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Short-term impacts of different intercropping times of maize and ruzigrass on soil physical properties in subtropical Brazil

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A R T I C L E I N F O

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A B S T R A C T

Intercropping maize (*Zea mays* L.) with ruzigrass (*Urochloa ruziziensis*) is a strategy for improving soil physical quality. However, effects of ruzigrass sowing time on soil physical properties with maize intercropping are unknown. Therefore, this study aimed to evaluate the short-term effects of intercropping times of maize and ruzigrass over three years (2019/2020–2021/2022) on the soil physical properties and grain yield of maize and soybean (*Glycine max* L.). The study was conducted in southern Brazil, in an Oxisol (602 g kg^{-1} of clay) under no-tillage. Under rainfed conditions, different intercropping times were evaluated during fall-winter, (i) ruzigrass sown before maize, (ii) sown at the time of maize sowing, (iii) sown 15 days after maize, and (iv) no intercropping (sole maize). Soybeans were grown every year during summer. The physical properties of the soil were evaluated during the six growing seasons. In the short-term, the bulk density in the 10–20 cm layer was 10% lower in the intercropping of ruzigrass sown before maize than that of sole maize. Macroporosity was 17% greater when ruzigrass was sown before maize compared with sowing performed 15 days after maize and it was 33% greater compared with no ruzigrass (sole maize) between the rows of maize. Although intercropping improved soil physical conditions, the soybean grain yield was not affected in two of the three years and was not correlated with the physical soil properties. In contrast, the maize yield was 17% higher when ruzigrass was intercropped 15 days after sowing maize than in the intercropping before maize sowing. The results suggest that the benefits of intercropping maize with ruzigrass on soil physical quality were greater when ruzigrass was sown before or at the time of maize sowing. The intercropping of maize with ruzigrass can be recommended as a management practice that improves the physical quality and other ecosystem services of the soil.

1. Introduction

In the absence of crop diversification in no-tillage systems, the predominance of crops with little root growth results in the formation of compacted soil layers (Ferreira et al., 2021), restricting root growth and affecting crop yields (Sarto et al., 2021). Oxisols with a compacted soil layer have been frequently reported (Blanco-Canqui and Ruis, 2018), and require alternative soil compaction relief practices (Ferreira et al., 2021). However, replacing commercial crops, such as maize (*Zea mays* L.) and soybean (*Glycine max* L.), by ecological principles of Conservation Agriculture (CA) which are permanent soil mulch cover and crop diversification, is not well accepted by farmers (Fuentes-Llanillo et al., 2021). Owing to the global market and profitability of commercial crops, replacing soybean or maize with another crop on a large scale is extremely difficult (Anghinoni et al., 2021).

Therefore, a strategy to increase crop rotation with plants with greater root growth involves using forage grasses in integrated intercropping systems with maize (Garbeline et al., 2020). Intercropping is a system in which two or more species are cultivated simultaneously on the same land (Crusciol et al., 2012). The main objective of this system is to increase the amount of above- and belowground biomass following maize harvest (Sarto et al., 2021); forage can grow after the maize harvest until soybean sowing. Among the forage grasses, ruzigrass (*Urochloa ruziziensis* (R. Germ. and C.M. Evrard) Crins) has been adopted

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in integrated intercropping systems (Crusciol et al., 2012).

The root structure of ruzigrass offers great potential for intercropping (Baptistella et al., 2020). Ruzigrass roots are vigorous, abundant, and deep, as opposed to the more shallow and scarce roots of commercial crops (Rosolem et al., 2019). Ruzigrass roots can promote the recovery of soil physical conditions through the formation of new aggregates, leading to a decrease in soil bulk density and an increase in soil macroporosity (Silva et al., 2021). Ruzigrass has a large volume of fine roots that easily grows in deep soil layers (Sarto et al., 2021). These fine roots fill existing soil pores during their growth, thereby increasing pore space. Furthermore, ruzigrass roots can change pore connectivity, which enhances hydraulic conductivity and water availability at the root–soil interface (Galdos et al., 2020). The interaction of the ruzigrass roots with soil microbiota helps C sequestration and can increase the availability of nutrients and reduce its losses, influencing the cycling of these elements (Sarto et al., 2020). However, the ruzigrass root system can vary depending on the intercropping management strategy (Carvalho et al., 2010).

In intercropping, species are usually sown simultaneously (Crusciol et al., 2012; Borghi et al., 2013). However, belowground interspecies interactions affect the root growth (Sarto et al., 2021), which can consequently influence soil physical properties. When intercropping is established after sowing maize, the length of time that maize and forage grow together is reduced and competition between these species may also be reduced (Borghi et al., 2013). Thus, following the establishment of maize, the emergence and development of ruzigrass does not affect maize grain yield. However, sowing ruzigrass after maize can reduce forage biomass growth and production (Borghi et al., 2013), reducing root growth and impacting soil physical properties.

Several authors have observed that intercropping maize with ruzigrass can potentially improve the physical properties of soil (Bertollo et al., 2021). However, the effects of the sowing time of ruzigrass intercropped with maize on the soil physical properties are unknown. This study hypothesized that the time of sowing of ruzigrass affects the soil physical properties differently. Therefore, the objective of this study was to evaluate the effect of intercropping maize and ruzigrass over three years on the soil physical properties and grain yield of maize and soybean.

