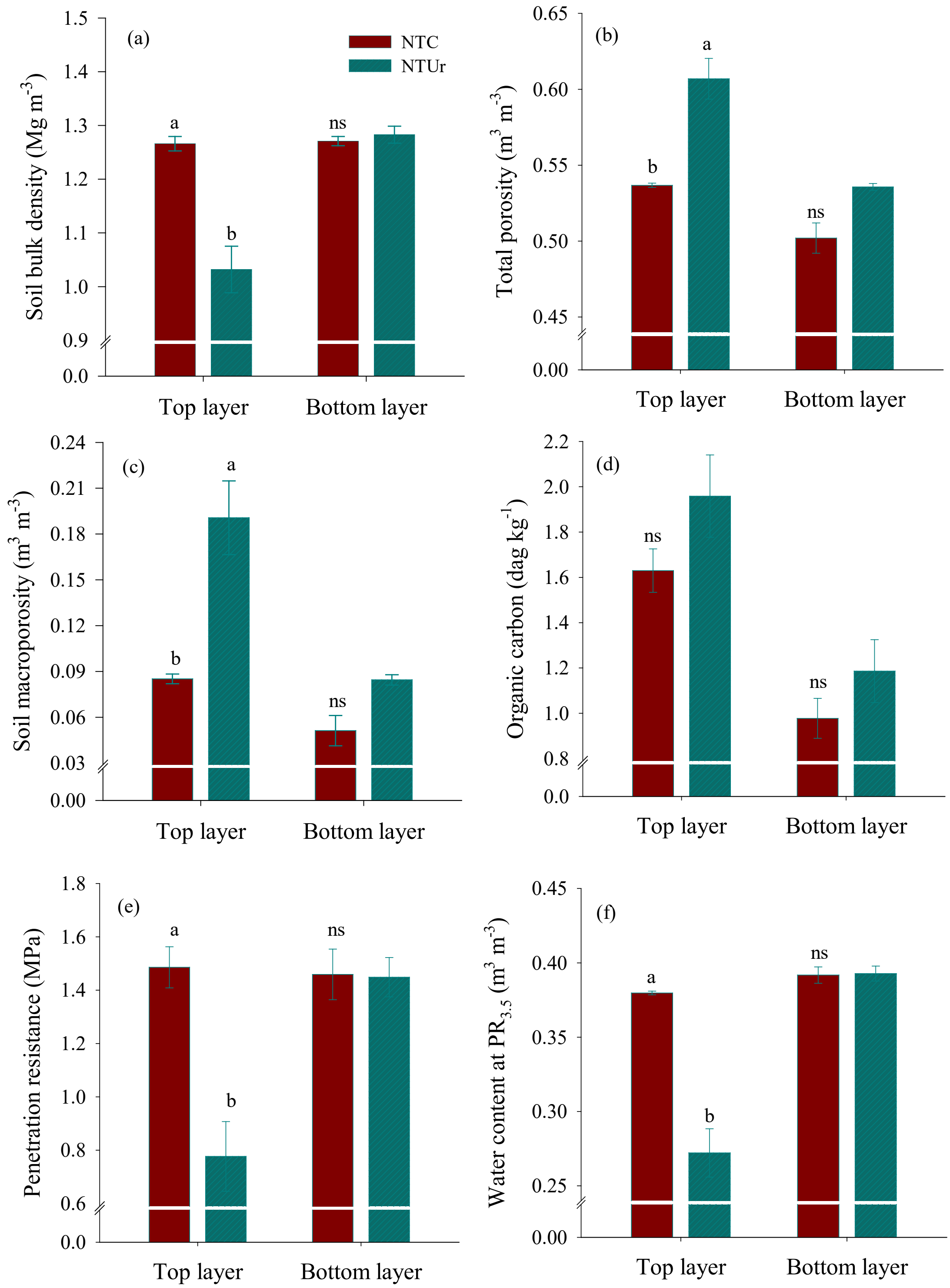

Figure 4. Soil bulk density (a), total porosity (b), macroporosity (c), soil organic carbon (d), penetration resistance (e) water content at PR equal to 3.5 MPa (f) for the treatments studied. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*. Bars: standard errors. Different lowercase letters indicate significant differences between systems by t-test $p<0.05$. ns: not significant. Top layer: 0.0 and 0.10 m; bottom layer: 0.11 and 0.25 m.

Regression analyses showed significant positive relationships (Figure 6) between the VESS Sq scores ($p<0.01$) and soil bulk density ($r^2 = 0.56$), soil water storage capacity ($r^2 = 0.77$) and water content at PR = 3.5 MPa ($r^2 = 0.64$). Significant negative relationships were found between VESS Sq score and total porosity ($r^2 = 0.69$), macroporosity ($r^2 = 0.72$), soil air permeability at ψ = -10 kPa ($r^2 = 0.55$), and air-filled porosity at ψ = -10 kPa ($r^2 = 0.59$). In addition, the significance for SOC was r^2 equal to 0.45 ($p<0.05$).

