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Abstract: A favorable physical environment in the soil is necessary and of fundamental importance for the growth and root development of the sorghum crop, in order to maximize the productivity of the planted crops. In this study we evaluated the physical aspects of the soil in no-tillage system in a sorghum grain area intercropped with *Urochloa ruziziensis* and *Crotalaria spectabilis* and the productivity of the crop, in off-season (second crop season), based in a long field experiment. The experimental design was a randomized block design in a 4 x 4 factorial arrangement (four cropping systems: sorghum, sorghum + *Urochloa ruziziensis*, sorghum + *Crotalaria spectabilis*, sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis*; four soil depths: 0 - 0.10 m, 0.10 - 0.20 m, 0.20 - 0.30 m, 0.30 - 0.40 m). It was analyzed the productivity and the physical soil attributes that were: Soil Bulk Density (DS), Gravimetric Moisture (GM), Total Porosity (TP), Microporosity (MI), Macroporosity (MA) and Resistance to Root Penetration (RP). The study asserts that intercropping sorghum with *Crotalaria spectabilis* is a promising strategy to increase productivity. The Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* combination significantly improves soil structure by reducing penetration resistance and increasing macroporosity, especially at depths greater than 0.20 m. The inclusion of Urochloa enhances moisture retention, while Crotalaria contributes to greater porosity.

Keywords: cover crops; soil management; Sorghum *bicolor L.*; rotation

1. Introduction

The no-tillage system (NTS) is a conservation management technique that involves minimal soil disturbance, permanent soil cover maintenance, crop rotation, and species diversification. Additionally, it includes a harvest-sowing process aimed at increasing the number of crops and the duration the soil remains covered with plants (Possamai et al., 2022).

Within the scope of conservation agriculture, adopting a no-tillage approach can significantly boost soil health. This method enhances soil structure, promotes biological activity in the soil, optimizes nutrient cycling, and improves both the soil's capacity to retain water and its infiltration properties. (Hellner et al., 2018, Borges et al., 2018). As a result, conservation tillage is acknowledged as a sustainable practice for long-term agricultural productivity (Li et al., 2019).

However, these fundamental principles of the no-tillage system (NTS) are not always applied, with many areas adopting a simplified model, which often results in changes in the structural quality of the soil and an increase in soil compaction (Drescher, 2015a).

In summary, areas with compacted layers exhibit decreased macroporosity and increased microporosity, bulk density, and soil penetration resistance (Drescher, 2015b). This results in reduced water infiltration and gas exchange in the soil (Valicheski et al., 2012), higher water retention

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(Reichert et al., 2007), and diminished growth of both root systems and above-ground parts of plants (Shaheb, 2020).

An additional practice to reduce or prevent soil compaction is the use of Crop Rotation Systems, which involve species with strong and diverse root systems that can thrive in compacted soils (Michelon, 2023).

This practice enhances soil quality by increasing macroporosity and water infiltration rates, decreasing soil resistance to penetration (Moraes et al., 2016; Sulzbach et al., 2017; Ruffato et al., 2019), and forming stable bio-pores that facilitate water flow, air movement, and root growth for subsequent crops (Haskel, 2020). Moreover, the accumulation of organic matter helps retain moisture, making soils more resistant to compaction (Braida et al., 2006).

Therefore, sorghum can be an excellent crop for rotation, because stands out for its considerable productivity potential, showing tolerance to wide temperature variations and prolonged drought periods. According to records, sorghum cultivation is of substantial importance both for human and animal consumption, as well as for energy production, noted for its adaptability to a wide range of regions (Silva et al., 2014; Ferreira et al., 2019).

Compared to monoculture of sorghum, the benefits of intercropping are varied, particularly highlighting greater biomass production per unit area, soil preservation against erosion, carbon sequestration, nutrient cycling, and the ability to integrate multiple economic activities in the same area (Martin-Guay et al., 2018).

The implementation of intercropping with forage grasses, like *Urochloa ruziziensis*, and legumes, like *Crotalaria spectabilis*, is conducive to improving the soil's vegetation cover index, in contrast to weeds, emphasizing the preference for no-tillage planting in the subsequent season (Balbinot Junior et al., 2017).

Considering the importance that soil practices have, we evaluated the influence of intercropping grain sorghum with *Urochloa Ruziziensis* and *Crotalaria spectabilis* on the physical aspects of the soil and the productivity of the crop in no-tillage system.