2. Material and methods

2.1. Site description

The experiment was performed in the city of Anahy (24°66’ S, 53°12’ W, and 483 m a.s.l.), Paraná State, southern Brazil (Supplementary Fig. S1), for three years (2019/2020, 2020/2021, and 2021/2022). The

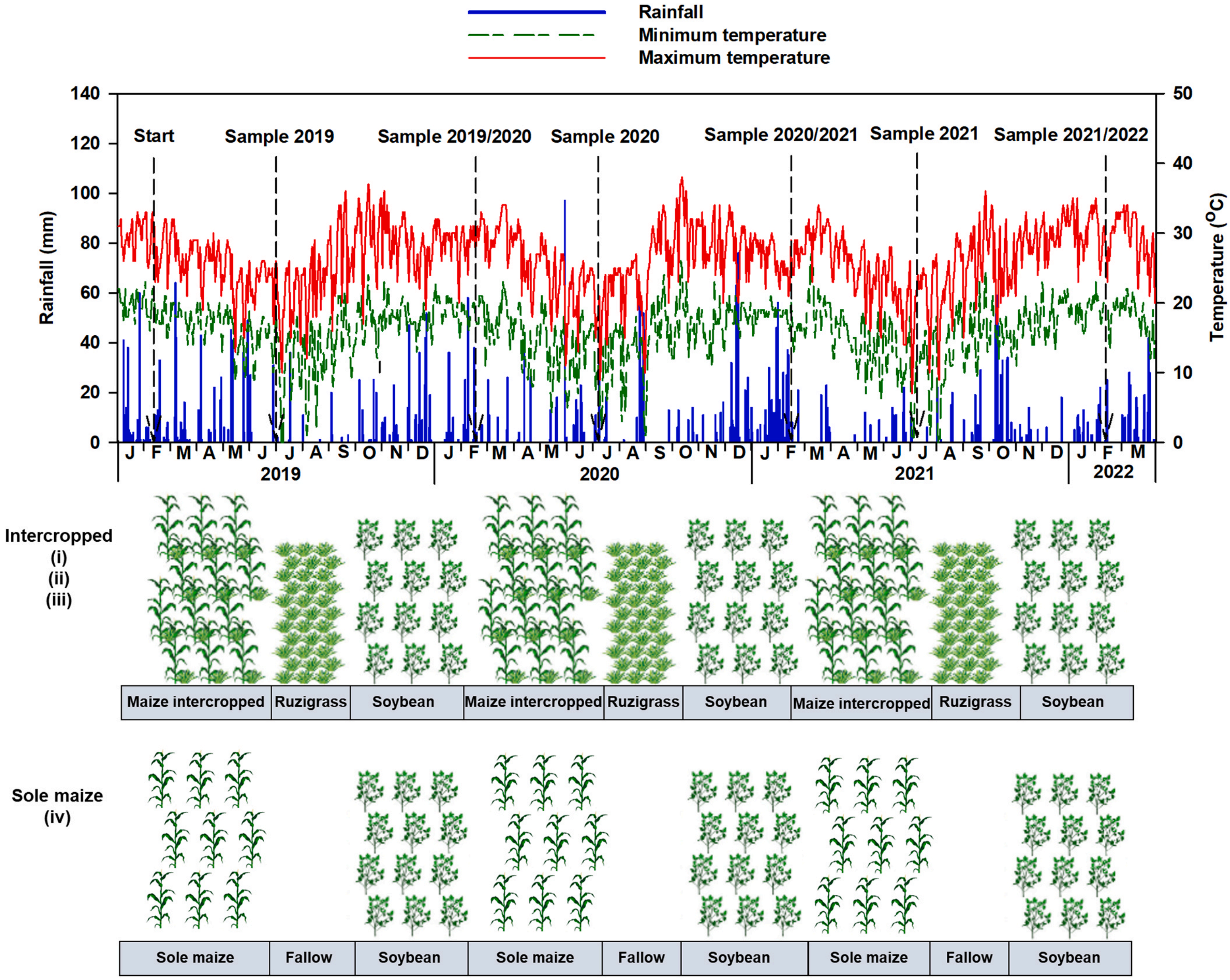

Fig. 1. Rainfall and maximum and minimum temperatures of the experimental area, and schematic representing the intercropped of ruzigrass and sole maize. Intercropping of ruzigrass before maize (i), ruzigrass at the time maize (ii), ruzigrass 15 days after maize (iii), and sole maize (iv).

climate is classified as humid mesothermal (Cfa) by the Köppen classification, with hot summers and no defined dry season. The annual average temperature ranges between 22 and 23 °C, and rainfall between 1400 and 1600 mm. The precipitation and temperature were measured in this study (Fig. 1). Rainfall throughout the maize cycle was 665, 528, and 191 mm in 2019, 2020, and 2021, respectively. In the soybean cycle, the rainfall was 686, 858, and 450 mm in 2019/2020, 2020/2021, and 2021/2022, respectively.

