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Productive response of corn in intercropping systems under different nitrogen doses and the use of phosphate

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Abstract: The intercropping of corn with forage species has been widely used, aiming to combine grain production with the potential for straw accumulation on the soil surface. However, this study focused exclusively on the agronomic performance and grain yield of the corn component. The objective was to evaluate the morphological components and grain yield of corn intercropped with forages under nitrogen (N) topdressing rates, in two areas: one without phosphate (P) application and another with P. Two experiments were carried out in the 2021/2022 growing season, in a randomized block design with four replications, in a factorial scheme. The first factor consisted of six intercrops: single corn (C); corn + *Urochloa ruziziensis* (CR); corn + *Urochloa brizantha* cv. Piatã (CP); corn + *Stylosanthes* cv. Campo Grande (CS); corn + *U. brizantha* + *Stylosanthes* (CPS); and corn + *U. ruziziensis* + *Stylosanthes* (CRS). The second factor consisted of four N rates (0, 60, 120, and 240 kg ha^{-1}). Plant height (PH), ear insertion height (EIH), stem diameter (SD), number of rows per ear (NRE), number of grains per ear (NGE), and grain yield (PROD) were evaluated. Among the evaluated systems, single corn (C) and corn + *Stylosanthes* (CS) showed higher grain yield at the maximum N rate. However, these comparisons should be interpreted with caution due to differential weed management between treatments (chemical control in single corn vs. no herbicide in intercropped plots). Morphological components were positively influenced by increasing N rates up to 160 kg ha^{-1}, and yield components up to 240 kg ha^{-1}.

Keywords: Nitrogen; phosphate; *Stylosanthes*; *Urochloa*; *Zea mays* L.

Introduction

Corn (*Zea mays* L.) is estimated to have a production of 138.9 million tons in the 2025/2026 crop season (CONAB, 2026). It is a crop of great economic importance, widely cultivated throughout the world, due to its adaptation to different ecosystems, the development of high-yielding varieties and hybrids, and efficient responses to fertilization. Global production exceeds 1 billion tons per year, with the United States, Brazil, and China standing out, together accounting for 64.6% of this production (USDA, 2022).

The intercropping of corn with forage species has been widely used, aiming at high grain production of the crop and accumulation of straw on the soil surface, generating benefits for the soil and cultivated plants, optimizing the production area. The adoption of cover crops is widely recognized as an effective strategy to increase the sustainability of agricultural production, particularly in regions such as the Brazilian Cerrado (Araújo et al., 2024). When this strategy is adopted, in addition to the supplied mineral nitrogen (N), the introduction of cover crop species with a lower carbon/nitrogen (C/N) ratio are alternatives that can increase the availability of N in the soil (Kappes et al., 2013a).

Among the various nutrients necessary for the good development of this crop, nitrogen stands out as a fundamental and indispensable element in crop fertilization, acting strongly in maintaining and increasing productivity (Ribeiro et al., 2024). These same authors report that nitrogen stands out from other nutrients for presenting marked dynamism in the soil system and for usually being the nutrient required in the greatest quantity by crops. Like N, phosphorus (P) is essential to achieve high productivity in corn cultivation. Increasing doses of phosphorus affected plant heights, stem diameter, and ear insertion height in corn cultivation (Oliveira et al., 2021).

High doses of P are needed due to low absorption and low soil content, resulting in limited amounts available to meet plant demand (Eichert and Fernández, 2023; Vinas et al., 2020). In this sense, research has focused on improving the efficiency of this nutrient and using new alternatives, with the aim of optimizing the application of phosphate fertilizers (Heuer et al., 2017).

Excessive application of fertilizers can compromise the success of agricultural production, in addition to negatively impacting groundwater and surface water (Dhakal and Lange, 2021). Given the above, the objective of this study was to evaluate the morphological components and grain yield of corn intercropped with forage species under different nitrogen topdressing rates, with and without rock phosphate application. While intercropping systems are known to provide additional benefits such as straw accumulation, this study did not measure forage biomass production; therefore, the results and conclusions are limited to the agronomic performance of the corn component.

Results

This study evaluated two distinct areas where maize was intercropped with forage crops under different nitrogen (N) topdressing doses, one with rock phosphate application and one without. The results are described below separately for each area, as the areas were not combined in a single statistical model.