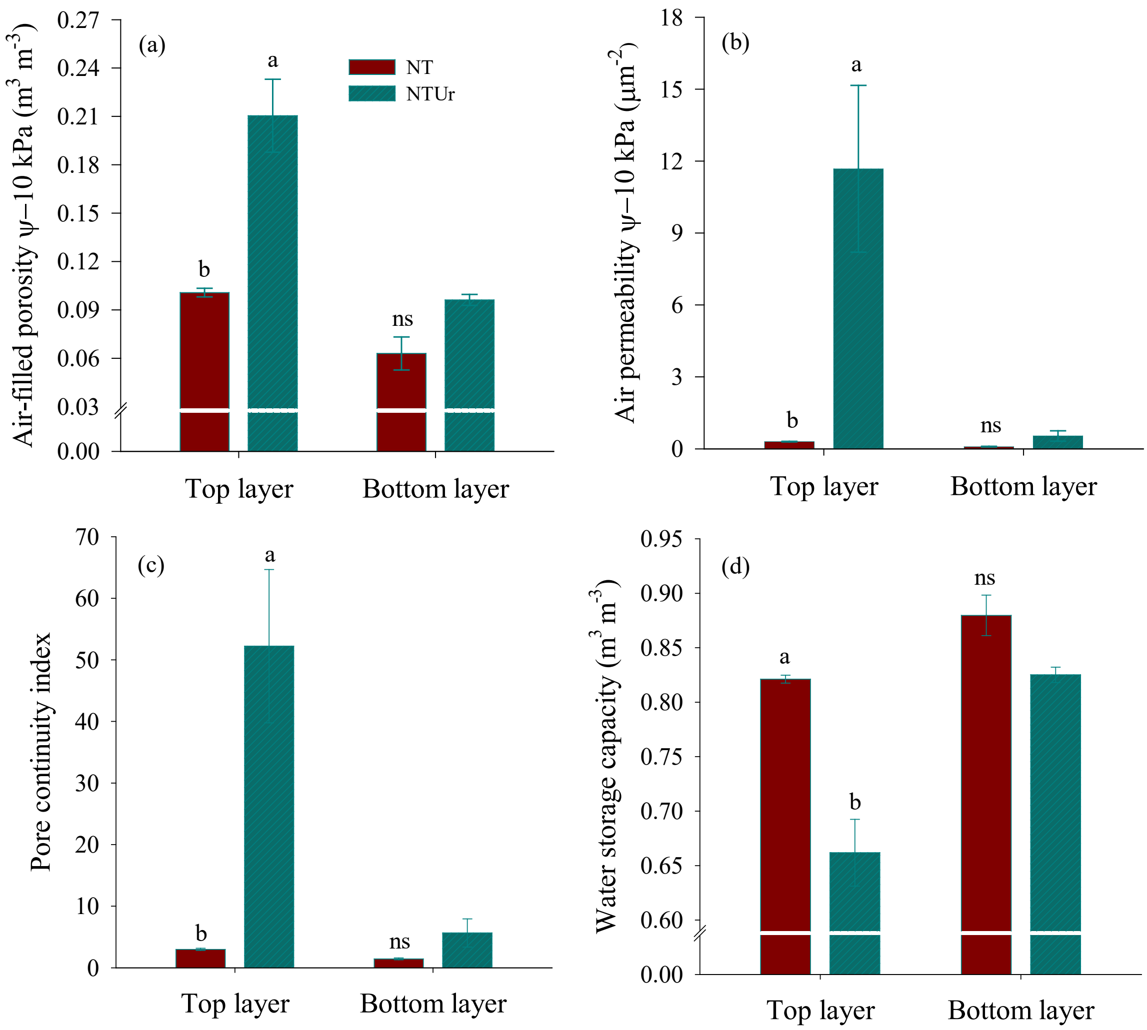

Figure 5. Air filled porosity (a), soil permeability to air (b), soil pore continuity index (c), and water storage capacity (d) for the treatments studied. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*. Bars: standard error. Different lowercase letters indicate significant differences between systems by t-test p<0.05. ns: not significant. Top layer: 0.0 and 0.10 m; bottom layer: 0.11 and 0.25 m.

The VESS Sq scores for the NTC treatment were in a range where soil structure is considered inadequate and requires changes in management strategies (Sq VESS 2.9 to 5). In contrast, the majority of points of NTUr were positive (Sq 1 to 2.9), corresponding to physical soil properties that are more favorable to plant development (Figure 6).

Principal component analysis indicated that the two principal components (PC) were responsible for 93.78 % of the total variance, with PC1 explaining 88.25 % and PC2 5.53 % (Figure 7). In PC1, there was a large overlap of the positive effects of pore space-related variables (total porosity, soil air permeability, pore continuity index, air-filled porosity at ψ = -10 kPa and macroporosity) and negative effects with soil bulk density, penetration resistance, and VESS (Figure 7). On second axis, the SOC was positively grouped, while the water content at PR was equal to 3.5 MPa, and the water storage capacity was negatively grouped.

