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Integrated Crop–Livestock Systems as a Strategy for the Sustainable Production of Corn and Soybean Grain in Tropical Sandy Soils

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Abstract: Integrated crop–livestock systems (ICLS) have sustainably intensified modern agricultural practices worldwide. This research assessed how production systems and crop types impact the chemical properties of an Oxisol in the Brazilian Cerrado, the grain yield of corn intercropped with palisade grass (*Urochloa*) in the off-season in an ICLS, and the grain yield (GY) of soybean in succession. Intercropped and monocropped systems were assessed in a three-year field experiment: corn + *Urochloa ruziziensis*–soybean; corn + *U. brizantha* cv. Piatã–soybean; corn + *U. brizantha* cv. Paiaguás–soybean (ICL–Paiaguás); corn–soybean under a no-tillage system (NTS); corn–soybean under a conventional tillage system (CTS); Piatã grass–continuous grazing (Perennial Piatã); and Paiaguás grass–continuous grazing (Perennial Paiaguás). The residual impact of phosphate fertilization was more pronounced in the ICLS treatments. In the soil layer from 0.0 to 0.2 m depth, ICLS–Paiaguás and Perennial Piatã had the most positive effects on soil chemical quality. In the last year, grain yield was highest in corn monoculture under the NTS and soybean in succession under the ICLS. ICL–Paiaguás improved soil chemical properties for soybean in succession. These results confirm that an intermittent pasture system for legume crops in sequence is an alternative that can maintain or improve soil chemical composition, and that CTS should be avoided in tropical sandy soils.

Keywords: *Glycine max* L.; *Zea mays* L.; intercropping; grain yield; soil fertility

1. Introduction

The growth in global grain production over the last decade is mainly the result of increased productivity and crop intensification, as the expansion of cultivated areas has been limited (1.3% globally) [1]. Global agricultural production is expected to grow by 15% by 2029 (582 Mt), with increases in cereals (375 Mt) and legumes (16 Mt). This projected growth will be slower than that in the last decade and will be supported by food self-sufficiency policies, particularly for cereals.

A challenge for food security is ensuring sustainable production systems that can meet population growth under various climate change and land-use scenarios [2,3]. Agricultural production is expected to grow by up to 50% between 2020 and 2029 in emerging and low-income regions, particularly in Sub-Saharan Africa (17%) and Latin America (15%), which have greater land and labor availability [1]. An expansion of cultivated area of 19.6 Mha is projected for this period, of which 30% will occur in Brazil and Argentina, where the intensified use of the existing cultivated area will increase corn, wheat, and soybean production.

In Brazil, extensive livestock grazing has overexploited soil nutrients because of insufficient replacement by fertilization. Moreover, severe soil depletion is widespread as a result of the predominance of conventional tillage systems that repeatedly use plows and heavy harrows. These practices contribute to pasture degradation and soil erosion (biological, chemical, and physical aspects) and gradually reduce the productive capacity of soil and the diversity of fauna and flora. Recovering these areas and reincorporating them into production requires strategies that consider cultural, technical, and climatic factors.

One such strategy is the adoption of integrated crop–livestock systems (ICLSs) in association with no-tillage systems (NTSs) [4–6]. An ICLS combines grain crops and livestock in a sequential manner within the same area. and has been proven efficient for optimizing land use and capturing ecosystem services [7,8]. Examples include nutrient cycling, enhancing nutrient-use efficiency, increasing crop yields, reducing external inputs via plant–animal–environment synergism, and providing socioeconomic benefits [9–12]. The inclusion of animals in the integrated crop–livestock system (ICLS) fosters both biotic and abiotic alterations in the soil–plant–atmosphere system and alters the biogeochemical processes of nutrients, mainly carbon (C) and nitrogen (N) [4,12,13]. Moreover, in an ICLS, two or more crops are grown concurrently within the same area, a practice known as intercropping [14]. Compared with monoculture, the predominant system, intercropping is a more sustainable, modern agricultural practice [15–18].

Corn–forage grass intercropping offers a viable solution to improve grain yield (GY) and land use [11,19–22], increase dry matter (DM) content in the soil, and protect the soil surface [8,23]. The presence of crop straw, animal residues, and roots helps increase carbon inputs in the soil [24–28]. However, most studies of corn–forage grass intercropping have evaluated clayey soils and in-season crops (spring/summer in the Southern Hemisphere). Little information is available for sandy soils, where agriculture has expanded in tropical regions.

The spatial arrangement of plants and sowing type are important factors in designing an appropriate ICLS [29]. The plant density must be adjusted to the local water regime [30], particularly in tropical sandy soils, where adverse environmental conditions during the off-season can affect corn grain yield (GY) because of competition with forage grasses [31,32]. The effect of intercropping on in-season crops may vary depending on the cultivar used [33]. In the Cerrado biome of Brazil, tropical *Urochloa* (Syn. Brachiaria) forage species are widely used [4,34,35]; however, the selection of the most appropriate cultivar for intercropping should be based on the local conditions [34].

We hypothesized that in tropical sandy soils, the GY of corn intercropped with *Urochloa* varies with the *Urochloa* cultivar used, and the GY of soybean is higher in succession to an ICLS, similar to the effects observed in clayey soils [36]. Accordingly, in this study, we evaluated the effects of production systems and crop types on the chemical properties of a sandy textured soil (Oxisol) in the Brazilian Cerrado, the GY of corn intercropped with *Urochloa* in an ICLS during the off-season, and the GY of soybean grown in succession.

2. Materials and Methods

2.1. Study Area Location and Characteristics

The experiment was carried out in Caiuá/SP, Brazil (21°49′ W, 51°59′ S, 330 m above sea level), over the course of three consecutive growing seasons (2016/17, 2017/18, and 2018/19). The local soil is categorized as dystrophic Latossolo Vermelho with a sandy texture (Oxisol, USDA Soil Taxonomy) [37] and contains 816, 116, and 68 g kg^{-1} of sand, clay, and silt, respectively [38].

Based on Köppen's classification, the local climate is categorized as Aw [39], i.e., humid tropical with dry winters and hot, rainy summers. The average annual temperature is 24.3 °C, and the annual average rainfall is 1353 mm. The hottest months are January, February, and December (average 27 °C), and the coldest months are June and July (average 21 °C) [40]. Rainfall and temperature were measured during the experiment [41], and the data are shown in Figure 1.

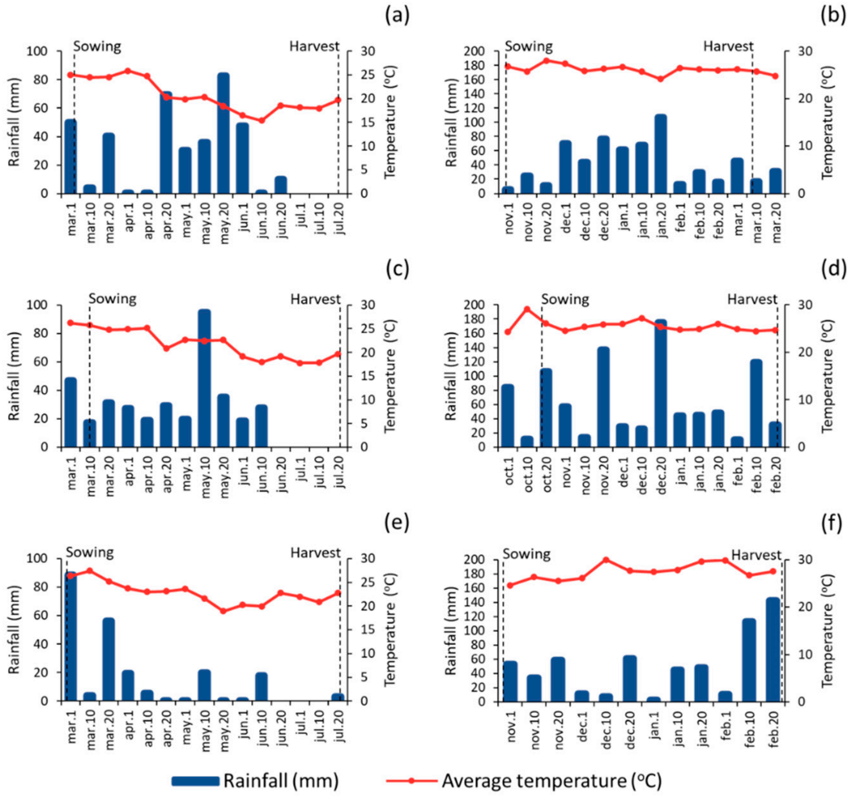

Figure 1. Accumulations of rainfall (mm) and average temperatures (°C) every ten days during the experiment. Caiuá—SP, Brazil 2016 (**a**), 2016/17 (**b**), 2017 (**c**), 2017/18 (**d**), 2018 (**e**), and 2018/19 (**f**).