Without phosphate

Table 1 presents the mean squares and the significance of the F-test for the variables analyzed, as well as their interactions. Among the sources of variation, intercropping (C) responded significantly for number of grains per ear (NGE) and grain yield (PROD).

Nitrogen (N) showed a positive response for plant height, ear insertion height, number of rows per ear, number of grains per ear, and productivity. The effect of nitrogen fertilization represents its importance for the crop, acting in plant development through photosynthetic processes, cell expansion and division, directly impacting productivity.

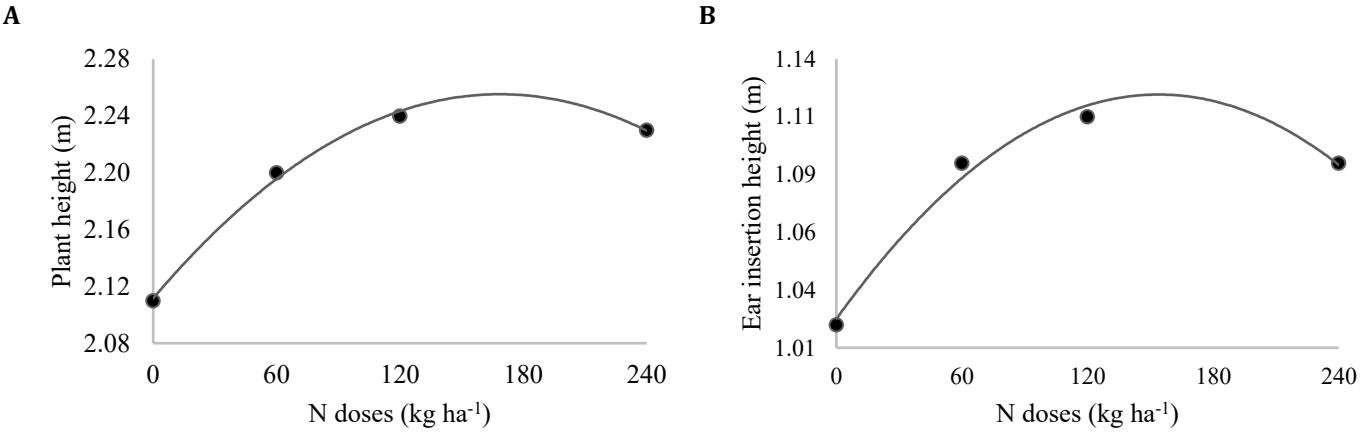
The interaction effect between C × N showed significance only for productivity (PROD). This result demonstrates that productivity responds differently depending on the doses and intercropping systems.

Table 1. Summary of the analysis of variance for plant height (PH), ear insertion height (EIH), stem diameter (SD), number of rows per ear (NRE), number of grains per ear (NGE) and grain yield (PROD), evaluated in a split-plot design (intercropping = main plots; N rates = sub-plots), in the area without rock phosphate in the 2021/2022 growing season.

SV	DF	PH	EIH	SD	NRE	NGE	PROD
Block	3	0.02^{ns}	0.01^{ns}	1.60^{ns}	0.74*	0.29*	15632^{ns}
C	5	0.02^{ns}	0.01^{ns}	1.02^{ns}	0.46^{ns}	4707.10**	349962***
Error a	15	0.01	0.01	0.69	0.19	908.90	10711
N	3	0.08***	0.04***	3.00^{ns}	0.83*	20177.80***	12267210***
C × N	15	0.00^{ns}	0.01^{ns}	1.54^{ns}	0.32^{ns}	2761.00^{ns}	141398***
Error b	54	0.02	0.01	1.22	0.29	1583.20	25552
CV1 (%)		5.78	5.60	3.12	6.30	1.00	1.00
CV2 (%)		6.77	7.45	3.87	8.31	1.55	1.54

*, **, ***: significant at 5%, 1%, and 0.1% probability, respectively; ^{ns}: not significant; SV: source of variation; CV: coefficient of variation; DF: degrees of freedom.