DISCUSSION

In the top layer, which is particularly important for many physical and hydrological soil processes, the VESS Sq scores differed between treatments, with the lowest values indicating an agronomically more favorable soil structure in the NTUr treatment (Figure 3).

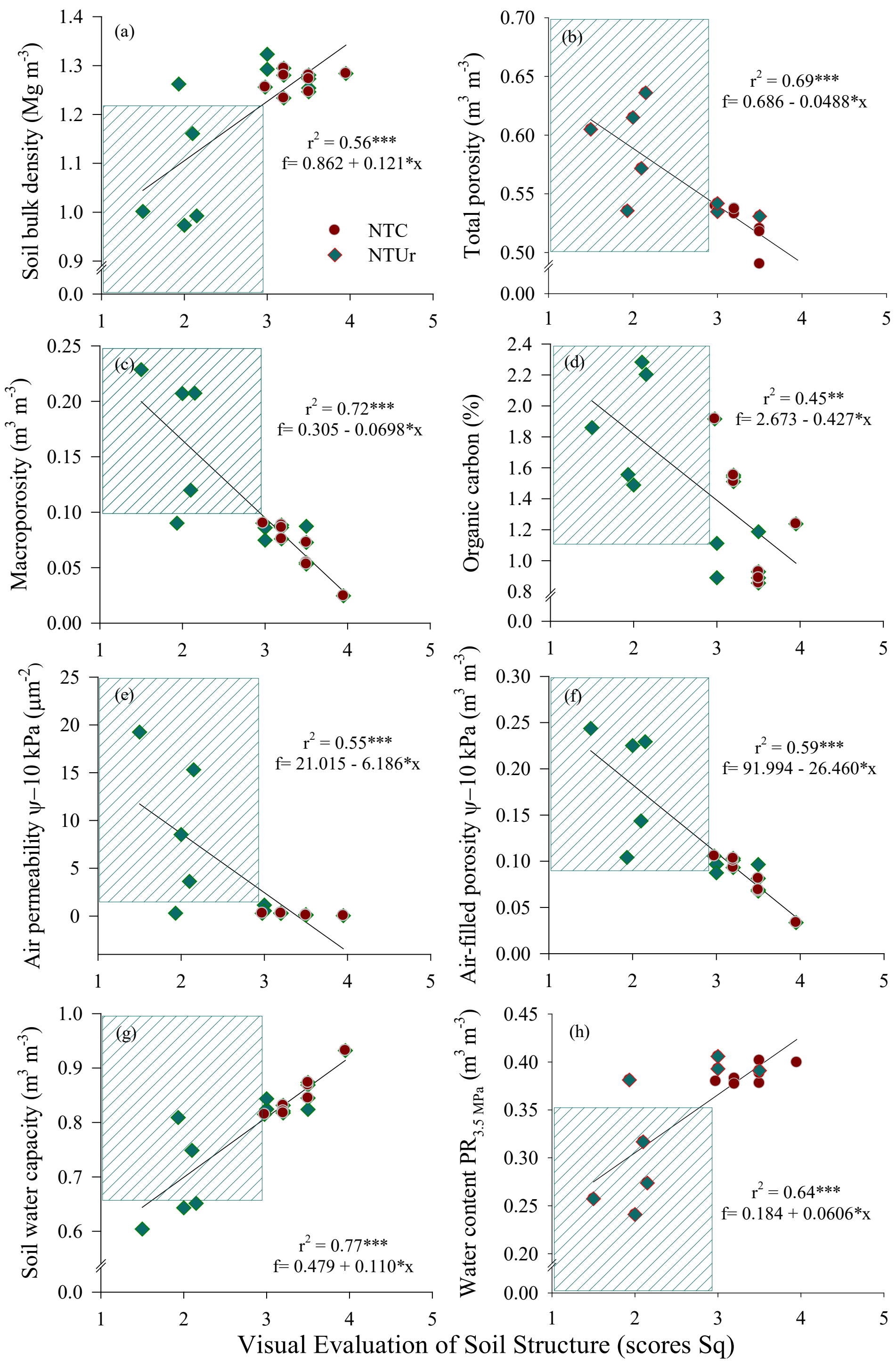

Figure 6. Relationships between VESS Sq scores and soil bulk density (a), total porosity (b) soil macroporosity (c), soil organic carbon (d), soil air permeability at ψ equal to -10 kPa (e), air filled porosity at ψ equal to -10 kPa (f), water storage capacity (g) and water content at PR equal to 3.5 MPa (h) for the treatments studied. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*. *** p<0.01; ** p<0.05. The area outlined in green indicates adequate soil structure.