2.2. Experimental Area History

From 2007 to 2014, the experimental area (42 ha) was cultivated with *Megathyrsus maximus* (Syn. *Panicum maximum*) cv. Massai for seed production. Next, the area was cultivated with corn from March to July 2015 and soybean in the rainy season from November to February 2016. Before starting the experiment, the chemical composition of the soil was analyzed at a depth of 0.0–0.2 m according to [42]. The results were as follows: pH 6.0; organic matter (OM), 14 mg kg^{-1}; P, 21 mg kg^{-1}; S-SO_4, 4 mg kg^{-1}; K, 1.1 mg kg^{-1}; Ca, 21 mg kg^{-1}; Mg, 11 mg kg^{-1}; H+Al, 12 mg kg^{-1}; cation exchange capacity (CEC), 45.2 mmol$_c$ dm^{-3}; and base saturation (V%), 70% (Supplementary Table S1).

Before starting the experiment, the soil total porosity and bulk density were determined according to [38]; in brief, undisturbed soil samples from a depth of 0.0–0.2 m were collected using stainless steel rings. The macroporosity, microporosity, and total porosity were 0.08, 0.28, and 0.35 m^3 m^{-3}, respectively, and the soil bulk density was 1.58 Mg m^{-3}.

2.3. Experimental Design and Treatments

The experiment was conducted using a completely randomized block design with four replications. The treatments consisted of the following cropping systems: (1) corn intercropped with *Urochloa ruziziensis* cv. Piatã, followed by soybean (ICL–Ruziziensis); (2) corn intercropped with *U. brizantha* cv. Piatã, followed by soybean (ICL–Piatã); (3) corn intercropped with *U. brizantha* cv. Paiaguás, followed by soybean (ICL–Paiaguás); (4) corn followed by soybean under a no-tillage system (NTS); (5) corn followed by soybean under a conventional tillage system (CTS); (6) Piatã grass—continuous grazing (Perennial Piatã); and (7) Paiaguás grass—continuous grazing (Perennial Paiaguás).

2.4. Corn and Urochloa Grass Intercropping

After the soybean harvest each year, the corn hybrids DKB 390 (in 2016) and DKB 177 (in 2017 and 2018) were sown mechanically in March (under NTS or CTS) with a row spacing of 0.90 m and plant density of around 50,700 plants per hectare.

In ICL–Paiaguás, ICL–Piatã, and ICL–Ruziziensis, the palisade grass cultivars *U. brizantha* BRS Paiaguás, *U. brizantha* BRS Piatã, and *U. ruziziensis* were sown simultaneously with corn at a seed density of 5 kg ha^{-1} 0.06 m below and 0.08 m beside the corn seeds [43]. Crop management practices were performed according to each crop's requirements. The emergence of corn seedlings occurred five days after sowing; meanwhile, grass emergence occurred 9 and 10 days after sowing.

In 2016 and 2017, corn base fertilization was applied in the sowing furrows with 24 kg ha^{-1} N, 36.7 kg ha^{-1} P, and 40 kg ha^{-1} K. In 2016, N topdressing was performed, and herbicide subdoses were applied to suppress forage growth due to a lack of rain at critical stages in April (Figure 1). In 2017, topdressing mineral fertilization with 50 kg ha^{-1} N and 41 kg ha^{-1} K was performed on the soil surface between corn rows without incorporation into the soil. Topdressing was conducted when the corn plants reached the stage of having five fully expanded leaves (V5 stage) [44]. After emergence, subdoses of nicosulfuron (8 g ha^{-1}) and atrazine (1.5 kg ha^{-1}) were administered to suppress forage growth [45]. For pasture maintenance (Perennial Paiaguás and Perennial Piatã), topdressing was conducted by applying 72 kg ha^{-1} N and 24 kg ha^{-1} K twice in the rainy season. The corn was harvested in July in 2016 and 2017.

In 2018, corn's base fertilization entailed the application of 16 kg ha^{-1} N, 25 kg ha^{-1} P, and 26 kg ha^{-1} K in the sowing furrows. Topdressing mineral fertilization was performed on the soil surface between corn rows without incorporation into the soil: 150 kg ha^{-1} ammonium nitrate was applied at V5, and 60 kg ha^{-1} KCl was applied at V8, at the end of the rainy season. After emergence, subdoses of mesotrione (120 mL ha^{-1}) and atrazine (2 L ha^{-1}) were applied to suppress forage growth [46]. The corn was harvested in July 2018. After the corn harvest, Nellore steers were left to graze pasture in ICL–Ruziziensis, ICL–Piatã, and ICL–Paiaguás. The animals were initially 12 months old and had an average live weight of 250 kg, and were randomly assigned to each treatment in homogeneous groups.

The pastures in Perennial Piatã and Perennial Paiaguás were also grazed by Nellore steers randomly assigned to homogeneous groups and maintained throughout the year. The grazing method employed was continuous stocking with a fluctuating stocking rate [47] Each experimental unit contained at least five animals; an average pasture height of 30 cm was maintained by using different grazing regulators or adjusting the stocking rate [48].

2.5. Soybean Cultivation

For NTS maintenance, the forage remaining after the corn harvest (ICL–Ruziziensis, ICL–Piatã, and ICL–Paiaguás) was terminated two weeks before soybean sowing (October of each year) by spraying glyphosate (1.4 kg ai ha^{-1}) at a volume of 200 L ha^{-1}.

Soybean seeds of the cultivar TMG 7063 were mechanically planted in October 2017 and November 2016 and 2018. Sowing was performed with a row spacing of 0.45 m at 14 seeds per linear meter of row to obtain a density of 300,000 plants per hectare under NTS. The seeds were inoculated with bacteria of the genus *Bradyrhizobium japonicum*: 80 g of peaty solid inoculant and 150 mL of liquid inoculant per 40 kg of seed. Corn base fertilization was applied in the sowing furrows with 14 kg ha^{-1} N, 44 kg ha^{-1} P and 28 kg ha^{-1} K in the 2016/2017 crop season and 8 kg ha^{-1} N, 26 kg ha^{-1} P and 63.8 kg ha^{-1} K in the 2017/2018 and 2018/2019 crop seasons. Management practices were performed according to each crop's requirements.

The soybean was harvested manually by cutting plants from eight rows of each plot in February 2018 and March 2017 and 2019, when the grains were at a moisture level of approximately 15%. Following harvest, the plants were threshed using a stationary harvester, and the grain was sent to the laboratory to determine the moisture correction factor (Usable plot area: 30 m^2). The grains were weighed, and the data were transformed to soybean yield ha^{-1}. The data were normalized to a moisture level of 130 g kg^{-1} (wet basis), which is the maximum moisture content for soybean grain marketing in Brazil.

2.6. Soil Collection for Chemical Analysis

Following the soybean harvest, soil samples were collected for soil chemical analysis (macro- and micronutrients) [42] from the 0.0–0.1, 0.1–0.2, and 0.2–0.4 m layers of all plots with soil auger. Each composite sample was generated by blending 20 subsamples by plots for each soil depth (experimental unit ≅ 2 ha).

The soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil/solution), and the P and exchangeable Ca, Mg, and K concentrations were determined by extracting with an ion exchange resin and using atomic absorption spectrophotometry. The base saturation values were calculated using the exchangeable bases and total acidity at pH 7.0 (H+Al). The soil organic matter content was determined using the calorimetric method (the absorption of the solution at 660 nm was measured using a B220 photoelectric colorimeter [Micronal]).

2.7. Statistical Analysis

Data were subjected to the Shapiro–Wilk normality test [49] ($p > 0.05$, $W \geq 0.90$) and Levene's homoscedasticity test ($p \geq 0.05$) [50] using R-studio version 4.0.1 [51]. When the statistical test assumptions were met, analysis of variance (ANOVA) was performed. As recommended by Pimentel-Gomes (2000), the data were analyzed separately for each year, given the heterogeneity between the mean squares of extreme residuals (≥7). When significant, means were compared using Tukey's test ($p \geq 0.05$) with the statistical software SISVAR version 5.3 [52].