The soil in the experimental area was classified as Oxisol (clayey, kaolinitic, Rhodic Hapludox; Soil Survey Staff, 2014) with 602, 356, and 42 g kg^{-1} of clay, silt, and sand, respectively, in the 0–20 cm depth layer. Prior to October 2019, the study site was cultivated with annual crops (maize and soybean) for five years using no-tillage. Table 1 shows the chemical and physical characteristics of the soil in the experimental area in the 0–40 cm layer. The following chemical properties (EMBRAPA, 1997) were analyzed: soil pH ($CaCl_2$); P and K^+ (Mehlich 1); exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} (KCl 1 mol L^{-1}); organic matter (Walkley Black); and base saturation (BS%).

2.2. Experimental design and treatments

The experimental design was a completely randomized block with five repetitions. Different intercropping times, under rainfed conditions, were evaluated during fall-winter. Three ruzigrass intercropping conditions (Supplementary Fig. S2), namely, (i) sown before maize, (ii) sown at the time of maize sowing, (iii) sown 15 days after maize, were compared to (iv) sole maize. The ruzigrass was sown for each condition by manual broadcast, within the maize rows at the time of maize sowing, and between rows of maize in open furrows, respectively. The intercropping of maize with ruzigrass was repeated in the same location for three years in autumn and winter (i.e., 2019, 2020, and 2021). The soybean crop was sown in summer (2019/2020, 2020/2021, and 2021/2022) (Fig. 1). Each plot measured 10 × 30 m.

2.3. Crop management

In January 2019, the weeds were desiccated by applying glyphosate (isopropylamine salt of N-(phosphonomethyl glycine); 1800 g of acid equivalent ha^{-1}), using a spray volume of 200 L ha^{-1} 20 days before sowing maize. The maize hybrid K9960 VIP 3 was sown with a seeder-fertilizer machine on February 11, 2019, February 10, 2020, and February 15, 2021, at a depth of 3 cm and density of 5.6 seed m^{-1} with 90 cm spacing between rows (62,222 seed ha^{-1}). In all treatments, the formulated fertilization of the sowing furrows consisted of 29 kg ha^{-1} N as urea, 43 kg ha^{-1} P_2O_5 as triple superphosphate, and 43 kg ha^{-1} K_2O as KCl. For all intercropping treatments, ruzigrass was used at a density of 7.5 kg ha^{-1} (70% viable seeds) (Borghi et al., 2013). Mesotrione (2-(4-mesyl-2-nitrobenzoyl) cyclohexane–1,3-dione) was applied at a sub-dose of 31 g ai ha^{-1} to suppress ruzigrass growth in treatments in which ruzigrass was sown before maize sowing and at the time of maize sowing in all years. When ruzigrass was intercropped 15 days after maize sowing no herbicide was applied to suppress ruzigrass due to lower growth.

Before soybean sowing, the ruzigrass was desiccated by applying glyphosate (N-(phosphonomethyl glycine) isopropylamine salt; 1800 g of acid equivalent ha^{-1}) using a solution volume of 200 L ha^{-1} 20 days before soybean sowing. The soybean cultivar Monsoy 5947 was sown with a seeder-fertilizer machine on September 10, 2019; September 12, 2020; and September 13, 2021, at a depth of 5 cm and density of 12 seed m^{-1} with 45 cm spacing between rows. In all treatments, the formulated fertilization in the seeding furrows consisted of 5 kg ha^{-1} N as urea, 45 kg ha^{-1} P_2O_5 as triple superphosphate, and 50 kg ha^{-1} K_2O as KCl.

2.4. Soil physical properties

Soil bulk density, macroporosity, microporosity, total porosity, and saturated hydraulic conductivity were analyzed using a cylinder (5.0 cm high, 4.8 cm internal diameter) at 0–10, 10–20, and 20–30 cm. Undisturbed soil samples were collected each year after intercropping and soybean harvesting (Fig. 1); the physical properties of the soil were evaluated during six growing seasons (winter and summer). Trenches 30 cm wide, 40 cm long, and 30 cm deep were opened in each plot, and samples were collected in the plant- and inter-row positions. The undisturbed soil samples were capillary-saturated for 48 h, and saturated hydraulic conductivity was measured using a constant-head permeameter (Klute, 1986). Afterwards, the samples were again capillary saturated and subjected to a tension of 6 kPa on a sand column (Reinert and Reichert, 2006). Finally, the samples were dried at 105 °C to constant weight to determine bulk density (ρ_b), according to Blake and Hartge (1986). The total porosity (TP) was calculated from the bulk density and particle density (ρ_p) values ($TP = 1—[\rho_b/\rho_p]$). Microporosity was calculated based on the volumetric 6 kPa tension, while macroporosity was the difference between TP and microporosity.

2.5. Soybean and maize yield

After the physiological maturation of maize and soybeans, a manual harvest was performed. Maize was harvested in three rows of 5 m (13.5 m^2) and soybean in four rows of 5 m (9 m^2). Grain weights were transformed into grain yield ha^{-1} (130 g kg^{-1} wet basis).