Urochloa has a high potential for root production, improving soil structure quality (Silva et al., 2022). In this case, the crop rotation system should be adapted to avoid further damage to the soil structure, such as intercropping *corn* and *Urochloa*. Intercropping corn with forage grasses under no-tillage conditions improves aggregate stability, reduces bulk density, and increases total porosity in the 0.00-0.10 m soil layer (Cagna et al., 2023).

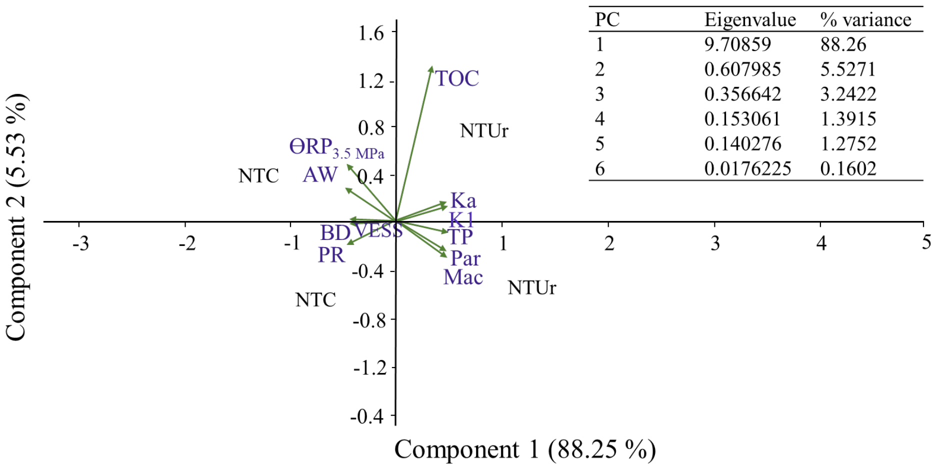

Figure 7. Multivariate analysis of the principal components of variables related to the physical properties and quality of the soil for the studied treatments. NTC: control - corn crop without *Urochloa*; NTUr: intercropping corn and *Urochloa*; VESS: visual evaluation of soil structure; TOC: total organic C; Bd: bulk density; Mac: macroporosity; PR: penetration resistance; AW: available water; θ_{PR}: water content at PR 3.5 Mpa; Ka: air pemeability; PT: total porosity; Par: air porosity; Ka: permeability of the soil to air soil; and K1: pore continuity index.

Roots interactions with soil microbiota help the formation and stabilization of soil aggregates and increase soil porosity (Bardgett et al., 2014). The presence of *Urochloa* increased the depth of the layer of good soil quality to 0.10 m (Figure 3b). Most annual crops grow their roots in the first 0.10 m of soil; therefore, the better environment provided by *Urochloa* reduces crop constraints (Guimarães et al., 2011).

In soils similar to this study, Guimarães et al. (2013) found that for VESS Sq scores >3.0, there was a predominance of the Least Limiting Water Range (LLWR) equal to 0, indicating severely restrictive physical conditions for the development of crops. The reduction in the VESS Sq score in NTUr (38 % in top layer) and 21 % (bottom layers) indicates a substantial improvement in the physical and structural quality. The good soil structure identified by the VESS Sq score confirms the physical and hydric attributes studied, which showed better physical conditions in the NTUr (Figures 4 and 5). These results are probably related to the diversification of plants, which accumulate on the soil surface, allowing the growth of fine roots (Cagna et al., 2023), creating a porosity network in the soil, and improving the soil recovery (Baptstella et al., 2020). *Urochloa* is known for its ability to protect the soil while enhancing soil health and carbon sequestration; however, these effects were not evidenced in the present study.

The VESS Sq scores observed in NTUr (Figure 3) was classified as 'good' (ranging from 1 to 2.9) and indicate that Urochloa induced short-term improvements in soil structure within just 83 days of cultivation. These changes demonstrate that Urochloa intercropping can be an efficient and low-cost alternative to chisel plowing for rapidly enhancing soil quality. However, the long-term effects of intercropping need to be further investigated. Roots improve microbial activity, abundance, and diversity and produce organic compounds, such as exudates (e.g., enzymes and proteins), that improve soil health (Koudahe et al., 2022), which does not occur with plowing.

The increased macroporosity of the top layer recorded in the short term is fundamental to the dynamics of air and water in the soil profile and, consequently, favors the growth of roots, which could reach more layers in the subsurface, especially if grown in the medium and long-term. Therefore, the positive effects on the soil are due to the growth of roots and the intensification of drying cycles and wetting cycles through the absorption and transpiration of water, affecting the structural and physical quality of the soil.

Urochloa has a high potential for biomass production of its aerial parts (13.6 Mg ha^{-1}) and the roots (8.4 Mg ha^{-1}), evaluated in the 0 to 0.2 m layer (Bonetti et al., 2015). This protects the soil against erosion and compaction and has a greater impact on productivity than straw (Balbinot Junior et al., 2017). The biomass of the aerial part and the roots promotes the formation and stabilization of the structure with improvements in the pore system, in terms of temperature moderation, reduction of penetration resistance, increase in water infiltration, and the stability of aggregates and nutrient cycling (Santos et al., 2018a; Oliveira et al., 2019).