3. Results

3.1. Soil Macronutrients

In 2017, the first year of evaluation, the treatments did not affect soil pH at any soil depth (Figure 2A). In 2018, soil pH in the top layer (0.0–0.1 m) was significantly higher in ICL–Piatã, CTS, and Perennial Paiaguás than in Perennial Piatã (Figure 2B). In 2019, soil pH in the 0.1–0.2 m layer exhibited a significant increase in ICL–Ruziziensis, NTS, and CTS than in Perennial Piatã. These differences are not meaningful for decision-making in practice because soil pH in the more intensive systems (ICLS, NTS, and CTS) was similar and differed only from that in Perennial Piatã. As the latter system is a perennial pasture, base exports and other acidifying mechanisms are expected to be less intense, resulting in lower soil pH [53].

In 2018, the treatments influenced potential acidity (H+Al) only in the 0.2–0.4 m layer, where H+Al was higher in ICL–Ruziziensis than in Perennial Piatã (Figure 2E). However, the H+Al values in these treatments showed no significant difference compared to the other treatments.

In 2017, soil CEC in the 0.2–0.4 m layer was greater in ICL–Paiaguás compared to the ICL–Ruziziensis (Figure 2G). In 2018, differences in soil CEC were observed only in the 0.1–0.2 m layer, with higher soil CEC in Perennial Piatã than in ICL–Ruziziensis, ICL–Piatã and Perennial Paiaguás (Figure 2H). In 2019, soil CEC values in the 0.0–0.1 m layer were highest in ICL–Paiaguás and Perennial Piatã, which differed significantly from CTS (Figure 2I); in the 0.1–0.2 m layer, soil CEC was lowest in ICL–Ruziziensis, which differed significantly from Perennial Piatã.

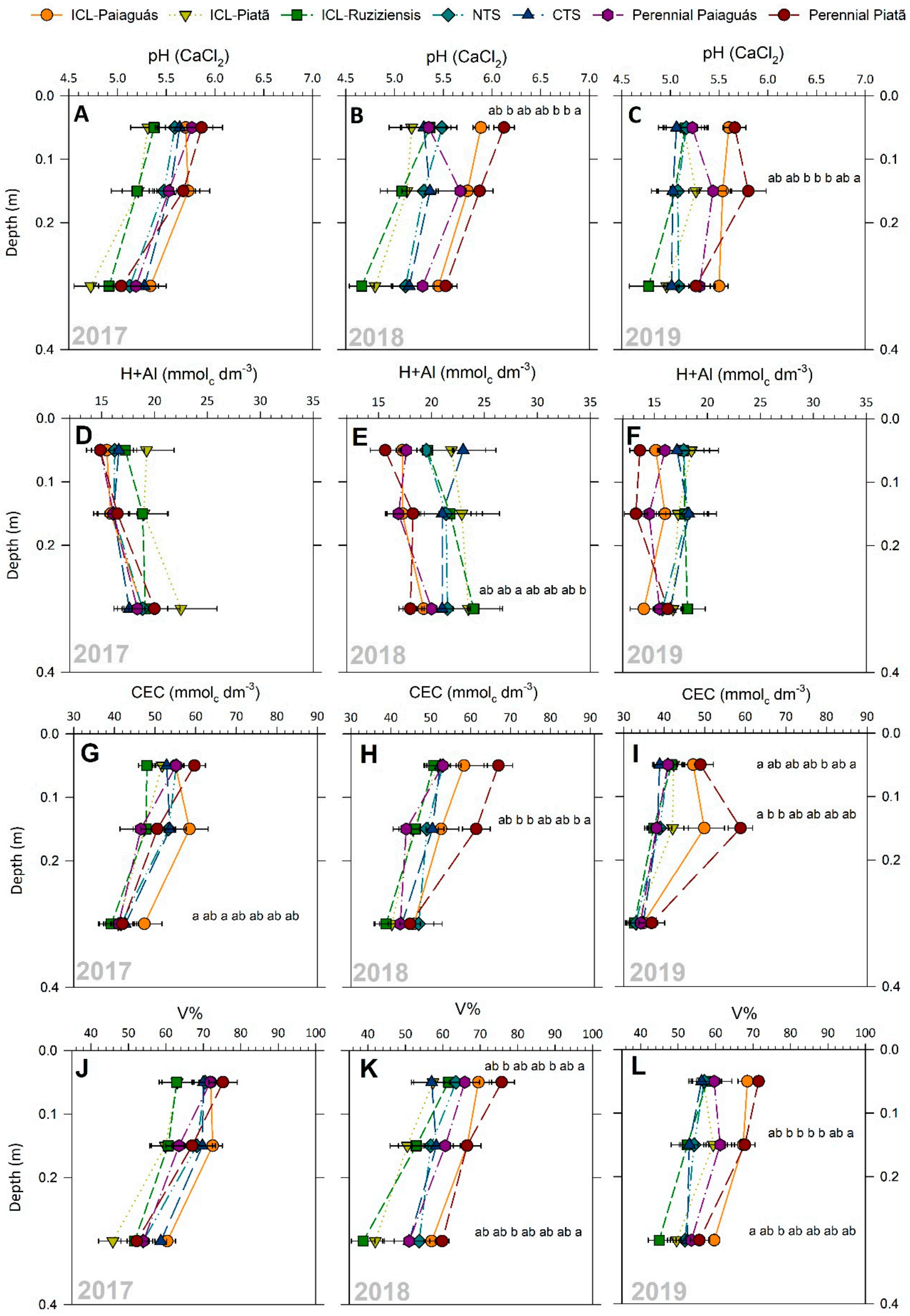

Figure 2. Soil pH (pH in $CaCl_2$) (**A**–**C**), potential acidity (H+Al) (**D**–**F**), cation exchange capacity (CEC) (**G**–**I**) and base saturation (V%) (**J**–**L**) at depths of 0.0–0.1, 0.1–0.2, and 0.2–0.4 m in the different treatments. ICL–Paiaguás: corn + *Urochloa brizantha* cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system. Perennial Paiaguás: Paiaguás grass—continuous grazing. Perennial Piatã: Piatã grass—continuous grazing. Means indicated by distinct horizontal letters (in accordance with the identical sequence displayed on the treatment labels) exhibit significant differences by Tukey's test ($p < 0.05$).

The treatments affected base saturation (V%) only in 2018 and 2019. In 2018, V% in Perennial Piatã was higher than that in CTS in the 0.0–0.1 m layer and higher than that in ICL–Ruziziensis in the 0.2–0.4 m layer (Figure 2K). In 2019, V% was higher in Perennial Piatã than in CTS, NTS, and ICL–Ruziziensis in the 0.1–0.2 m layer, and was higher in ICL–Paiaguás than in ICL–Ruziziensis in the 0.2–0.4 m layer (Figure 2L).

In 2018, the treatments influenced potential acidity (H+Al) only in the 0.2–0.4 m layer, where H+Al was higher in ICL–Ruziziensis than in Perennial Piatã (Figure 2E). However, the H+Al values in these treatments showed no significant difference compared to the other treatments.

In 2017, soil CEC in the 0.2–0.4 m layer was greater in ICL–Paiaguás compared to the ICL–Ruziziensis (Figure 2G). In 2018, differences in soil CEC were observed only in the 0.1–0.2 m layer, with higher soil CEC in Perennial Piatã than in ICL–Ruziziensis, ICL–Piatã and Perennial Paiaguás (Figure 2H). In 2019, soil CEC values in the 0.0–0.1 m layer were highest in ICL–Paiaguás and Perennial Piatã, which differed significantly from CTS (Figure 2I); in the 0.1–0.2 m layer, soil CEC was lowest in ICL–Ruziziensis, which differed significantly from Perennial Piatã.

The treatments affected base saturation (V%) only in 2018 and 2019. In 2018, V% in Perennial Piatã was higher than that in CTS in the 0.0–0.1 m layer and higher than that in ICL–Ruziziensis in the 0.2–0.4 m layer (Figure 2K). In 2019, V% was higher in Perennial Piatã than in CTS, NTS, and ICL–Ruziziensis in the 0.1–0.2 m layer, and was higher in ICL–Paiaguás than in ICL–Ruziziensis in the 0.2–0.4 m layer (Figure 2L).