2.6. Statistical analyses

Normal distributions (Shapiro–Wilk test) and variance of homogeneity (Levene test) were used ($p < 0.05$). Analysis of variance (ANOVA) was performed using the statistical software R (version 3.5.2). The intercropping systems were considered fixed factors and blocks were treated as random effects. If the null hypothesis was rejected, a comparison of the means was performed using Tukey test at $p < 0.05$. A simple correlation (Pearson) analysis was performed to determine the degree of association between variables.

3. Results

3.1. Soil physical properties

The bulk density after three years in the 10–20 cm layer in the sole maize (1.28 Mg m^{-3}) was significantly ($p < 0.05$) higher (10%) than that when ruzigrass was sown before maize (1.16 Mg m^{-3}; Fig. 2e and f). In general, intercropping of ruzigrass sown before maize was more effective in reducing (6%) the bulk density than when ruzigrass was sown 15 days after maize. However, compared with sole maize, sowing ruzigrass

Table 1
Soil characteristics before the experiment started.

Layer	P $_{(Mehlich-1)}$	OM	pH	H+Al	Al^{3+}	K^+	Ca^{2+}	Mg^{2+}	CEC	BS
cm	mg dm^{-3}	g kg^{-1}	$CaCl_2$	————	$cmol_c$ kg^{-1}	————				%
0 – 10	10.07	26.01	4.48	7.27	0.46	0.37	7.80	2.07	17.16	59.7
10 – 20	4.21	23.17	4.56	6.96	0.72	0.32	7.50	2.06	17.10	57.8
20 – 40	2.38	20.16	4.69	5.84	0.90	0.23	6.80	1.97	15.92	56.5

OM: Organic matter. CEC: Cations exchange capacity. BS: Base saturation.

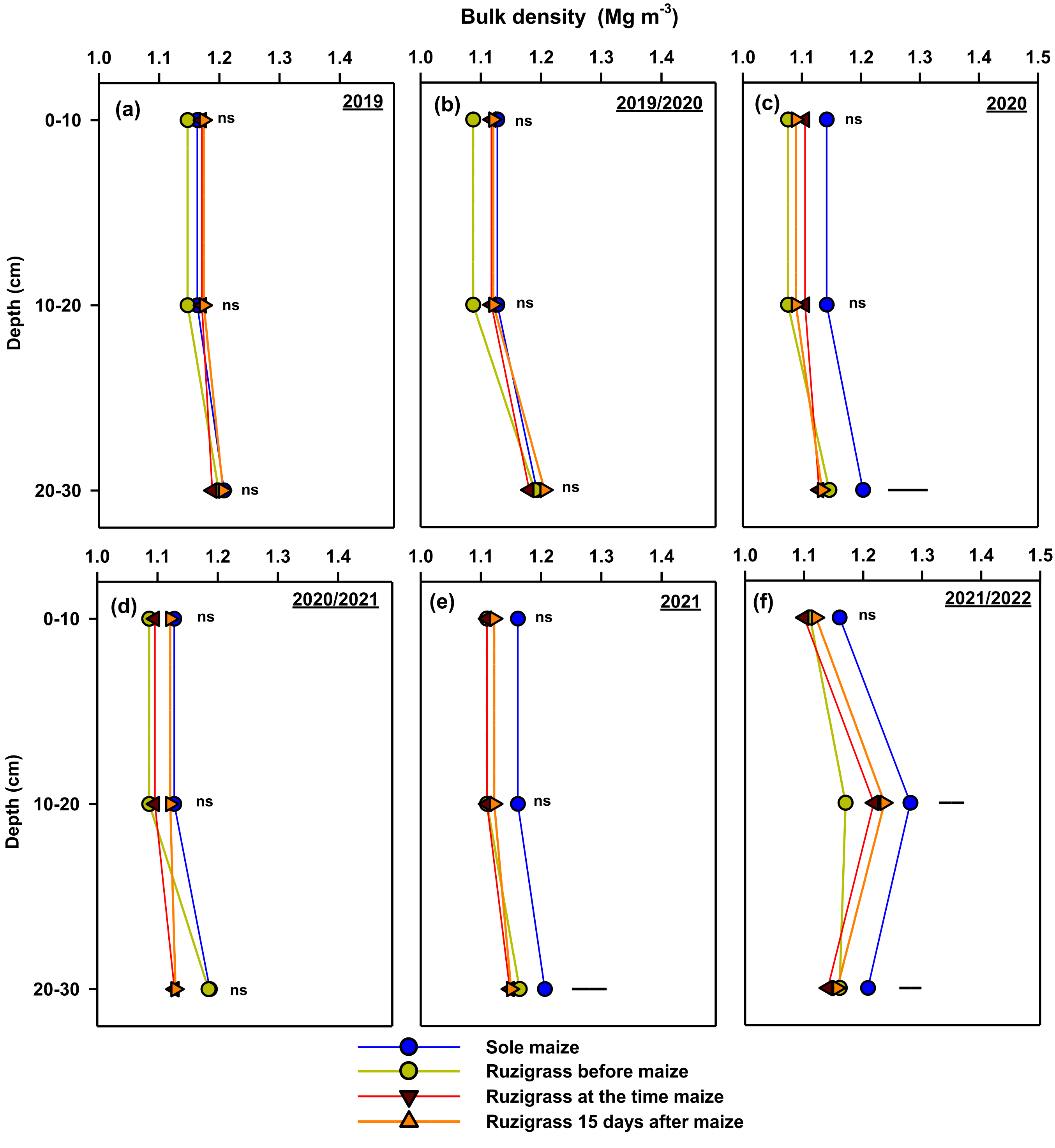

Fig. 2. Bulk density affected by intercropped of ruzigrass and sole maize for three years (2019/2020–2021/2022; a–f). Within each depth range, horizontal bars represent the least significant difference at $p < 0.05$ according to Tukey test. ns: Not significant according to Tukey test at $p < 0.05$.