The lower water content at a penetration resistance of 3.5 MPa observed in the NTUr area suggests a greater degree of drying in the surface layer, likely associated with higher air permeability (Figure 5d). This condition may facilitate water redistribution toward deeper soil layers, where higher moisture content is retained.This may be a consequence of the increased addition of SOC (not confirmed in this study), as well as the number of fine roots (Crusciol et al., 2023), which are common in *Urochloa* plants (Galdos et al., 2020) and improve subsequent grain yields (Crusciol et al., 2023). Fine roots with a diameter <0.5 mm influenced the decomposition rate, remaining in the soil for 243 and 261 days less than roots with a diameter between 1.0 and 2.0 mm (Bieluczyk et al., 2023). This rapid improvement in soil structure promoted by *Urochloa* during the corn crop can prevent limitations during drought periods, which are common in southern Brazil, as corn root growth is favored by the reduction of mechanical and hydric stresses (Moraes et al., 2019). These benefits positively impact plant growth and development and can last for several harvests, benefiting multiple crops, as confirmed by Balbinot Junior et al. (2017).

The NTUr is a possible window for cattle grazing after corn cultivation, as has been widely implemented by producers in the central south of Brazil. In the absence of *Urochloa*, the soil under NTC showed high Sq VESS and physical degradation, defined for this soil as 1.21 Mg m^{-3} (Ferreira et al., 2020), resulting in soil compaction (Figures 4 and 5). In another study, the regression analysis between bulk density and macroporosity (considering the critical macroporosity for plant growth of 0.10 m^3 m^{-3}), Suzuki et al. (2022) defined for clay soils the bulk density of 1.33 to 1.36 Mg m^{-3} and the critical penetration resistance of 2 to 3.5 MPa. Our results suggest a negative evolution of density (1.27 Mg m^{-3}) and penetration resistance (1.48 MPa). Thus, intercropping with forage and cattle grazing is an alternative to recover compacted soils or reduce the evolution of compaction observed in the no-tillage (Glaze-Corcoran et al., 2020; Bonetti et al., 2023).

The VESS Sq score was related to the quantitative physical properties of the soil, as suggested by Cherubin et al. (2017) and also observed in several studies (Hargreaves et al., 2019; Paschoal et al., 2020). Thus, the significant relationships observed between VESS and the soil properties (physical $p<0.01$; SOC $p<0.05$; Figure 6) indicate that VESS adequately detects the structural quality of the managed soils with different plant diversity, showing it to be an efficient tool for assessing the structural quality of subtropical and tropical soils, in line with the results of Franco et al. (2019). Other studies have already found a close relationship between the VESS Sq score and soil properties such as SOC, soil bulk density, water capacity, air permeability, and pore space (Cherubin et al., 2017; Guimarães et al., 2017). In particular, aggregates' shape and ease of breaking (rounded shapes connected by roots indicate stable aggregates, and right angles and lack of roots indicate low stability), high visible biological porosity, and activity of macroorganisms are easily observed and associated with conservation management and soil physical quality.

Furthermore, a VESS Sq score <2.9 or > 3.0, used as a boundary between good and moderate to poor soil structural conditions (Ball et al., 2017), converged with limiting values for the physical properties for plant growth for the soil texture class studied, which had a soil bulk density of 1.21 Mg m^{-3} (Ferreira et al., 2020), macroporosity of 0.10 m^3 m^{-3} (Baquero et al., 2012); 1.1 dag kg^{-1} SOC for maintaining tropical soils quality (Pawar et al., 2017), water storage capacity of 0.66 m^3 m^{-3} (Reynolds et al., 2002); air-filled porosity of 0.09 m^3 m^{-3} (Reynolds et al., 2015); and soil air permeability of 1 μm^2 (McQueen and Shepherd, 2002). However, it was observed that the average scores for the NTUr treatment were close to those indicated to represent a good structural condition of the soil.

Principal components (PC) analysis technique grouped the treatments according to the variation of the properties studied. The NTC was associated with properties indicative of compaction, such as soil bulk density, penetration resistance, and water parameters (AW and $\Theta PR_{3.5\ MPa}$). In contrast, NTUr was associated with increased SOC and permeability parameters. The physical effects, negative for NT (Li et al., 2020) and positive for intercropping corn and *Urochloa* (Cagna et al., 2023), are observed, especially in compaction parameters (penetration resistance, bulk density, and soil porosity parameters). Thus, the results of the PC analysis indicate that the adoption of corn with *Urochloa* intercropping is associated with an increase in soil quality, allowing fewer restrictions on root growth and better access to water, as well as improving the quality of soil pores and airflow.