2. Material and Methods

2.1. Experiment Location

The study was conducted at the experimental field of the Federal University of Mato Grosso do Sul, Chapadão do Sul- MS (18°46'17.7"S, 52°37'27.7"W, altitude 813 m), during the second crop of 2023. The climate of the region, according to the Köppen classification, is tropical humid (Aw), with a rainy season in summer and dry season in winter, with average annual precipitation of 1,850 mm and average annual relative humidity of 64.8%, presenting an average annual temperature ranging from 13°C to 28°C. The soil in the region was classified as Dystrophic Red Latosol, with clayey texture (Santos et al., 2018).

2.2. Area History

The experiment area has been managed since February 2021 with crop rotation in no-tillage system. It started with the planting of corn intercropped with *Urochloa ruziziensis*, pigeon pea, and Stylosanthes campo grande, followed by soybean in the 2021/2022 season. In the 2022 season, forage radish and millet were implemented, and subsequently, soybean were planted in the 2022/2023 season, continuing the rotation system. In the 2023 season, the grain sorghum intercropping experiment began, that is the evaluation of this experiment.

2.3. Experimental Design and Treatments

The design was a randomized block design in a 4 x 4 factorial scheme (four types of cultivation: sorghum, sorghum + *Urochloa ruziziensis*, sorghum + *Crotalaria spectabilis*, sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis*; four soil depths: 0 - 0.10 m, 0.10 - 0.20 m, 0.20 - 0.30 m, 0.30 - 0.40 m), totaling 16 experimental units and 4 replications. Each experimental unit consisted of 12 rows of 7

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meters in length with a spacing of 0.45 m between rows and a population of 9 seeds per meter, totaling a population of 915 plants per experimental unit and 186,000 plants per hectare.

2.4. Planting and Cultural Treatments

The grain sorghum hybrid used was ADV1151IG (tannin-free), with ultra-early cycle, which features herbicide resistance technology from the imidazolinone family, Imazapic + Imazethapyr, called igrowth®, allowing the intercropping of sorghum with cover crops. The intercropping of *Urochloa ruziziensis* (350 PVC between rows) and *Crotalaria spectabilis* (15 kg ha^{-1} between rows) was carried out manually.

The fertilizer rate used was 313 kg ha^{-1} of the 04-14-08 formulation applied through the planting furrow, based on soil analysis and fertilization recommendations for sorghum grain extracted from the Cerrado correction and fertilization bulletin (Sousa and Lobato, 2004).

For weed control, the herbicide formulation Imazapic + Imazethapyr was used in pre-emergence (plant-apply) at a dose of 1.2 L ha-1, meeting the requirements for the use of igrowth® technology and the herbicide Atrazine at a dose of 1.5 L ha-1 in post-emergence.

During the crop cycle, insecticide applications were carried out for pest control using the following doses: Acephate + Bifenthrin at 1.2 kg ha^{-1} for control of caterpillars, aphids, and stink bugs; Teflubenzuron at 240 mL ha^{-1} for caterpillar control; Chlorfenapyr at 750 mL ha^{-1} for caterpillar and aphid control; and Alpha-cypermethrin + Teflubenzuron at 500 mL ha^{-1} for caterpillar control. For disease control (mainly anthracnose, turcicum, and ergot), the fungicide Trifloxystrobin + Tebuconazole was used at a dose of 0.6 L ha^{-1}. All applications were made using an adjuvant containing 60 g L^{-1} of orange peel oil at a dose of 0.15 L ha^{-1}.

2.5. Productivity Analysis

First, the count of plants was done at 0.5 linear meters along the planting row, then the average number of plants per linear meter was determined using the following equation (Ciampitti & Carcedo; 2023):

$$Plants\ per\ linear\ (m) = (Total\ counted\ plants)/(Linear\ (m)\ per\ sampling\ point)$$

Afterwards, the plant population was determined using the area spacing with the following equations (Ciampitti & Carcedo; 2023):

$$Linear\ (m)\ per\ hectare = (10.000\ m^2)/(spacing\ (m))$$

$$Population = Linear\ (m) per\ hectare\ x\ Plants\ per\ linear\ (m)$$

Finally, grain weight was determined to estimate yield by collecting 3 to 6 sorghum panicles per plot. Using a scale, the grains from the panicles were weighed to find the average weight in kilograms, and then yield estimation in kilograms per hectare was performed using the following equations (Ciampitti & Carcedo; 2023):

$$Grain\ weight\ per\ panicle = (Sum\ of\ sampled\ grain\ weight)/(Total\ sampled\ panicles)$$

$$Productivity\ estimate = Population\ x\ Grain\ weight\ per\ panicle$$

2.6. Physical Soil Evaluations

For the physical analyses, trenches were dug with dimensions of 0.50 m width by 0.50 m length and 0.40 m depth. Soil samples were collected at depths of 0.00 - 0.10 m, 0.10 - 0.20 m, 0.20 - 0.30 m, and 0.30 - 0.40 m. The physical soil attributes analyzed were Soil Bulk Density (SD), Gravimetric

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Moisture (GM), Total Porosity (TP), Microporosity (MI), Macroporosity (MA) and Resistance to Root Penetration (RP).