15 days after maize significantly ($p < 0.05$) improved the bulk density (3%; Fig. 2).

The macroporosity when ruzigrass was sown before maize was 17% higher than that when ruzigrass was sown 15 days after maize, whereas it was 33% higher than that of sole maize (Fig. 3f). The macroporosity in the sole maize reached a critical level of 0.10 $m^3 m^{-3}$, whereas it was 0.15 $m^3 m^{-3}$ when ruzigrass was sown before maize (Fig. 3f). In contrast, the microporosity showed little change (Table 2). Thus, the total porosity was correlated with the physical properties, except for microporosity (Table 3). The total porosity in the three layers was 5% greater in treatments with ruzigrass intercropping than in those with maize alone (Table 2).

The saturated hydraulic conductivity in topsoil layers was not significantly affected ($p > 0.05$) by the different times of intercropping of maize with ruzigrass (Table 2). In the 20–30 cm layer, the saturated hydraulic conductivity values were lower (55%) in the sole maize than those observed when maize was intercropped with ruzigrass (Table 2).

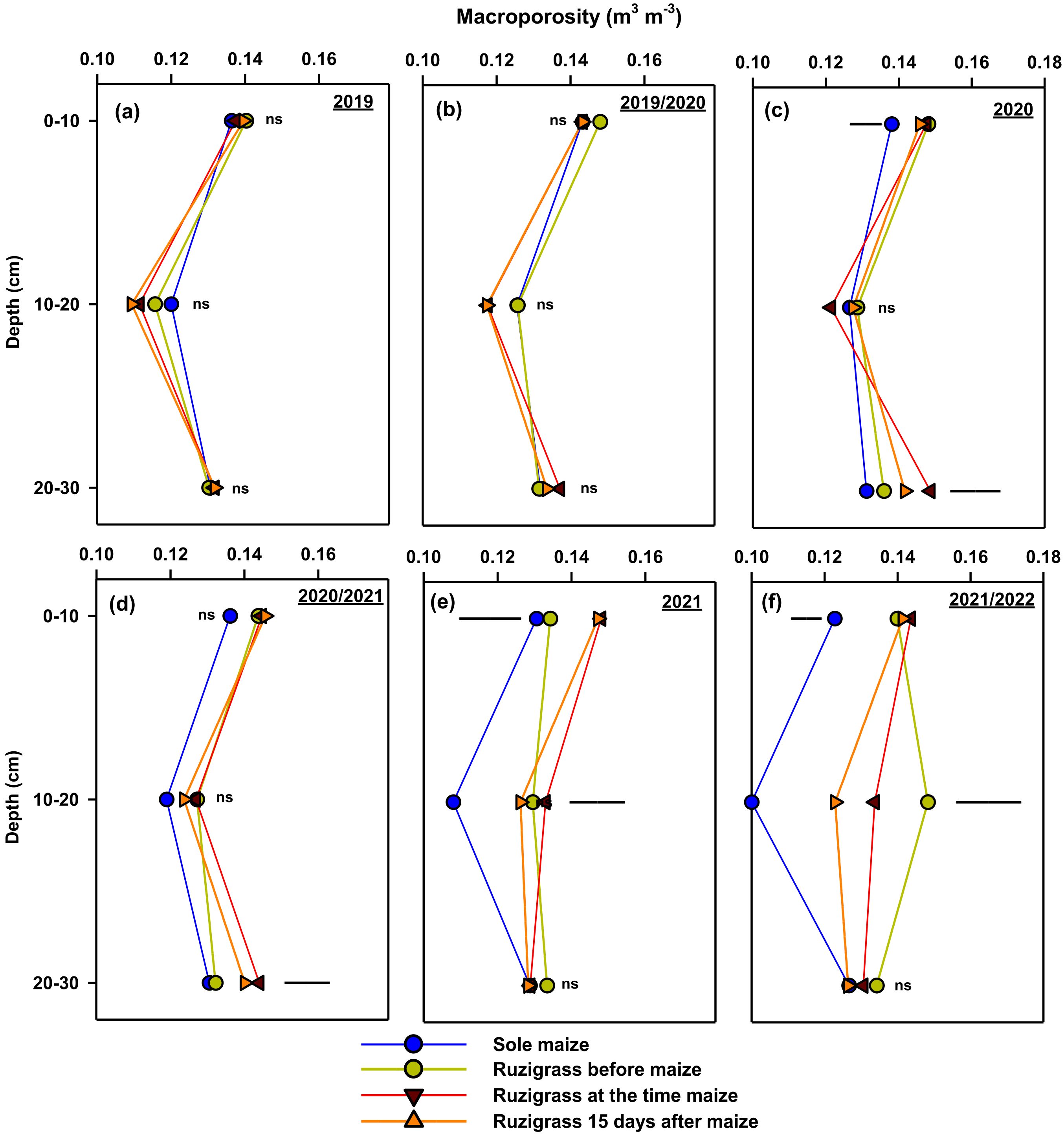

Fig. 3. Macroporosity affected by intercropped of ruzigrass and sole maize for three years (2019/2020–2021/2022; a–f). Within each depth range, horizontal bars represent the least significant difference at $p < 0.05$ according to Tukey test. ns: Not significant according to Tukey test at $p < 0.05$.

3.2. Maize yield

Maize grain yield varied significantly ($p < 0.05$) across all three years and was penalized by competition between maize and ruzigrass. When ruzigrass was sown before maize sowing, the grain yield from the intercropped maize was significantly ($p < 0.05$) lower (28%) than that of sole maize in 2019 and 2021 (Fig. 4a and c). Conversely, when ruzigrass was intercropped 15 days after maize sowing, the grain yield was similar to that of sole maize in all the three years (Fig. 4a–c).

3.3. Soybean yield

Soybean grain yield did not vary significantly ($p > 0.05$) in two of the three years (Fig. 4d–f). No correlation was observed between soybean grain yield and the soil physical properties (Table 3).