In 2017 and 2018, the treatments had no effect ($p < 0.05$) on OM, P, and S contents in the three soil layers evaluated (Figure 3). In 2019, the treatments significantly affected OM and P contents but not S content. P content in the 0.0–0.1 m layer was highest in ICL–Piatã, ICL–Paiaguás, and NTS, whereas P content in the 0.1–0.2 m layer was highest in ICL–Paiaguás and NTS. Thus, residual effects of phosphate fertilization were evident in these treatments. OM content differed significantly ($p < 0.05$) only in the 0.0–0.1 m layer and was highest in ICL–Paiaguás and Perennial Piatã; however, the difference in OM content was significant only when ICL–Paiaguás and Perennial Piatã were compared with NTS.

In 2017, Ca content in the 0.2–0.4 m soil layer was higher in ICL–Paiaguás than in ICL–Piatã, but the Ca contents in both of these treatments were similar to those in the other treatments (Figure 4A). Although the mean Ca content in the 0.2–0.4 m layer was highest in ICL–Paiaguás in 2017, it decreased by approximately 6 $mmol_c\ dm^{-3}$ between 2017 and 2019 (19 and 13 $mmol_c\ dm^{-3}$ Ca, respectively) (Figure 4A,C). This was the largest decrease in mean soil Ca content in the 0.2–0.4 m layer over time, and as a result, the soil Ca content in this layer in ICL–Paiaguás matched that in the other treatments in 2019. In 2019, the treatments significantly affected Ca content in the 0.1–0.2 m layer, with higher values in Perennial Piatã than in ICL–Ruziziensis, CTS, and NTS. The latter two treatments had the lowest sustainability of soil Ca content, with decreases of 13 and 15 $mmol_c\ dm^{-3}$, respectively, between 2017 and 2019.

In 2018, Mg content was significantly greater in Perennial Piatã compared to ICL–Ruziziensis and ICL–Piatã in all soil layers (Figure 4E). In the 0.2–0.4 m layer, the relationship between base (Mg) and H+Al content stood out [54,55] (Figures 2 and 4). Specifically, Mg content was low and H+Al content was high in ICL–Piatã, whereas Mg content was high and H+Al content was low in Perennial Piatã. In 2019, the mean Mg content in the 0.0–0.1 and 0.1–0.2 m layers was higher in ICL–Piatã and Perennial Piatã than in NTS and CTS. By contrast, the treatments did not show a significant impact on soil K content in any of the assessed years (Figure 4F).

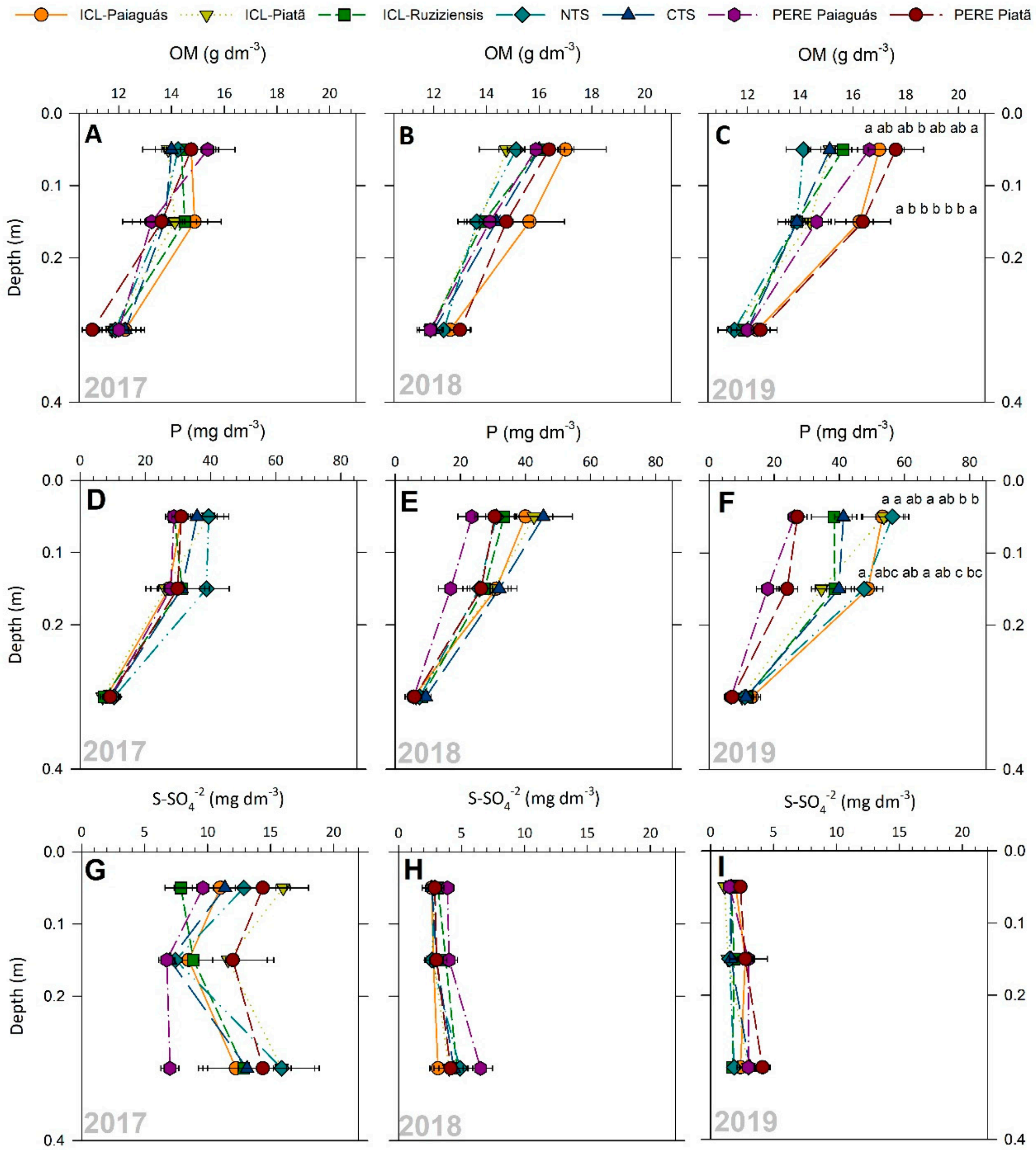

Figure 3. Soil organic matter (OM) (**A**–**C**), available phosphorus (P) (**D**–**F**), and sulfur (S-SO_4^{-2}) (**G**–**I**) contents at depths of 0.0–0.1, 0.1–0.2, and 0.2–0.4 m in the different treatments. ICL–Paiaguás: corn + *Urochloa brizantha* cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system. Perennial Paiaguás: Paiaguás grass—continuous grazing. Perennial Piatã: Piatã grass–continuous grazing. Means indicated by distinct horizontal letters (in accordance with the identical sequence displayed on the treatment labels) exhibit significant differences by Tukey's test ($p < 0.05$).