Soil bulk density (SD) was determined using the volumetric ring method based on the mass/volume relationship and for porosity determination (Teixeira et al., 2017), with the following equation:

$$Tp = ([(a - b) - (c - d)])/e$$

TP - Total porosity, in $m^3\ m^{-3}$.

a - Mass of the saturated sample-cylinder-fabric-clip assembly, in kg.

b - Mass of the dry sample-cylinder-fabric-clip assembly at 105°C, in kg.

c - Mass of the saturated cylinder-fabric-clip assembly, in kg.

d - Mass of the dry cylinder-fabric-clip assembly at 105°C, in kg.

e - Total volume of the sample, in m^3. In this case, it is assumed that the total volume of the sample is equal to the volume of the cylinder.

Microporosity was determined following the methodology described by (TEIXEIRA et al.,2017), by subjecting the samples to a tension of -6 kPa. Macroporosity was calculated as the difference between total porosity and microporosity (Teixeira et al., 2017). Disturbed soil samples were collected to determine gravimetric moisture content (UG) using a Dutch auger.

The penetration resistance was evaluated using the electronic digital penetrometer (PenetroLOG), manually operated and primarily dependent on the operator's strength. It indicates the depth of the rod penetration and includes the calculation of the penetration speed, as well as alerting the user if the speed is out of the standard range (Molin, 2012).

2.7. Statistical Analysis

The data were analyzed using R software for analysis of variance, and when significant, means were compared using the Scott-Knott test ($P < 0.05$). Excel software was used to draw the figures.

3. Results and Discussion

The analysis of variance (ANOVA) table evaluates the effect of different sources of variation, including crop type and depth, on various soil properties such as Soil Bulk d

Density (DS), Gravimetric Moisture (GM), Total Porosity (PT), Microporosity (Micro), Macroporosity (Macro), Resistance to Root Penetration (RP), and Productivity (Prod).

Table 1. The analysis of variance (ANOVA) table.

Sources Variations	D.F.[1]	Prod	SD	GM	TP	Micro	Macro	RP
		kg ha^{-1}	g cm^{-3}	-----------------------%-------------------- -----				MPa
BLOCK	3	8,451	0,0039	13,002	17,62	13,96	4,11	0,18
Crops (C)	3	38,01*	0,0040^{ns}	4,92*	81,0*	133,45*	11,06^{ns}	0,142^{ns}
Depth (D)	3	0,16^{ns}	0,0512*	0,70^{ns}	1,42^{ns}	13,39^{ns}	0,58^{ns}	7,56^{ns}
C x D	9	0,27^{ns}	0,0056^{ns}	0,89^{ns}	10,96^{ns}	6,47^{ns}	10,47*	2,48*
Error	45	0,17^{ns}	0,0052^{ns}	0,96^{ns}	9,60^{ns}	6,33^{ns}	4,29^{ns}	3,90^{ns}
CV (%)	-	12,66	4,54	4,53	6,83	6,94	21,5	17,19
Mean	-	6,45	1,59	21,61	45,35	36,26	9,83	1,71

[1]Degrees of freedom. * Significant and ns not significant by F-test at the 5% probability level.

For productivity, the crops were significant, with no significant interaction between the factors. O coeficiente de variação de 12,66% indica uma variabilidade moderada dos dados em relação à média.

Crops had a significant effect on soil moisture (UG), total porosity (PT), and macroporosity (Macro), as indicated by the significant (*) F-values. Soil moisture (UG) showed significant variation

(81.0%), while total porosity (PT) and macroporosity (Macro) also exhibited significant differences among crop types, with values of 133.45% and 11.06%, respectively.

Depth had a significant effect only on soil density (DS), indicating that soil density varies significantly with depth, as expected due to natural soil compaction at deeper layers.

The interaction between crop type and depth showed a significant effect on macroporosity (Macro) and penetration resistance (RP), suggesting that the combination of different crop types and depths can influence macroporosity and penetration resistance in a more complex manner than the individual effects of each factor.