Table 2
Microporosity, total porosity, and saturated hydraulic conductivity in intercropping of ruzigrass before maize (i), ruzigrass at the time maize (ii), ruzigrass 15 days after maize (iii), and sole maize (iv).

Depth (cm)	Treatments							
	i	ii	iii	iv	i	ii	iii	iv
	Microporosity (m^3 m^{-3})							
	2019				2019/2020			
0–10	0.35	0.35	0.35	0.35	0.35	0.35	0.36	0.35
10–20	0.35	0.35	0.35	0.34	0.35 a	0.34 b	0.35 a	0.36 a
20–30	0.35	0.35	0.34	0.35	0.35	0.35	0.35	0.35
	2020				2020/2021			
0–10	0.35	0.35	0.35	0.35	0.36	0.35	0.36	0.35
10–20	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
20–30	0.35	0.35	0.35	0.35	0.35	0.35	0.36	0.35
	2021				2021/2022			
0–10	0.35	0.35	0.36	0.35	0.35	0.36	0.36	0.36
10–20	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.36
20–30	0.36	0.36	0.36	0.35	0.35	0.36	0.36	0.35
	Total porosity (m^3 m^{-3})							
	2019				2019/2020			
0–10	0.49	0.49	0.49	0.49	0.50	0.50	0.50	0.50
10–20	0.46	0.46	0.45	0.46	0.48	0.46	0.47	0.47
20–30	0.48	0.48	0.47	0.48	0.48	0.49	0.49	0.48
	2020				2020/2021			
0–10	0.50	0.50	0.50	0.49	0.50	0.50	0.50	0.49
10–20	0.48	0.47	0.48	0.48	0.48	0.47	0.48	0.48
20–30	0.49	0.50	0.49	0.48	0.49 b	0.50 a	0.49 b	0.48 b
	2021				2021/2022			
0–10	0.49 ab	0.50 a	0.50 a	0.48 b	0.49 a	0.50 a	0.50 a	0.48 b
10–20	0.48	0.48	0.48	0.46	0.50 a	0.49 a	0.48 ab	0.46 b
20–30	0.49	0.48	0.49	0.48	0.49 a	0.50 a	0.48 ab	0.48 b
	Saturated hydraulic conductivity (mm h^{-1})							
	2019				2019/2020			
0–10	131.0	126.0	135.3	126.9	137.2	148.2	180.0	130.1
10–20	18.4	27.3	16.6	17.1	29.8	31.3	22.5	32.9
20–30	44.4	51.4	72.7	47.4	58.1	55.2	74.5	44.2
	2020				2020/2021			
0–10	136.0	142.8	137.1	127.9	137.9	145.1	135.3	121.1
10–20	51.0	44.8	57.7	35.3	45.0	44.6	55.6	35.0
20–30	63.5 ab	107.1 a	104.5 a	37.6 b	55.2 ab	92.6 a	103.3 a	41.4 b
	2021				2021/2022			
0–10	136.4	145.2	135.6	114.9	134.0	143.3	135.2	118.7
10–20	48.5	49.9	54.2	39.3	58.7	52.5	47.4	38.7
20–30	59.8	58.2	59.1	40.7	55.1	56.1	47.7	40.6

Different letters indicate significant differences according to Tukey test at $p < 0.05$.

Table 3
Pearson correlation of maize yield, soybean yield, and soil physical properties.