CONCLUSIONS

Corn with *Urochloa* intercropping improved soil physical quality in the top layer (0.00 to 0.10 m) of the Latossolo Vermelho Distroférrico in a short time, 83 days, evaluated by visual and analytical methods. The VESS scores were significantly correlated with the quantitative physical properties, showing that visual observations can guide soil compaction management decisions for the studied soil and anticipate soil management problems. Intercropping *corn* with *Urochloa* improves soil quality and is an interesting option for managing compacted soils in cereal production.

FUNDING

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

AUTHOR CONTRIBUTIONS

Conceptualization: Cássio Antonio Tormena (lead) and Rachel Muylaert Locks Guimarães (supporting).

Data curation: Cássio Antonio Tormena (lead) and João de Andrade Bonetti (supporting).

Formal analysis: Helio Henrique Soares Franco (lead) and João de Andrade Bonetti (supporting).

Funding acquisition: Cássio Antonio Tormena (lead).

Investigation: Cássio Antonio Tormena (supporting), Helio Henrique Soares Franco (lead) and Rachel Muylaert Locks Guimarães (equal).

Methodology: Cássio Antonio Tormena (supporting) and Helio Henrique Soares Franco (lead).

Project administration: Cássio Antonio Tormena (lead) and Rachel Muylaert Locks Guimarães (supporting).

Resources: Cássio Antonio Tormena (lead).

Software: Cássio Antonio Tormena (supporting) and João de Andrade Bonetti (lead).

Supervision: Cássio Antonio Tormena (lead) and João de Andrade Bonetti (supporting).

Validation: Helio Henrique Soares Franco (lead).

Visualization: Cássio Antonio Tormena (supporting) and João de Andrade Bonetti (lead).

Writing – original draft: Cássio Antonio Tormena (supporting), João de Andrade Bonetti (lead) and Rachel Muylaert Locks Guimarães (supporting).

Writing – review & editing: Cássio Antonio Tormena (supporting), João de Andrade Bonetti (lead) and Rachel Muylaert Locks Guimarães (supporting).

REFERENCES

Balbinot Junior AA, Santos JCF, Debiasi H, Yokoyama AH. Contribution of roots and shoots of *Brachiaria* species to soybean performance in succession. Pesq Agropec Bras. 2017;52:592-8. https://doi.org/10.1590/S0100-204X2017000800004

Ball BC, Guimarães RML, Cloy JM, Hargreaves PR, Shepherd TG, McKenzie BM. Visual soil evaluation: A summary of some applications and potential developments for agriculture. Soil Till Res. 2017;173:114-24. https://doi.org/10.1016/j.still.2016.07.006

Ball BC, Hunter R. The determination of water release characteristics of soil cores at low suctions. Geoderma. 1988;43:195-212. https://doi.org/10.1016/0016-7061(88)90043-2

Baptistella JLC, Andrade SAL, Favarin JL, Mazzafera P. *Urochloa* in tropical agroecosystems. Front Sustain Food Syst. 2020;4:119. https://doi.org/10.3389/fsufs.2020.00119

Baquero JE, Ralisch R, Medina CC, Tavares Filho J, Guimarães MF. Soil physical properties and sugarcane root growth in a Red Oxisol. Rev Bras Cienc Solo. 2012:36:63-70. https://doi.org/10.1590/s0100-06832012000100007

Bardgett RD, Mommer L, De Vries FT. Going underground: Root traits as drivers of ecosystem processes. Trends Ecol Evol. 2024;29:692-9. https://doi.org/10.1016/j.tree.2014.10.006

Bieluczyk W, Piccolo MC, Pereira MG, Lambais GR, Germon A, Moraes MT, Soltangheisi A, Camargo PB, Bosi C, Bernardi ACC, Pezzopane JRM, Batista I, Cherubin MR. Fine root dynamics in a tropical integrated crop-livestock-forestry system. Rhizosphere. 2023;26:100695. https://doi.org/10.1016/j.rhisph.2023.100695

Bonetti JA, Anghinoni I, Bredemeier C, Moraes MT, Tormena CA, Gubiani PI. Physical recovery of an Oxisol under an integrated crop-livestock system in southern Brazil. Arch Agron Soil Sci. 2023;69:507-18. https://doi.org/10.1080/03650340.2021.2013471

Bonetti JA, Paulino HB, Souza ED, Carneiro MAC, Silva GN. Influência do sistema integrado de produção agropecuária no solo e na produtividade de soja e braquária. Pesq Agropec Trop. 2015;45:104-12. https://doi.org/10.1590/1983-40632015v4529625

Busscher WJ. Adjustment of flat-tipped penetrometer resistance data to a common water content. Trans Am Soc Agric Eng. 1990;33:519-24. https://doi.org/10.13031/2013.31360

Cagna CP, Guedes Filho O, Caroline M, Paschoal G. Soil structural quality and development of second-crop corn intercropping with forage grasses under no-tillage. Bragantia. 2023;82:e20230110. https://doi.org/10.1590/1678-4499.20230110