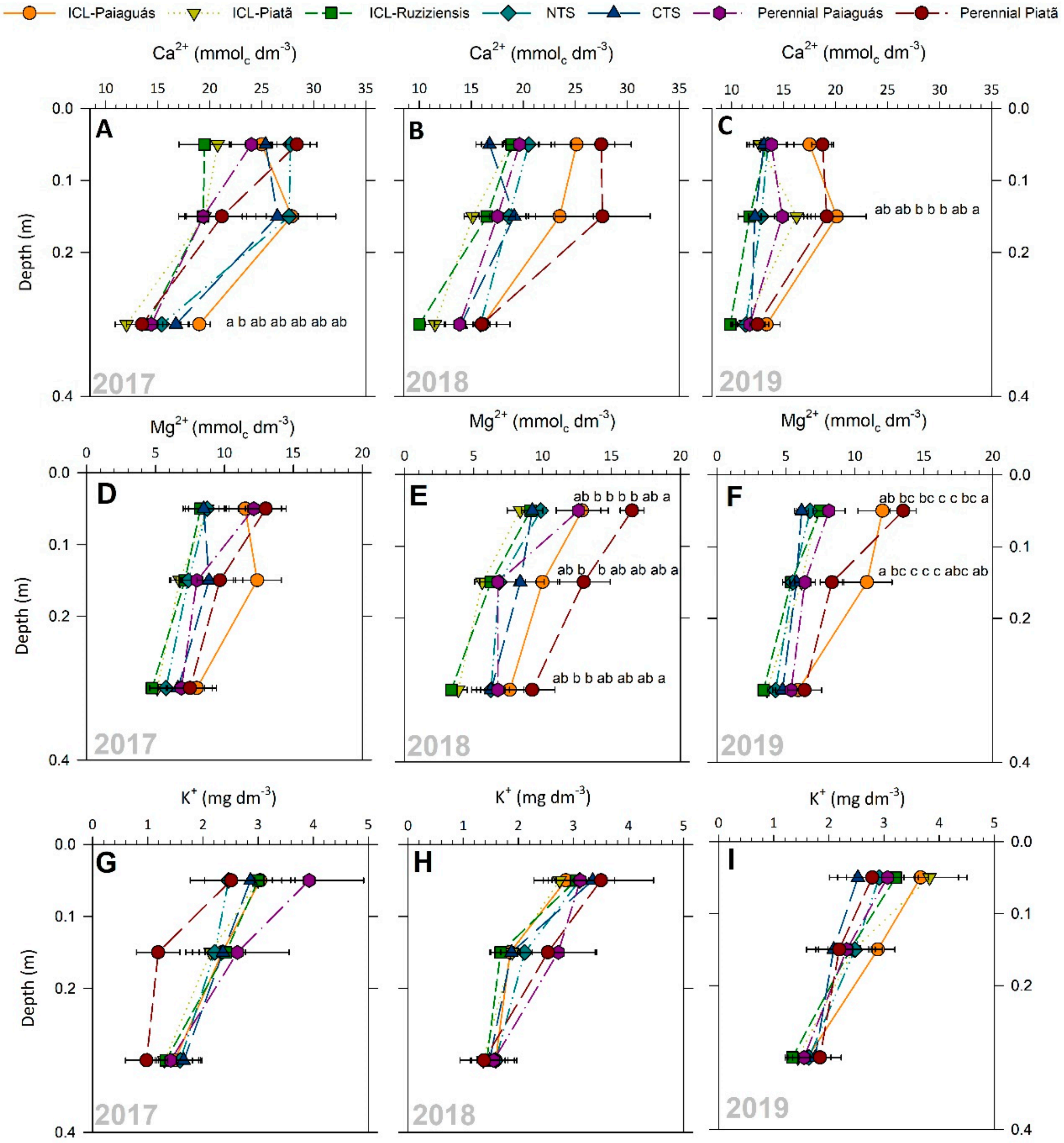

Figure 4. Soil exchangeable calcium (Ca) (**A**–**C**), magnesium (Mg) (**D**–**F**), and potassium (K) (**G**–**I**) contents at depths of 0.0–0.1, 0.1–0.2, and 0.2–0.4 m in the different treatments. ICL–Paiaguás: corn + *Urochloa brizantha* cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system. Perennial Paiaguás: Paiaguás grass—continuous grazing. Perennial Piatã: Piatã grass—continuous grazing. Means indicated by distinct horizontal letters (in accordance with the identical sequence displayed on the treatment labels) exhibit significant differences by Tukey's test ($p < 0.05$).

3.2. Soil Micronutrients

The treatments showed minimal impact on soil micronutrient dynamics; the only differences were in B levels in 2018 (in the 0.1–0.2 m layer) and Fe levels in 2019 (in the 0.1–0.2 m and 0.2–0.4 m layers) (Figures 5 and 6).

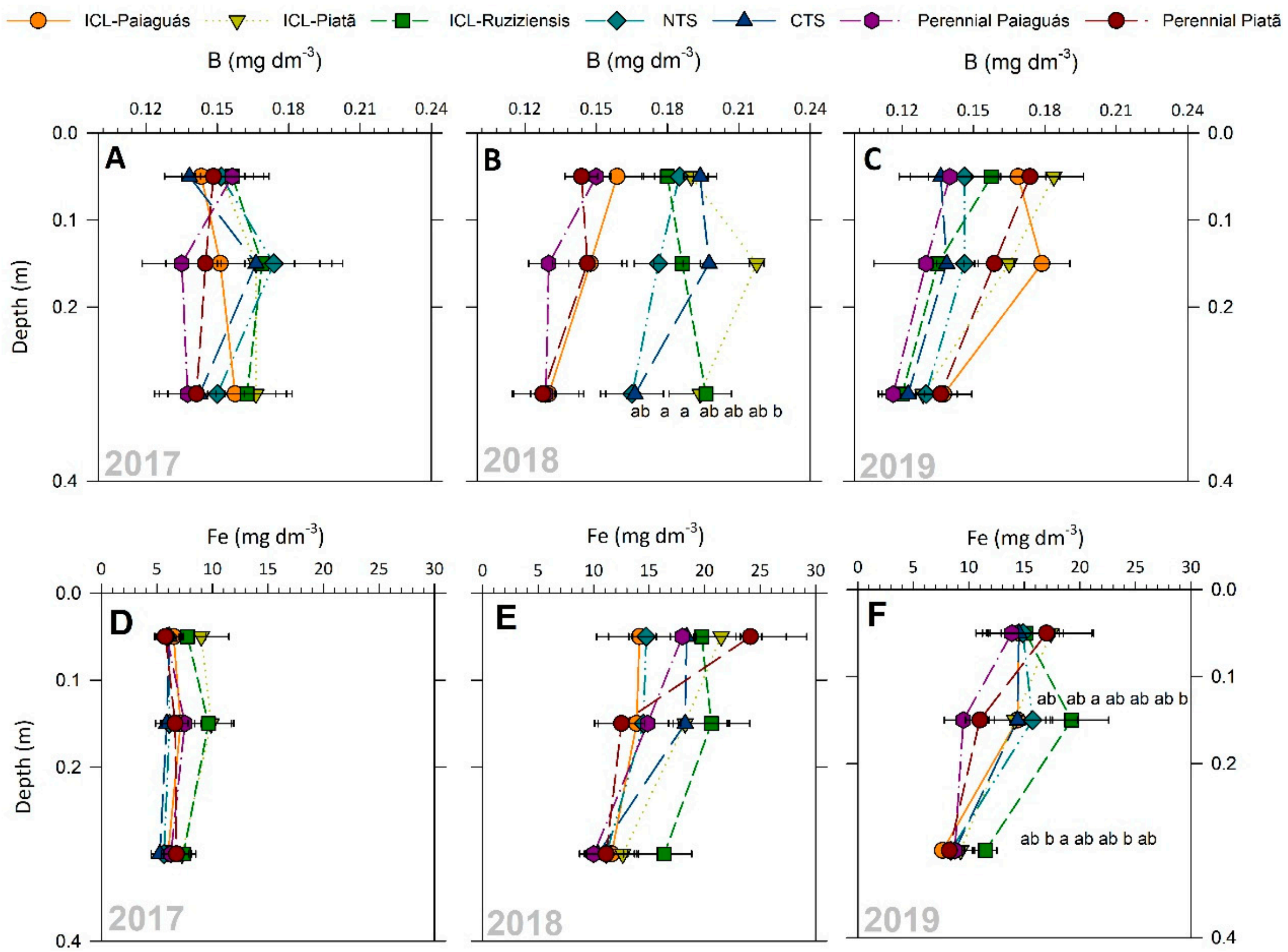

Figure 5. Soil boron (B) (**A**–**C**) and iron (Fe) (**D**–**F**) contents at depths of 0.0–0.1, 0.1–0.2, and 0.2–0.4 m in the different treatments. ICL–Paiaguás: corn + *Urochloa brizantha* cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system. Perennial Paiaguás: Paiaguás grass—continuous grazing. Perennial Piatã: Piatã grass—continuous grazing. Means indicated by distinct horizontal letters (in accordance with the identical sequence displayed on the treatment labels) exhibit significant differences by Tukey's test ($p < 0.05$).

In the second year of evaluation (2018), soil B content in the 0.2–0.4 m layer was greater in ICL–Ruziziensis and ICL–Piatã than in Perennial Piatã. In 2019, soil Fe content in the 0.1–0.2 m layer was greater in ICL–Ruziziensis than in Perennial Piatã; in the 0.2–0.4 m layer, soil Fe content was greater in ICL–Ruziziensis than in ICL–Paiaguás and Perennial Paiaguás (Figure 5C).