Variables	Maize yield	Soybean yield	ρ_b	Mac	Mic	TP	Ks
Maize yield	–	–0.31	0.15	–0.25	0.25	–0.24	0.07
Soybean yield		–	0.04	0.06	0.15	0.07	–0.03
ρ_b			–	–0.30	0.35	–0.70 * *	–0.30
Mac				–	0.13	0.50 *	0.19
Mic					–	0.11	0.33
TP						–	0.51 *
Ks							–

Bulk density (ρ_b), macroporosity (Mac), microporosity (Mic), total porosity (TP), and saturated hydraulic conductivity (Ks). * , * * Significant at $p < 0.05$ and 0.01 probability, respectively.

4. Discussion

4.1. Soil physical properties

Intercropping maize with ruzigrass decreased bulk density and increased macroporosity from the second year, particularly when ruzigrass was sown before and at the time of maize sowing. When ruzigrass was sown under these conditions, it presumably had more time to grow over the area. Thus, higher above- and belowground biomass was expected in these treatments compared to that in ruzigrass sown 15 days after maize as well as sole maize. However, we do not have data on measured to confirm this.

The improvement in soil structure may have resulted from the above- and belowground supply of residues and root activities from the ruzigrass. Aboveground biomass production directly protects aggregates from the impact of raindrops and reduces load pressures from agricultural machinery (Blanco-Canqui and Ruis, 2018; Keller et al., 2021), whereas belowground root growth and the addition of organic residues are active sources of organic exudates, which are effective stabilizing agents in soil aggregation (Acuña and Villamil, 2014). Roots can affect soil structure through various mechanisms, including the direct creation/modification of soil pores and increases in soil organic carbon, root

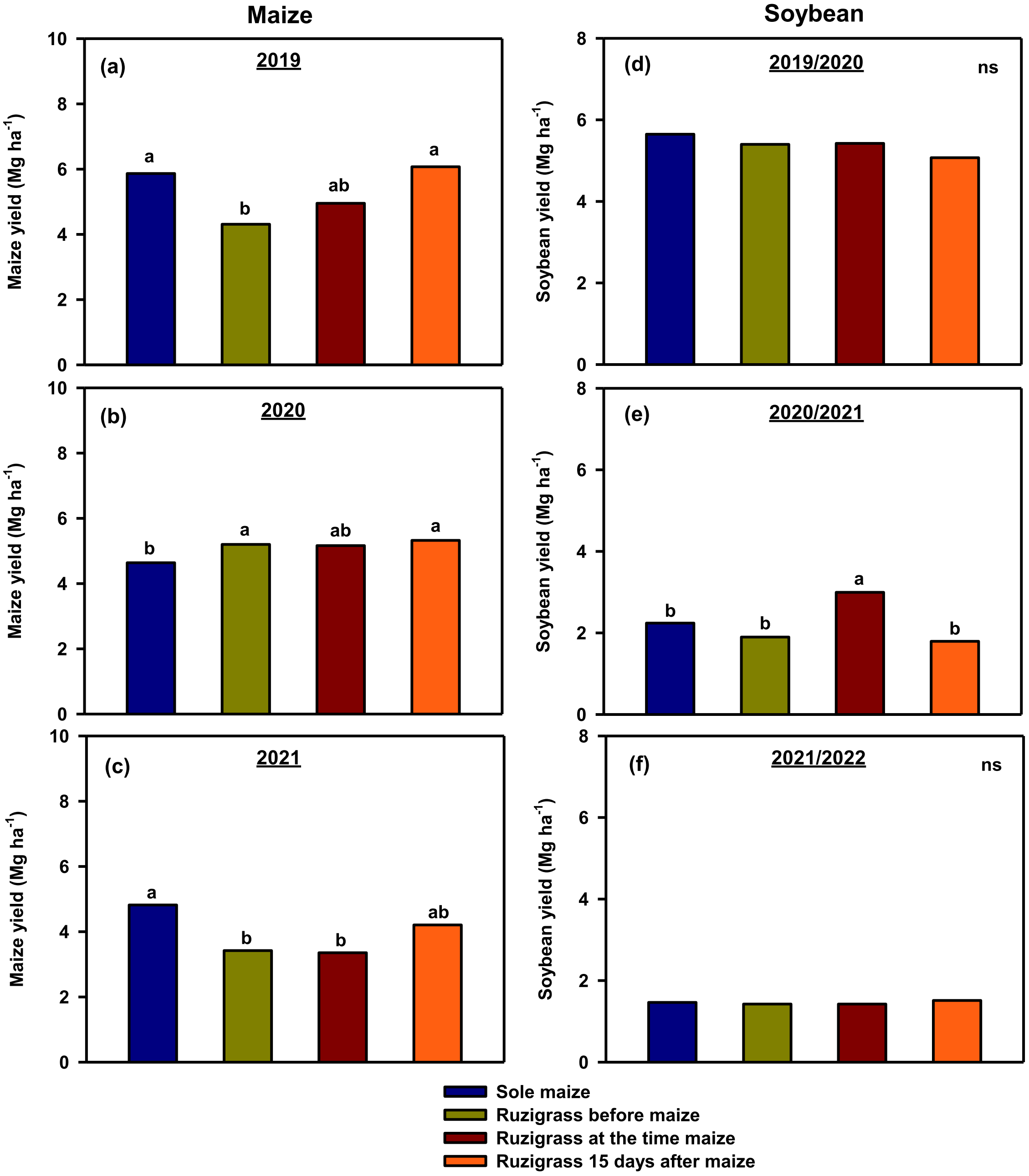

Fig. 4. Maize (a–c) and soybean yield (d–f) affected by intercropped of ruzigrass and sole maize for three years (2019/2020–2021/2022). Different letters indicate significant differences according to Tukey test at $p < 0.05$. ns: Not significant according to Tukey test at $p < 0.05$.

exudates, and water uptake (Colombi and Keller, 2019; Gregory, 2022). In addition, after the decomposition of plant roots, channels are formed that are preferentially used by the roots of subsequent crops (Colombi et al., 2017).