Cherubin MR, Franco ALC, Guimarães RML, Tormena CA, Cerri CEPC, Karlen DL, Cerri CEPC. Assessing soil structural quality under Brazilian sugarcane expansion areas using Visual Evaluation of Soil Structure (VESS). Soil Till Res. 2017;173:64-74. https://doi.org/10.1016/j.still.2016.05.004

Crusciol CAC, Ferreira JHS, Momesso L, Portugal JR, Campos M, Volf MR, Borghi E, Soratto RP, Calonego JC. Lasting effect of *Urochloa brizantha* on a common bean-wheat-maize rotation in a medium-term no-till system. Front Sustain Food Syst. 2023;7:940996. https://doi.org/10.3389/fsufs.2023.940996

Deeks LK, Bengough AG, Low D, Billett MF, Zhang X, Crawford JW, Chessell JM, Young IM. Spatial variation of effective porosity and its implications for discharge in an upland headwater catchment in Scotland. J Hydrol. 2004;290:217-28. https://doi.org/10.1016/j.jhydrol.2003.12.008

Ferreira CJB, Tormena CA, Severiano EDC, Zotarelli L, Betioli Júnior E. Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. Arch Agron Soil Sci. 2020;67:383-96. https://doi.org/10.1080/03650340.2020.1733535

Ferreira DF. Sisvar: A computer analysis system to fixed effects split plot type designs. Rev Bras Biom. 2011;37:529-35. https://doi.org/10.28951/rbb.v37i4.450

Figueiredo GC. Avanços metodológicos e instrumentais em física do solo [thesis]. Piracicaba: Universidade de São Paulo; 2010.

Franco HHS, Guimarães RML, Tormena CA, Cherubin MR, Favilla HS. Global applications of the Visual Evaluation of Soil Structure method: A systematic review and meta-analysis. Soil Till Res. 2019;190:61-9. https://doi.org/10.1016/j.still.2019.01.002

Galdos MV, Brown E, Rosolem CA, Pires LF, Hallett PD, Mooney SJ. Brachiaria species influence nitrate transport in soil by modifying soil structure with their root system. Sci Rep. 2020;10:5072. https://doi.org/10.1038/s41598-020-61986-0

Glaze-Corcoran S, Hashemi M, Sadeghpour A, Jahanzad E, Keshavarz AR, Liu X, Herbert SJ. Understanding intercropping to improve agricultural resiliency and environmental sustainability. Advn Agron. 2020;199:256. https://doi.org/10.1016/bs.agron.2020.02.004

Gotelli NJ, Ellison AM. Princípios de estatística em ecologia. 2. ed. Porto Alegre: Atmed; 2011.

Groenevelt PH, Kay BD, Grant CD. Physical assessment of a soil with respect to rooting potential. Geoderma. 1984;34:101-14. https://doi.org/10.1016/0016-7061(84)90016-8

Guimarães RML, Ball BC, Tormena CA. Improvements in the visual evaluation of soil structure. Soil Use Manag. 2011;27:395-403. https://doi.org/10.1111/j.1475-2743.2011.00354.x

Guimarães RML, Ball BC, Tormena CA, Giarola NFB, Silva AP. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil Till Res. 2013;127:92-9. https://doi.org/10.1016/j.still.2012.01.020

Guimarães RML, Neves Junior AF, Silva WG, Rogers CD, Ball BC, Montes CR, Pereira BFF. The merits of the Visual Evaluation of Soil Structure method (VESS) for assessing soil physical quality in the remote, undeveloped regions of the Amazon basin. Soil Till Res. 2017;173:75-82. https://doi.org/10.1016/j.still.2016.10.014

Hammer Ø, Harper DAT, Ryan PD. PAST: Paleontological statistics software package for education and data analysis. Palaeontol Electron. 2001;4:9178.

Hargreaves PR, Baker KL, Graceson A, Bonnett S, Ball BC, Cloy JM. Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years. Eur J Agron. 2019;109:125916. https://doi.org/10.1016/j.eja.2019.125916

IUSS Working Group WRB. World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps. 4th. ed. Vienna, Austria: International Union of Soil Sciences (IUSS); 2022. Available from: https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf.

Kiehl EJ. Manual de edafologia. São Paulo: Agronômica Ceres; 1979.