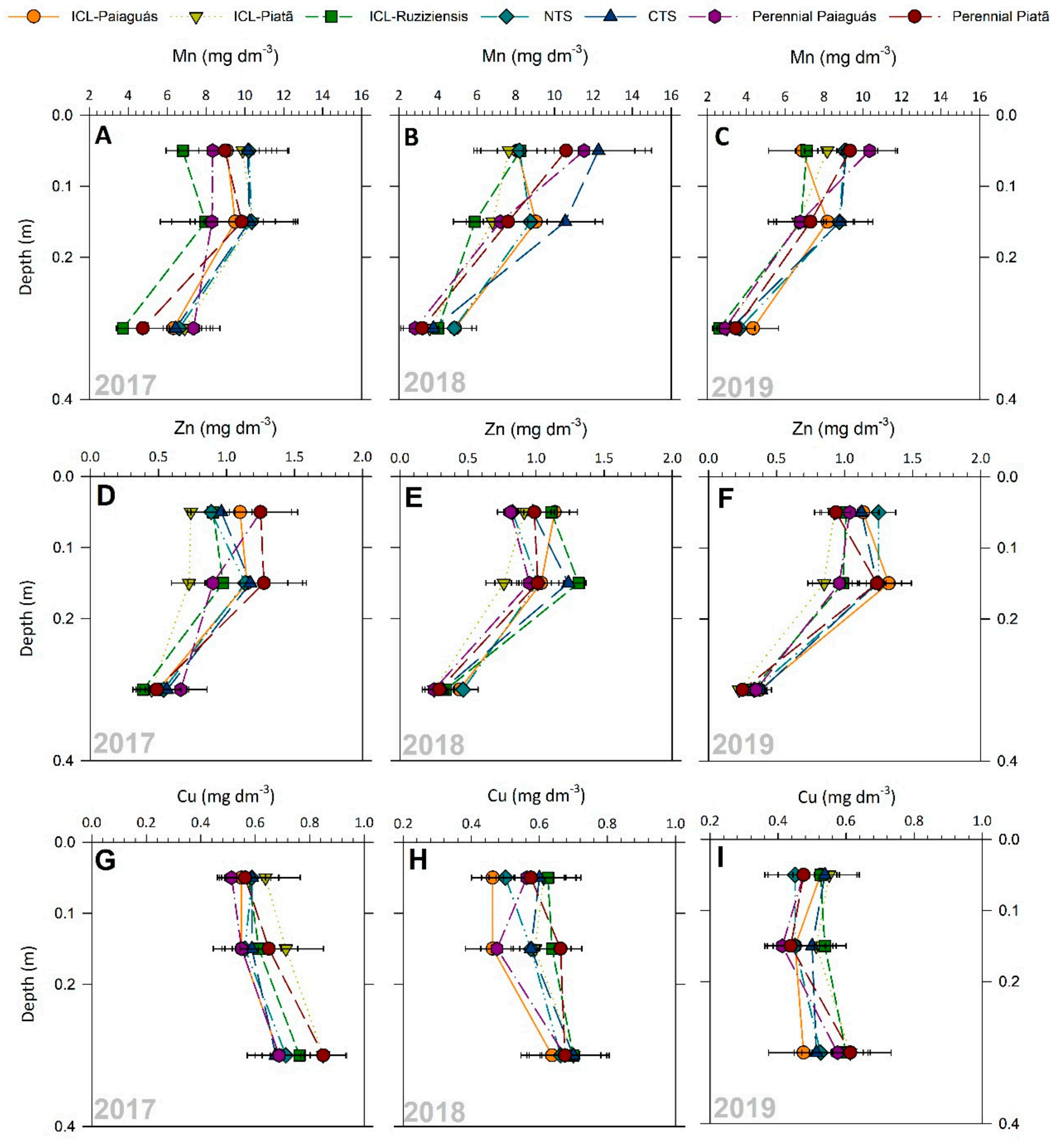

Figure 6. Soil manganese (Mn) (**A**–**C**), zinc (Zn) (**D**–**F**), and copper (Co) (**G**–**I**) contents at depths of 0.0–0.1, 0.1–0.2, and 0.2–0.4 m in the different treatments. ICL–Paiaguás: corn + *Urochloa brizantha* cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system. Perennial Paiaguás: Paiaguás grass—continuous grazing. Perennial Piatã: Piatã grass—continuous grazing.

3.3. Grain Yield

In 2016, 2017, and 2018, the average corn GY differed from the Brazilian national average by −28%, +18%, and −215%, respectively [56]. The average soybean GY differed from the Brazilian national average by −6, −18, and −43% [56] in the 2016/2017, 2017/2018, and 2018/2019 crop seasons, respectively (Table 1).

Table 1. [1] Grain yield (GY) of corn intercropped with forages of the genus *Urochloa* and grain yield (GY) of soybean grown in succession to the intercropped systems under integrated crop–livestock systems (ICLSs). Caiuá-SP, 2016/2017, 2017/2018, and 2018/2019 crop seasons.

GY	Treatment					F	CV%
	ICL–Ruziziensis	ICL–Piatã	ICL–Paiaguás	NTS	CTS		
Corn 2016	3644 ± 198	4110 ± 293	4496 ± 593	4471 ± 547	5026 ± 359	ns	15
Soybean 2016/17	3312 ± 102	3131 ± 126	3386 ± 18	3142 ± 107	2955 ± 152	ns	7
Corn 2017	5719 ± 434	5643 ± 648	5699 ± 449	5720 ± 453	5759 ± 636	ns	9
Soybean 2017/18	2911 ± 176	2852 ± 89	2873 ± 95	2911 ± 67	2816 ± 92	ns	7
Corn 2018	1465 ± 173 b	2062 ± 87 ab	1796 ± 163 ab	2182 ± 254 a	1773 ± 171 ab	**	15
Soybean 2018/19	2441 ± 180 a	2417 ± 144 a	2426 ± 189 a	2127 ± 57 ab	1828 ± 72 b	**	7

[1] Means in the same row followed by different letters differ from each other according to Tukey's test at 5% probability. ** significant at 5% probability by the F-test, respectively. ICL–Paiaguás: corn + *Urochloa* brizantha cv. Paiaguás–soybean. ICL–Piatã: corn + *U. brizantha* cv. Piatã–soybean. ICL–Ruziziensis: corn + *U. ruziziensis*–soybean. CTS: corn–soybean under conventional tillage system. NTS: corn–soybean under no-tillage system; CV%, coefficient of variation.

The differences in the GY of both crops compared with the Brazilian national averages can be explained by the conditions of the growing environment, particularly the water regimes in 2017 and 2018, which included periods of water deficiency during important crop stages. In the 2018/2019 crop season, the treatments affected the GY of both corn and soybean; however, the limiting climatic conditions in 2018/2019 were partially responsible for the short-term effects of the treatments.

4. Discussion

4.1. Soil Chemical Properties—2017

In the first year, the soil chemical properties in the 0.0–0.1 and 0.1–0.2 m layers did not differ among the treatments ($p > 0.05$). Soil pH, V%, and soil P and K contents were classified as average, while soil Ca, Mg, and S-SO_4^{-2} contents were categorized as high [57]. Uniform soil chemical composition among the treatments was expected because of the recent implementation of the treatments (Figure 2) and the recent history of forage seed production in the area (straw deposition and incorporation of root residues as a nutrient source). Over time, soil chemical fertility improves in ICLSs, and soil OM content tends to initially increase and then stabilize [58].

Unlike clayey soils, sandy and medium-textured soils have low buffering capacity [59]. As a result, alterations in land use and management practices have the potential to modify chemical properties more quickly in these soils than in clayey soils. None of the treatments in this study significantly altered soil chemical fertility in the surface layers, which highlights the importance of medium- to long-term studies for evaluating soil chemical dynamics.

Straw is a labile source of nutrients [60–64], and the decomposition of straw favors nutrient immobilization, primarily influenced by the high C/N ratio of straw residues [65]. Although the systems in this study are still being established, higher organic nutrient concentrations are expected in ICLSs, which will improve long-term soil fertility.

Furthermore, spatial and temporal variations in soil fertility are governed by several complex processes, including soil mineralogical properties, crop traits and root exploration ability. Accordingly, changes in soil chemical properties must be considered alongside other potential effects on the soil, as land-use and management benefits or losses may not be expressed in the short term.