Although belowground biomass has not been evaluated in treatments intercropped with ruzigrass, grasses have a large fine root system with the potential to produce up to 6 Mg ha^{-1} in the 0–30 cm layer (McNally et al., 2015; Sarto et al., 2021). Zheng et al. (2023) found that increasing the fine root biomass will strengthen the penetration and entanglement of soil particles, thereby positively affecting the soil structure. Ambus et al. (2023) observed that grass roots promote continuous and connected porosity, which may explain the higher saturated hydraulic conductivity during intercropping. According to Chen et al. (2021), fine roots enlarge existing pores and are extremely likely to decay, thus releasing previously clogged pores and improving saturated hydraulic conductivity. Conversely, the lower saturated hydraulic conductivity values under sole maize can be attributed to low total porosity due to soil compaction ($r = 0.51$ *).

Despite the highly favorable effects on physical soil quality when ruzigrass was sown before and at the time of maize sowing, intercropping 15 days after maize sowing is a more suitable practice for no-tillage than sole maize with fallow periods. Monocropping systems with fallow without crop residues in the soil are insufficient and lead to soil degradation (Crusciol et al., 2023). In the absence of crop residue, the probability of the bulk density attaining critical values in Oxisol is higher under no-tillage conditions because of the absence of tillage, which favors the natural accommodation of particles or pressures exerted on the soil surface (Calonego et al., 2017). Thus, intercropping can enhance the soil physical quality and other ecosystem services, such as nutrient cycling and microbial activity (Sarto et al., 2020; Crusciol et al., 2021). This finding is important in regions with limitations and poor soils, particularly in tropical regions, such as the Brazilian Cerrado and African savanna (Pariz et al., 2017).

4.2. Maize yield

The slow initial development of ruzigrass using sowing 15 days after maize was beneficial for maize grain yield, but was detrimental for the soil physical properties. In contrast, a decrease in maize grain yield was observed in 2019 and 2021 when ruzigrass was intercropped before maize. Our findings suggest that this observation may be due to the rapid growth of ruzigrass under these conditions, which generates greater competition between intercropped species and reduces maize grain yield (Crusciol et al., 2012). The decrease in maize yield and, presumably, competition when ruzigrass was intercropped before maize may possibly be attributed to the high dependence of maize yield on root growth to absorb more nutrients and water (Lynch, 2011). Competition between maize and forage species and a reduction in maize grain yield are common in the literature (Borghi et al., 2013).

The correlation between maize grain yield and soil physical properties in the short-term was not expected. This is because ruzigrass competes with maize for inputs in the treatments where ruzigrass was sown before and at the time of maize sowing. Despite the reduction in maize yield when ruzigrass was sown before and at the time of maize sowing, intercropping systems are beneficial for the production system in the long-term, with better land use per unit area and profitability than monocrops (Crusciol et al., 2021).

4.3. Soybean yield

Soybean grain yield was not affected in two of the three years. More time is likely required to improve the physical properties of the soil to positively affect soybean yield, which is in agreement with Calonego et al. (2017) and Bertollo et al. (2021). Although the bulk density and macroporosity reached critical levels (Reichert et al., 2009), soybean grain yield was not correlated with the physical soil properties. However, the impact of compaction strongly depends on weather conditions (Liu et al., 2022), which may have caused favorable water conditions for soybean grain yield. Finally, more studies are required to evaluate the dynamics of maize intercropping with ruzigrass by combining physical soil properties and weather conditions.

5. Conclusions

This study evaluated the soil physical properties and their short-term effects on soybean and maize grain yields for different times of maize intercropping with ruzigrass. After three years of intercropping of ruzigrass sown before maize, the bulk density in the 10–20 cm layer was 10% lower (1.16 Mg m^{-3}) than that in sole maize (1.28 Mg m^{-3}). Macroporosity was 17% greater when ruzigrass was sown before maize compared with sowing performed 15 days after maize and it was 33% greater compared with no ruzigrass (sole maize) between the rows of maize. Thus, intercropping ruzigrass 15 days after maize sowing is a more suitable practice for no-tillage than for sole maize. In addition, when ruzigrass was intercropped 15 days after maize sowing, the maize grain yield was 17% higher than that in the intercropping before maize sowing. These findings support the hypothesis that different ruzigrass implantation times with maize intercropping affect the soil physical properties and crop yields. The benefits of intercropping maize with ruzigrass on soil physical properties were greater when ruzigrass was sown before maize or at the time of maize sowing.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105838.

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