3.1. Productivity

The Figure 1 compares the productivity (kg ha^{-1}) of sorghum in different cultivation systems: sorghum, sorghum intercropped with *Urochloa ruziziensis*, sorghum intercropped with *Crotalaria spectabilis*, and sorghum intercropped with *Urochloa ruziziensis* and *Crotalaria spectabilis*.

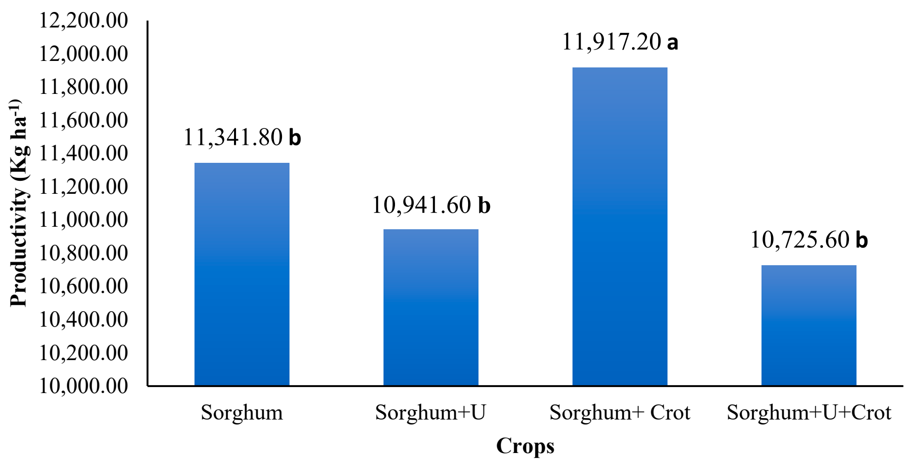

Figure 1. Productivity in Kg ha^{-1} of Sorghum intercropped with different crops in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level. .

The results show that the intercropping of sorghum with *Crotalaria spectabilis* presented the highest yield, reaching with 11,917.20 kg ha^{-1}. This increase can be attributed to the agronomic benefits of *Crotalaria spectabilis*, a legume known for its ability to fix nitrogen and improve soil fertility, resulting in higher grain yields (Mingotte et al., 2021; Cambaúva et al., 2019). Additionally, recent studies indicate that *Crotalaria spectabilis* can improve soil structure and increase the availability of essential nutrients, favoring the growth of sorghum (Mingotte et al., 2021).

In contrast, the intercropping of sorghum with *Urochloa ruziziensis* and the triple system (sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis*) showed lower yields, with 10,725.60 kg ha^{-1}. This can be explained by the competition for resources among plants, such as water, light, and nutrients, which is more intense in these systems. Although *Urochloa ruziziensis* offers advantages in terms of weed control and improvement of soil organic matter, its intercropping may not be as effective for sorghum grain yield (Crusciol et al., 2013; Soares de Faria et al., 2022).

The inclusion of *Urochloa ruziziensis* in intercropping systems is advantageous for crop-livestock integration systems, allowing the production of high-quality forage after the sorghum harvest, which can support a third crop with cattle (Mingotte et al., 2021). This practice has proven effective in increasing the total area productivity throughout the year, as well as improving the sustainability of the agricultural system, as highlighted by Soares de Faria et al. (2022).

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3.2. Soil Bulk Density

The depths of 0.10 - 0.20 m and 0.20 - 0.30 m, in Figure 2 showed the highest soil densities, with 1.66 g cm^{-3} and 1.63 g cm^{-3} and no significant difference between them. In contrast, depths of 0.00 - 0.10 m and 0.30 - 0.40 m exhibited lower soil densities, with 1.58 g cm^{-3} and 1.50 g cm^{-3} and no significant difference between these two depths.