The lower CEC (Figure 2) and Ca contents (Figure 4) in ICL–Ruziziensis and ICL–Piatã at a depth of 0.4 m are chemically consistent. Although the differences in pH between the treatments were not significant, acidity was high in ICL–Ruziziensis and ICL–Piatã and medium (pH in $CaCl_2$ > 5.1 to 5.5) in the other treatments [57]. Ca is more soluble at medium acidity, resulting in higher base saturation [66]. These results affirm the importance of subsurface acidity management, as pH is the main regulator of soil nutrient availability to plants [67–69].

4.2. Soil Chemical Properties—2018

In the second year, the treatments had significant effects on soil chemical properties in the three soil layers evaluated (Figures 2 and 3). The average contents in the 0.0–0.1 and 0.1–0.2 m layers were low for S-SO_4^{-2}, medium for P, pH, K, and V%, and high for Ca and Mg [57].

The soil acidification in the 0.0–0.1 m layer in ICL–Piatã, NTS, and Perennial Paiaguás compared to Perennial Piatã (−0.9, −0.8, and −0.8 units, respectively) is natural in production fields [70], especially in more intensive cultivation systems such as CTSs, NTSs, and ICLSs. This acidification is the result of the periodic fertilization of crops in rotation/succession [71]. In this study, corn topdressing was performed with ammonium nitrate, which has a high acidifying effect [72]. Moreover, soil acidification can occur in grain-producing systems such as soybean and corn [73–75] because cation absorption is greater than anion absorption [76] or due to climatic conditions [67]. In these recently implemented systems, the soil coverage was poor compared to pasture, which favored base leaching.

Soil pH is the main driver of chemical reactions and nutrient availability [77]. In Perennial Piatã, the pH range was adequate for the availability of most nutrients [57], and Mg content in the 0.0–0.1 m layer was higher than that in ICL–Ruziziensis, NTS, ICL–Piatã, and CTS (Figure 4), thus increasing V% (Figure 2). Similar dynamics were observed in the 0.1–0.2 m layer, where both Mg and CEC were higher in Perennial Piatã. In the 0.2–0.4 m layer, Mg content was higher in Perennial Piatã than in ICL–Piatã and ICL–Ruziziensis, whereas the latter treatments had higher H+Al contents, which are directly reflected in the lower V%.

4.3. Soil Chemical Properties—2019

In the third (final) year, the average contents in the 0.0–0.1 and 0.0–0.2 m layers were low for S-SO_4^{-2} (Figure 3), average for pH (Figure 2), P (Figure 3), Mg, and K (Figure 4), and high for Ca [57]. Notably, ICL–Paiaguás and Perennial Piatã had striking positive impacts on soil chemical properties in both the 0.0–0.1 m and 0.1–0.2 m soil layers.

The residual effect of phosphate fertilizers was evident in the ICLSs within the 0.0–0.1 m soil layer (ICL–Piatã and ICL–Paiaguás) and NTS. Phosphorus tends to accumulate in the topsoil in different “pools”, i.e., mineral versus organic and labile versus moderately labile. Thus the accumulation of P is strongly favored in conservation systems with minimal soil disturbance [78–80].

The highest OM content in the 0.0–0.1 m layer was observed in ICL–Paiaguás and Perennial Piatã (Figure 3). Thus suggests that ICLSs help incorporate OM into the soil in the short term, consistent with previous findings [81]. The greater input of plant residues in ICLSs maintains or increases OM content [25,26]. Therefore, the use of ICLSs in conservation systems is a great strategy to increase OM loads in sandy soils with low natural CEC [82].

CEC (Figure 2) and Mg content (Figure 4) were also higher in ICL–Paiaguás and Perennial Piatã, consistent with the higher soil OM content in these treatments (Figure 3). For Perennial Piatã, the results may be related to increased manure deposition on the soil [83,84] because of the higher animal stocking rate in January, which was adjusted according to [48]. The variation in stocking rates occurred two months prior to soil collection; the stocking rate was approximately 5.3 AU ha^{-1} in Perennial Piatã and 3.8 AU ha^{-1} in Perennial Paiaguás.

The soil CEC is expected to be maintained or increased in the evaluated conservation systems (Figure 2) based on results from previous years (Supplementary Table S1), when CEC in the area was uniform. The results for CEC in the last year of the study agree with other studies that have reported gradual increases in OM content over successive years [58,85].

One hypothesis for the superior results in Perennial Piatã and ICL–Paiaguás is that in these systems, the plants incorporated more C from the soil, increasing biomass and root system production. Roots are important for the incorporation of soil C, as approximately 40–60% of photosynthetically fixed C is allocated to roots and associated microorganisms via rhizodeposition (organic substances released from plant roots) [86]. Therefore, the differences in OM content, especially in the ICLSs, may reflect the root and shoot regrowth capacity of each cultivar as they are grazed [81,87]. This hypothesis can be tested in future studies.

In contrast to the results in 2018, the pH in the 0.0–0.1 m layer was not higher in Perennial Piatã than in the other treatments in 2019 (Figure 2). This may reflect the effect of greater animal stocking in the last year. According to [88], manure contains high concentrations of ammonium, which exerts an acidifying effect through absorption or nitrification. When organic N is mineralized, H^+ is consumed, resulting in the alkalization of the medium. However, this effect is offset by nitrification, which produces 2 H^+, leading to acidification. As a result, grazing leads to a heterogeneous pattern of acidification through urine-induced nitrification and alkalization/acidification through manure (mineralization).

Although ICL–Paiaguás and Perennial Piatã had significant effects on soil CEC in the 0.0–0.1 m layer (Figure 2), soil CEC in the conservation systems tended to remain unchanged in the short term compared to CTS. In conservation systems, straw serves as a physical barrier that not only reduces water infiltration in the soil profile, but also helps minimize base leaching [60] and incorporates OM into the soil [28,89]. In sandy soils, straw is responsible for a large part of CEC.

In the 0.1–0.2 m layer, ICL–Paiaguás had the highest CEC (Figure 2), P (Figure 3), and Mg (Figure 4) contents. Notably, P content in both the 0.0–0.1 m and 0.1–0.2 layers were higher in the grain-producing systems (ICLSs and monocropped) than in the pasture systems. Therefore, the residual/cumulative effect reported previously for P [78–80] was observed up to the 0.1–0.2 m layer. In this layer, pH, Ca and Mg contents, as well as V%, were higher in Perennial Piatã than in NTS, CTS, and ICL–Ruziziensis.

In the 0.2–0.4 m layer, base saturation (V%) was the only chemical property that was affected by the treatments. V% was higher in ICL–Paiaguás ($p < 0.05$) than in ICL–Ruziziensis. H+Al and CEC did not differ significantly between ICL–Ruziziensis and ICL–Paiaguás, but may have influenced V%. The occupation of sites in the soil sorption complex by Al reduces the potential of CEC to retain greater amounts of exchangeable bases, and this reduction may have been greater in ICL–Ruziziensis than in ICL–Paiaguás.

4.4. Soil Micronutrients

The treatments had little effect on soil micronutrient dynamics. The only differences were in soil B content in 2018 (in the 0.2–0.4 m layer) and soil Fe content in 2019 (in the 0.1–0.2 and 0.2–0.4 m layers) (Figures 4 and 5). In 2018, B content in the 0.2–0.4 m layer was higher in ICL–Ruziziensis and ICL–Piatã than in Perennial Piatã; however, the differences between treatments were not significant. Although these higher levels of B are at the upper limit of the range that is considered low [57], they are suitable for the study site, which features sandy soil with low OM content [90]. The higher levels of B in these two treatments might be a residual effect of B sources applied to the forages previously grown in the area for seed production, as B warrants special attention for seed production [91].

Furthermore, the soil B content in the 0.0–0.2 m layer was maintained in all three years without amendment, despite exports to grain and meat production. However, in the 0.2–0.4 m layer, soil B content decreased in Perennial Piatã in 2018. The maintenance of B levels in surface soil without replacement by chemical fertilization suggests that B is recycled from deeper layers. Similar phenomena have been observed for other nutrients, like Ca and Mn, in grass cultivation under NTS [92].