Koudahe K, Allen SC, Djaman K. Critical review of the impact of cover crops on soil properties. Int Soil Water Conserv Res. 2022;10:343-54. https://doi.org/10.1016/j.iswcr.2022.03.003

Li Y, Li Z, Cui S, Zhang Q. Trade-off between soil pH, bulk density and other soil physical properties under global no-tillage agriculture. Geoderma. 2020;361:114099. https://doi.org/10.1016/j.geoderma.2019.114099

McQueen DJ, Shepherd TG. Physical changes and compaction sensitivity of a fine-textured, poorly drained soil (Typic Endoaquept) under varying durations of cropping, Manawatu region, New Zealand. Soil Till Res. 2002;63:93-107. https://doi.org/10.1016/S0167-1987(01)00231-8

Moraes MT, Debiasi H, Carlesso R, Franchini JC, Silva VR. Critical limits of soil penetration resistance in a Rhodic Eutrudox. Rev Bras Cienc Solo. 2014;38:288-98. https://doi.org/10.1590/S0100-06832014000100029

Moraes MT, Debiasi H, Franchini JC, Bonetti JA, Levien R, Schnepf A, Leitner D. Mechanical and hydric stress effects on maize root system development at different soil compaction levels. Front Plant Sci. 2019;10:1358. https://doi.org/10.3389/fpls.2019.01358

Moreira WH, Petean LP, Betioli E, Tormena CA, Figueiredo GC, Silva AP. Método alternativo para quantificação do intervalo hídrico ótimo em laboratório. Rev Bras Cienc Solo. 2014;38:158-65. https://doi.org/10.1590/S0100-06832014000100015

Oliveira SM, Almeida REM, Pierozan Junior C, Reis AFB, Souza LFN, Favarin JL. Contribution of corn intercropped with *Brachiaria* species to nutrient cycling. Pesq Agropec Trop. 2019;49:e55018. https://doi.org/10.1590/1983-40632019v4955018

Paschoal MCG, Cagna CP, Guedes Filho O, Mazzini-Guedes RB. Visual evaluation of soil structure in maize and forage grasses intercropping under no-tillage. Braz Arch Biol Technol. 2020;63:e20190498. https://doi.org/10.1590/1678-4324-solo-2020190498

Pawar AB, Kumawat C, Verma AK, Meena RK, Raza MB, Anil AS, Trivedi VK. Threshold limits of soil in relation to various soil functions and crop productivity. Int J Curr Microbiol Appl Sci. 2017;6:2293-302. https://doi.org/10.20546/ijcmas.2017.605.256

Peel MC, Finlayson BL, Mcmahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007;11:1633-44. https://doi.org/10.5194/hess-11-1633-2007

Peng Y, Xu H, Wang Z, Long L, Jianying S, Li B, Xiang W. Effects of intercropping and drought on soil aggregation and associated organic carbon and nitrogen. Soil Use Manage. 2023;39:316-28. https://doi.org/10.1111/sum.12866

Pinheiro DP, Melo NC, Fernandes C. Soil quality indicators in an Ultisol subjected to chiseling in a sugarcane crop under mechanized management in southeastern Brazil. Sugar Tech. 2021;23:1064-74. https://doi.org/10.1007/s12355-021-01001-6

Reynolds WD, Bowman BT, Drury CF, Tan CS, Lu X. Indicators of good soil physical quality: Density and storage parameters. Geoderma. 2002;110:131-46. https://doi.org/10.1016/S0016-7061(02)00228-8

Reynolds WD, Drury CF, Tan CS, Yang XM. Temporal effects of food waste compost on soil physical quality and productivity. Can J Soil Sci. 2015;95:251-68. https://doi.org/10.4141/CJSS-2014-114

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Santos PRA, Chioderoli CA, Silva AO, Nicolau FEA, Lopes JEL, Amorim MQ, Mendonça CA. Physical attributes of the soil and maize productivity under an intercrop system. J Agric Sci. 2018a;10:358. https://doi.org/10.5539/jas.v10n12p358

Silva GSF, Andrade-Júnior AS, Cardoso MJ, Araújo-Neto RB. Soil water dynamics and yield in maize and *Brachiaria ruziziensis* intercropping. Pesq Agropec Trop. 2020;40:e59809. https://doi.org/10.1590/1983-40632020v5059809

Silva JF, Gontijo-Neto MM, Silva GF, Borghi E, Calonego JC. Soil organic matter and aggregate stability in soybean, maize and *Urochloa* production systems in a very clayey soil of the Brazilian savanna. Agronomy. 2022;12:1652. https://doi.org/10.3390/agronomy12071652

Stefan L, Hartmann M, Engbersen N, Six J, Schöb C. Positive effects of crop diversity on productivity driven by changes in soil microbial composition. Front Microbiol. 2021;12:660749. https://doi.org/10.3389/fmicb.2021.660749

Suzuki LEAS, Reinert DJ, Alves MC, Reichert JM. Critical limits for soybean and black bean root growth, based on macroporosity and penetrability, for soils with distinct texture and management systems. Sustainability. 2022;14:2958. https://doi.org/10.3390/su14052958

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Tuchtenhagen IK, Lima CLR, Bamberg AL, Guimarães RML, Pulido-Moncada M. Visual evaluation of the soil structure under different management systems in lowlands in southern Brazil. Rev Bras Cienc Solo. 2018;42:e0170270. https://doi.org/10.1590/18069657rbcs20170270