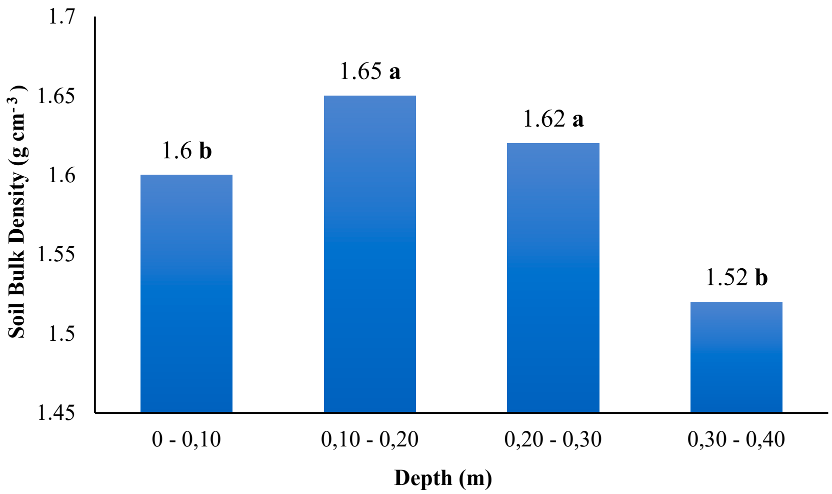

Figure 2. Comparison of depth for Soil Bulk Densities (g cm^{-3}) in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level.

In contrast, the depths of 0.00 - 0.10 m and 0.30 - 0.40 m showed lower soil densities, with 1.58 g cm^{-3} and 1.50 g cm^{-3}, respectively. This variation can be attributed to lower mechanical pressure and greater influence of organic matter and biological activity at the soil surface, which tends to reduce soil density (Keller et al., 2022). The reduction in density at depths greater than 0.30 m can be explained by the lower activity of heavy machinery in these layers and the possible presence of natural structural characteristics of the soil that prevent severe compaction (Liu et al., 2022).

These observations are crucial for agricultural management, as soil compaction can negatively influence porosity and water infiltration capacity, impacting root growth and crop productivity. Recent studies suggest that soil compaction can be mitigated by proper management of agricultural machinery traffic, the use of conservation tillage practices, and increasing soil organic matter (Blanco-Canqui et al., 2022). Additionally, practices such as using lower pressure tires and limiting traffic under wet soil conditions can significantly reduce the adverse effects of compaction (Pires et al., 2023).

3.3. Gravimetric Moisture

Results show in Figure 3, that Sorghum + *Urochloa ruziziensis* and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* exhibited the highest gravimetric moistures, with 22.1%, significantly higher than sorghum (21%) and Sorghum + *Crotalaria spectabilis* (21%). Statistical analyses indicate that the inclusion of *Urochloa ruziziensis* significantly increases soil moisture retention, whereas the addition of *Crotalaria spectabilis* does not demonstrate a similar effect. This indicates that the inclusion of *Urochloa ruziziensis* is effective in increasing soil moisture retention, possibly due to dense root development that enhances soil structure and water infiltration.

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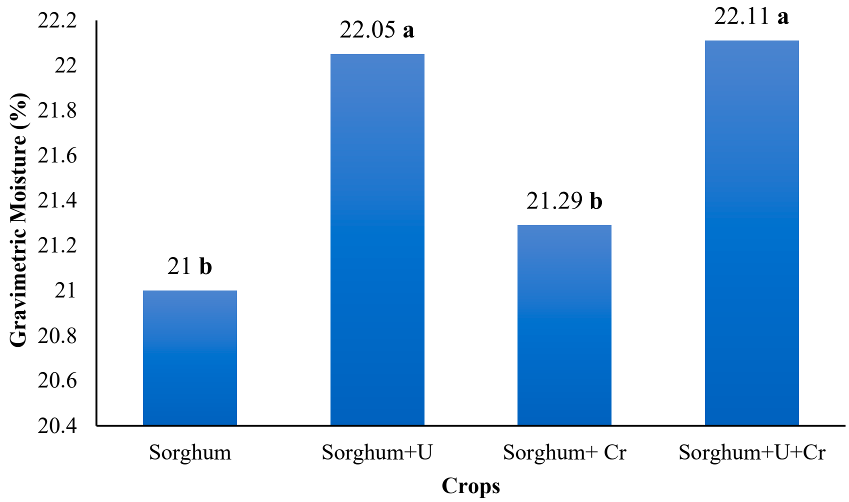

Figure 3. Comparison of Gravimetric Moisture (%) in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level.

Previous studies have also demonstrated that *Urochloa ruziziensis* can improve soil physical properties, resulting in greater water retention capacity. For instance, (Crusciol et al., 2010) reported that introducing *Urochloa spp.* into cropping systems increases soil porosity and water infiltration, contributing to better moisture conservation.

Furthermore, the lack of significant difference between pure sorghum and the Sorghum + *Crotalaria spctabilis* combination indicates that Crotalaria, when used alone with sorghum, does not have a notable impact on soil moisture. This aligns with studies suggesting that the effect of Crotalaria *spp.* on soil moisture may be less pronounced compared to other cover crops (Pacheco et al., 2011).