In 2019, the soil Fe content in the 0.1–0.2 m layer in ICL–Ruziziensis was greater than the soil Fe content in the 0.1–0.2 m layer in Perennial Piatã or in the 0.2–0.4 m layer in ICL–Paiaguás and Perennial Paiaguás. At both depths, Fe content was lowest in the treatments with less acidic soils classified as medium pH [57]. As pH increases, the availability of Fe in the soil solution decreases [93–95]. With the exception of the perennial pastures (Perennial Paiaguás and Perennial Piatã), available Fe content was high in all treatments [57]. Out of the micronutrients, the highest content in the soil was observed for Fe. In the Cerrado, the soils are naturally acidic due to the prevailing edaphic conditions, and Fe deficiency has rarely been reported. Moreover, in acidic soils, the Fe^{2+} concentration in the soil solution can be phytotoxic [69]. Fe content in the 0.1–0.4 m layer was highest in ICL–Ruziziensis; however, it remained within the range deemed sufficient for the evaluated crops [57].

4.5. Weather Conditions

Crop GY varied greatly over the three years of the experiment (Table 1) due to climatic factors (Figure 1). The higher volume of rainfall that was distributed more evenly during the corn and soybean cycles in the 2016/2017 and 2017/2018 seasons resulted in similar production patterns between treatments in both years. In the first two years, the systems were still being established, and thus the properties that foster soil resilience under extreme situations and benefit plants [96] were still developing.

From corn sowing to physiological maturity, total rainfall in 2016, 2017, and 2018 was 336, 316, and 156 mm, respectively. In the last year, the corn plants were severely affected by water shortage periods. The first period occurred during stage V3 and lasted 15 days, coinciding with the time of production potential definition. The second started in V7 (determining the number of rows of grains per year) and R1 (flowering and pollination) and lasted until harvest. These limitations, which occurred in critical development stages for the crop [97], resulted in low productivity (Table 1).

From soybean sowing to physiological maturity, total rainfall in 2016/2017, 2017/2018, and 2018/2019 was 530, 772, and 575 mm, respectively. Weather conditions were atypical in 2018, and although the accumulated rainfall was not lowest in the 2018/2019 crop season, its distribution was irregular, with water deficits during critical periods for soybean (from R1 to R6).

4.6. Corn and Soybean Grain Yields

The absence of significant effects on GY in the first two years (Table 1) indicates that the period of implementation of the treatments was too short to promote major changes in the production environment. Significant changes require more time in conservation systems [36,58,85].

Studies conducted under various conditions indicate that intercropping corn and forage grasses does not negatively impact GY [11,19–22]. Most of these studies, however, were performed in clayey soils and reported favorable climatic conditions in the main season (summer). In our study, the challenge was to grow corn intercropped with forage in the second season (autumn/winter) in sandy soil, which increases the risk of crop losses.

Although the differences in corn GY were not significant, the inadequate rainfall distribution (336 mm) in 2016 reduced corn GY by 23%, 13%, and 5% in ICL–Ruziziensis, ICL–Piatã, and ICL–Paiaguás, respectively, compared to the monocropped systems (NTS and CTS). These reductions were probably due to competition with the forage grasses [31,98]. GY reductions of 23% and 13% are large enough to reduce profit. In intercropped systems, corn represents a bonus for pasture recovery, greater profitability, and the amortization of production costs [99].

By contrast, the rainfall distribution was regular during most of the corn cycle in 2017 (Figure 1), resulting in GY variations of close to 0% when the intercropped systems ICL–Piatã, ICL–Paiaguás, and ICL–Ruziziensis were compared with monocropping (NTS and CTS). The lack of GY variations may also have been the result of low forage densities of 8, 7, and 9 plants per m-2 in ICL–Ruziziensis, ICL–Paiaguás, and ICL–Piatã, respectively. These low densities were due to the lack of rain soon after sowing (Figure 1), which also decreased forage dry matter production (Supplementary Figure S1). Successful forage establishment in intercropped systems is essential for the adequate accumulation and maintenance of straw in the ICLS [100], which increases soil moisture retention and reduces competition between species under restricted water regimes.

Spatial arrangement and sowing type are key considerations for proper corn crop establishment in an ICLS. These factors should align with the system's objectives [29]. Because our goal was grain production, the corn was sown in rows spaced 0.90 m apart, and forage was sown between the corn rows to reduce the effects of potential dry spells. Higher planting densities are recommended only in the absence of water restrictions [30], and arrangements must follow environmental conditions and consider cultural, technical, and climatic factors.

Among all crops in the three seasons, the 2018 corn crop was most affected by water shortages. Rainfall was approximately 159 mm during corn crop development in this season (Figure 1). Competition with forage can reduce corn GY in intercropped systems under limiting conditions of water, light, and nutrients [31]. In this study, corn GY was lower under intercropping with *U. ruziziensis* than under monocropping in the NTS. The forage cultivars BRS Paiaguás and BRS Piatã have thin stems that are easily lodged, which reduces their competitiveness with intercropped grain crops compared with *U. ruziziensis*, which has thicker and longer stems [33].

High soil acidity in the 0.2–0.4 m layer may have further enhanced the competition between intercropped *U. ruziziensis* and corn. Although there were no pH differences between this treatment and the others, we hypothesize that the high soil acidity [57] in this layer of the ICL–Ruziziensis system (Figure 3) prevented plant roots from reaching deeper layers and overcoming water deficits [101].

These results reinforce the importance of subsurface acidity correction. As pH is the main controller of soil nutrient availability for crops, it indirectly affects biomass production [67–69]. These findings can support decision-making on ICLS implementation and soil correction practices in subsurface layers to provide short-term or longer-term residual effects.

A major challenge for grain production in the agricultural frontier of tropical regions is water deficits associated with high temperatures, which can occur in critical stages of crop growth. Under these conditions, climate restriction is the main limitation to attaining stable high yields in tropical sandy soils, despite the availability of NTS and ICLS techniques [102]. Our results demonstrate that sandy soils, which are deemed sensitive to disturbance [82], can withstand intensive cropping throughout the year without yield losses for corn intercropped with forage and soybean grown in succession. Thus, sandy soils have the same soybean productive potential as clayey soils under favorable climatic conditions if suitable management is adopted [103].

In the 2017/2018 season, the severe dry spell during the most critical soybean phenological stage, i.e., grain filling [104], impaired crop performance, regardless of the treatment. Furthermore, water limitation during the establishment stage of forage intercropped with corn, before soybean sowing in the 2017/2018 season (Figure 1), reduced straw cover amounts and hence soil water retention, leading to medium/low GYs in all treatments, since water shortage also limits soybean yields [105].

In the 2018/2019 season, limiting weather conditions fully revealed the responses of the crops to the treatments. Soybean in succession was positively influenced by the ICLS, which may be related to the short-term (2016–2019) acquisition of soil resilience [96]. These results corroborate the literature on the short-term responsiveness of soybean in sandy soils. [106] studied soybean cultivation in the Cerrado in soils of different textures and observed that, within a decade, the mean yield rose from 3.1 to 3.5 t ha^{-1} in clayey soils and from 2.6 to 3.3 t ha^{-1} in sandy–medium-textured soils. These observations suggest that soybean is highly responsive to ICLS techniques in sandy soils, as long as adequate straw is supplied.

5. Conclusions

Among the treatments, intercropping corn with *Urochloa brizantha* cultivar BRS Paiaguás resulted in the greatest improvement in soil chemical quality for soybean in succession. For pasture (intermittent for legume cultivation in succession), cv. BRS Piatã is a good alternative for improving or maintaining soil chemical quality. Soybean GY increased when grown in succession to an ICLS. Notably, in this short-term evaluation, the benefits of crop rotation for soybean were greatest in years with climatic limitations, and the beneficial effects may increase in the long-term.

In tropical sandy soils, it is advisable to avoid continuous conventional tillage due to its detrimental effects on short-term sustainability. This conclusion is supported by the lower soybean yields under CTS in this study. The assumed benefits of conventional tillage to crops (e.g., greater soil aeration) are overridden by the deleterious effects of lower water retention, which are aggravated by the lack of surface protection, on soil quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14092071/s1, Figure S1: Dry matter of the aerial part of *Urochloa ruziziensis* (ICL-Ruziziensis), *U. brizantha* cv. Piatã (ICL-Piatã) and *U. brizantha* cv. Paiaguás (ICL-Paiaguás). Different letters denote significant difference between treatments (Tukey, $p \leq 0.05$); Table S1: Soil chemical properties of the experimental areas before field experiment.

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