Additionally, agricultural practices promoting organic matter incorporation and minimizing soil disturbance, such as cover cropping and no-till systems, are effective in increasing soil organic carbon stocks, thereby enhancing water retention capacity (Žiūraitis et al., 2024).

3.4. Total Porosity

The analysis of total porosity presented in Figure 4 indicates that Sorghum and Sorghum + *Crotalaria spectabilis* have the highest porosity percentages, approximately 47%, significantly greater than the Sorghum + *Urochloa ruziziensis* and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* combinations, which show around 44% and 42% respectively. This suggests that the inclusion of *Urochloa ruziziensis* reduces soil porosity compared to sorghum alone.

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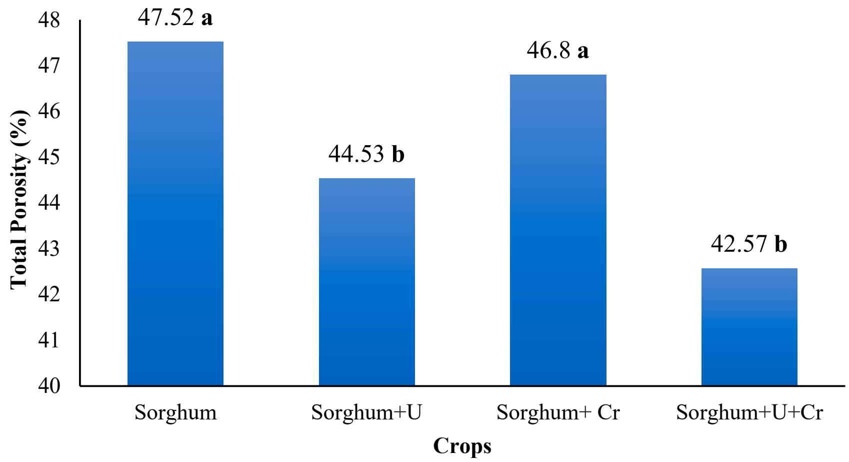

Figure 4. Comparison of Total Porosity (%) in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level. .

Research has demonstrated that while Urochloa species can improve certain soil properties, their impact on soil porosity can be complex. For instance, a study by da (Silva et al.,2021) noted that intercropping with Urochloa in coffee plantations altered soil hydraulic properties and porosity, which may not always lead to an increase in porosity.

Conversely, other cover crops like Crotalaria may not significantly affect porosity, as suggested by (Crusciol et al.,2021), who found that intercropping systems involving forage grasses like Urochloa can optimize nitrogen management without necessarily enhancing porosity.

3.5. Microporosity

The results from Figure 5 indicate that soil microporosity is significantly higher in treatments with Sorghum and Sorghum + *Urochloa ruziziensis* (~39%) compared to treatments with Sorghum + *Crotalaria spectabilis.* and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* (~36% and ~32%, respectively).

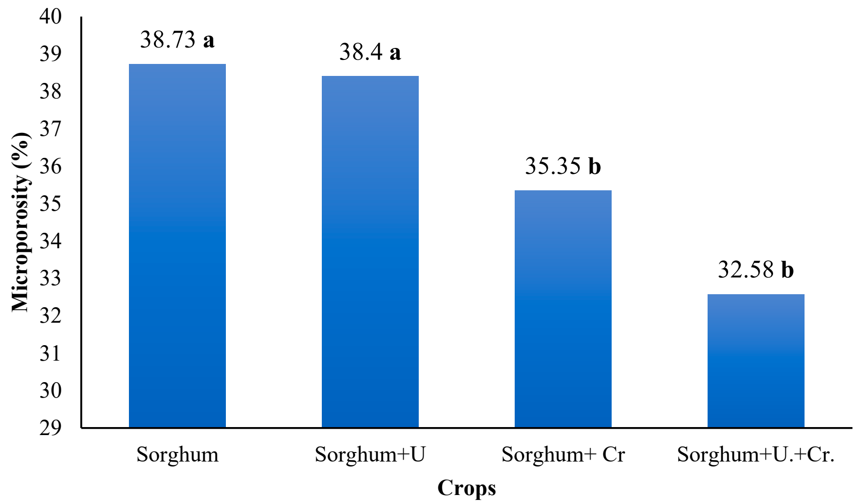

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Figure 5. Comparison of Microporosity (%) in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level.

The increased microporosity associated with Sorghum and *Urochloa ruziziensis* can be attributed to the fibrous root systems of these plants, which improve soil structure and facilitate the formation of micropores essential for water retention and aeration (Lal, 2020; Blanco-Canqui and Ruis, 2020).

In contrast, Crotalaria appears to reduce microporosity due to root competition and its morphological characteristics, resulting in less micropore formation (Stegarescu et al., 2021; Hudek et al., 2022). These findings underscore the importance of selecting crops that promote microporosity to optimize soil health and agricultural productivity (Gentsch et al., 2020).

3.6. Macroporosity

The Figure 6 shows the soil macroporosity (%) at different depths (0-0.10 m, 0.10-0.20 m, 0.20-0.30 m, and 0.30-0.40 m) under different crop combinations: Sorghum, Sorghum + *Urochloa ruziziensis*, Sorghum + *Crotalaria spectabilis*, and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis*.

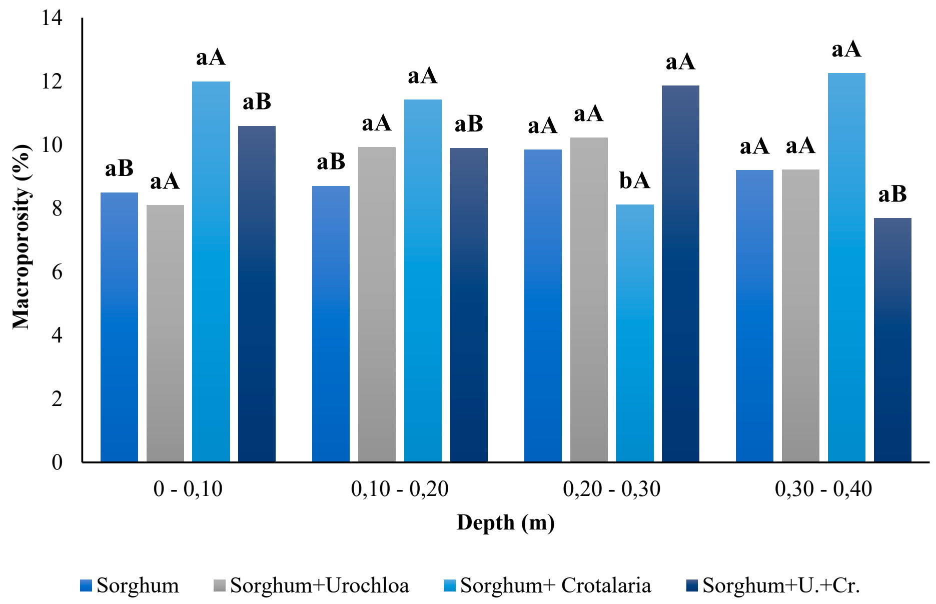

Figure 6. Comparison of Macroporosity (%) in no-tillage system. Different lower-case letters in the same layer indicate significant differences between depths by the Scott-Knott test at a 5% probability level.

At the depth of 0-0.10 m, the Sorghum + *Crotalaria spectabilis* combination exhibited the highest macroporosity at 12%, significantly greater than the other combinations. At the depth of 0.10-0.20 m, again, the Sorghum + *Crotalaria spectabilis* combination stood out with the highest macroporosity (11%). At the depth of 0.20-0.30 m, the Sorghum + *Crotalaria spectabilis* and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* combinations showed the highest microporosities (both 10%), while the Sorghum + *Urochloa ruziziensis* combination had the lowest macroporosity (7%). At the depth of 0.30-0.40 m, Sorghum + *Crotalaria spectabilis* remained the combination with the highest macroporosity (12%).

The Sorghum + *Crotalaria spectabilis* combination consistently resulted in the highest rates of macroporosity at all analyzed depths. Urochloa *spp.* is effective in weed suppression and soil cover, while Crotalaria *spp.* significantly contributes to soil structure improvement and nitrogen fixation (Gilbert et al., 2008; Desalegn et al., 2023). This combination provides denser soil cover and richer nutrient decomposition, resulting in more porous and well-structured soils.

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This result is consistent with recent studies highlighting the benefits of Crotalaria *spp.* in soil structure improvement. *Crotalaria juncea*, for instance, is known for its nitrogen-fixing ability and rapid decomposition, increasing organic matter and thereby improving soil structure and porosity (Melo et al., 2017b; Ferreira et al., 2021a).

3.7. Resistance to Root Penetration

The Figure 7 shows soil penetration resistance (RP) as a function of depth for different cover crop combinations: Sorghum, Sorghum + *Urochloa ruziziensis*, Sorghum + *Crotalaria spectabilis*, and Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis*. Penetration resistance is measured in MPa and depth in cm.

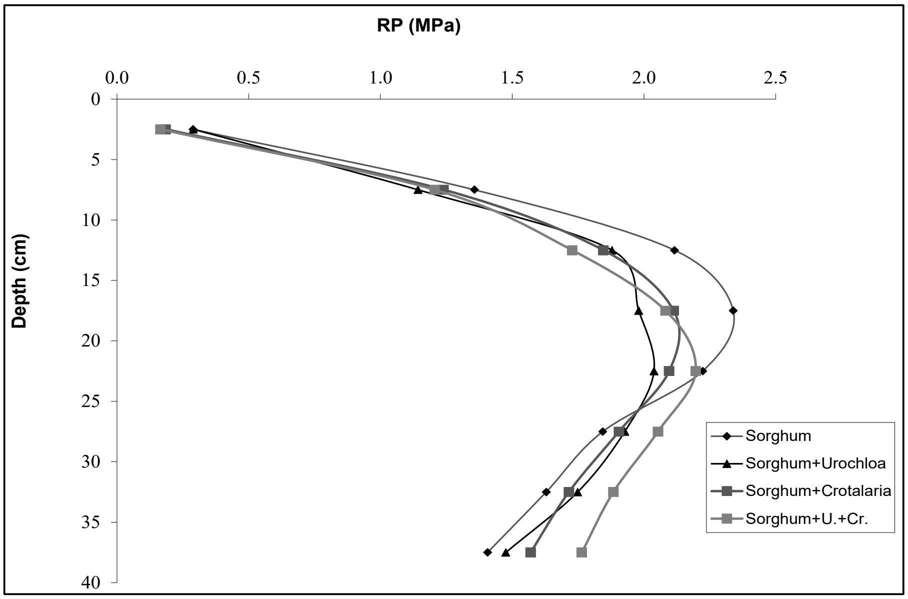

Figure 7. Resistance to Root Penetration in no-tillage system.

In Sorghum, it is observed that penetration resistance gradually increases with depth, with 2 MPa at a depth of 35 cm. Sorghum alone results in higher penetration resistance at all analyzed depths. This result is consistent with studies indicating that monocultures can lead to soil compaction due to the lack of root diversity (Carof et al., 2007).

Sorghum + *Urochloa ruziziensis* shows slightly lower penetration resistance than pure Sorghum up to about 25 cm depth but becomes equal at greater depths. The inclusion of *Urochloa Ruziziensis* with Sorghum resulted in a slight reduction in penetration resistance in the upper soil layers. Urochloa *spp.* is known for its ability to improve soil structure and reduce compaction due to its aggressive root system and soil cover capacity (Crusciol et al., 2013).

For Sorghum + *Crotalaria spectabilis*, penetration resistance is significantly lower at depths up to 30 cm compared to Sorghum and Sorghum + *Urochloa ruziziensis*. Crotalaria *spp.* is known for its nitrogen-fixing properties and for improving soil porosity (Pitol, 2008; Silva et al., 2011). Its rapid decomposition and contribution to organic matter are factors that may explain the lower penetration resistance observed (Melo et al., 2017b).

The Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* treatment shows the lowest penetration resistance among all, especially at depths greater than 20 cm, indicating a significant improvement in soil structure. The diversity of root systems and different decomposition rates may have contributed to higher macroporosity and a looser soil structure (Silva et al., 2021). This combination maximizes the individual benefits of each cover crop, providing a more substantial improvement in soil health (Ferreira et al., 2021b).

Based on the results obtained, we recommend the adoption of intercropping systems of sorghum with *Urochloa ruziziensis* and *Crotalaria spectabilis* as an effective practice to improve soil structure and

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increase crop productivity. This strategy not only promotes soil sustainability but can also lead to significant cost savings for farmers by reducing reliance on external inputs and enhancing moisture retention. Additionally, integrating legumes into the cropping system supports more efficient natural resource management, bolstering crop resilience against climate change.

4. Conclusions

The study asserts that intercropping sorghum with *Crotalaria spectabilis* is a promising strategy to increase productivity. Furthermore, it demonstrates that the Sorghum + *Urochloa ruziziensis* + *Crotalaria spectabilis* combination, significantly improves soil structure by reducing penetration resistance and increasing macroporosity, especially at depths greater than 0.20 m. The inclusion of *Urochloa ruzieiensis* enhances moisture retention, while *Crotalaria spectabilis* contributes to greater porosity. These intercropping practices are effective for sustainable soil management, promoting better soil health, structure and great productivities.

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