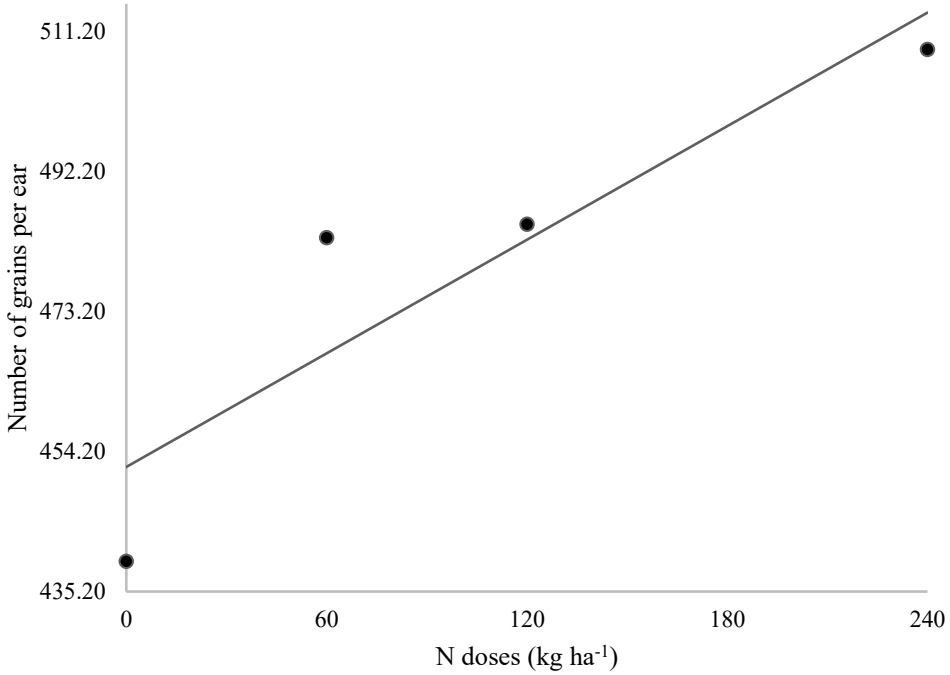
The variables plant height (PH) and ear insertion height (EIH) showed a quadratic effect in relation to N doses, highlighting the positive effect on parameters that make up the growth and productivity of the corn crop (Fig. 1). The estimated maximum point for PH and EIH was at doses of 160 kg ha^{-1} and 150 kg ha^{-1} of N, respectively.



(A) $\hat{Y} = -5E-06x^2 + 0.0016x + 2.1116$; $R^2 = 0.9925$
(B) $\hat{Y} = -4E-06x^2 + 0.0012x + 1.0258$; $R^2 = 0.9886$

Fig. 1. Plant height (A) and ear insertion height (B) for maize managed with N doses in the area without phosphate.

There was no model fit for the variable number of rows per ear (NRE). The equation presented in Fig. 2 shows that the number of grains per ear (NGE) fit the linear model with increasing N doses.



$\hat{Y} = 0.257057x + 452.114$; $R^2 = 0.825375$

Fig. 2. Number of grains per ear for maize managed with different nitrogen doses in an area without phosphate.

In analyzing the significant interaction between the consortia and N doses for PROD (Table 2), it is noted that the CRS showed higher productivity. There was adequate N supply, with proper formation of chlorophyll molecules reflecting the spectral bands appropriately.

Table 2. Unfolding of the significant interaction of the analysis of variance regarding consortia for grain productivity (PROD, t ha^{-1}) as a function of N doses for corn intercropped with forage crops, in an area without phosphate in the 2021/2022 growing season.

Doses of N (kg ha^{-1})	C	CR	CP	CS	CRS	CPS
0	9.53 ab	9.55 ab	9.42 ab	9.29 b	9.62 a	9.34 ab
60	10.16 abc	9.93 c	10.38 ab	9.92 c	10.46 a	10.08 bc
120	11.07 ab	11.28 a	10.80 bc	10.53 cd	11.07 ab	10.48 d
240	11.13 a	11.04 ab	10.79 b	11.13 a	11.09 ab	10.86 ab

Means followed by the same letters in the rows do not differ from each other by Tukey's test at 5% probability. C: single maize; CR: maize + U. ruziziensis; CP: maize + U. brizantha cv. Piatã; CS: maize + *Stylosanthes*; CRS: maize + U. ruziziensis + *Stylosanthes*; CPS: maize + U. brizantha + *Stylosanthes*.

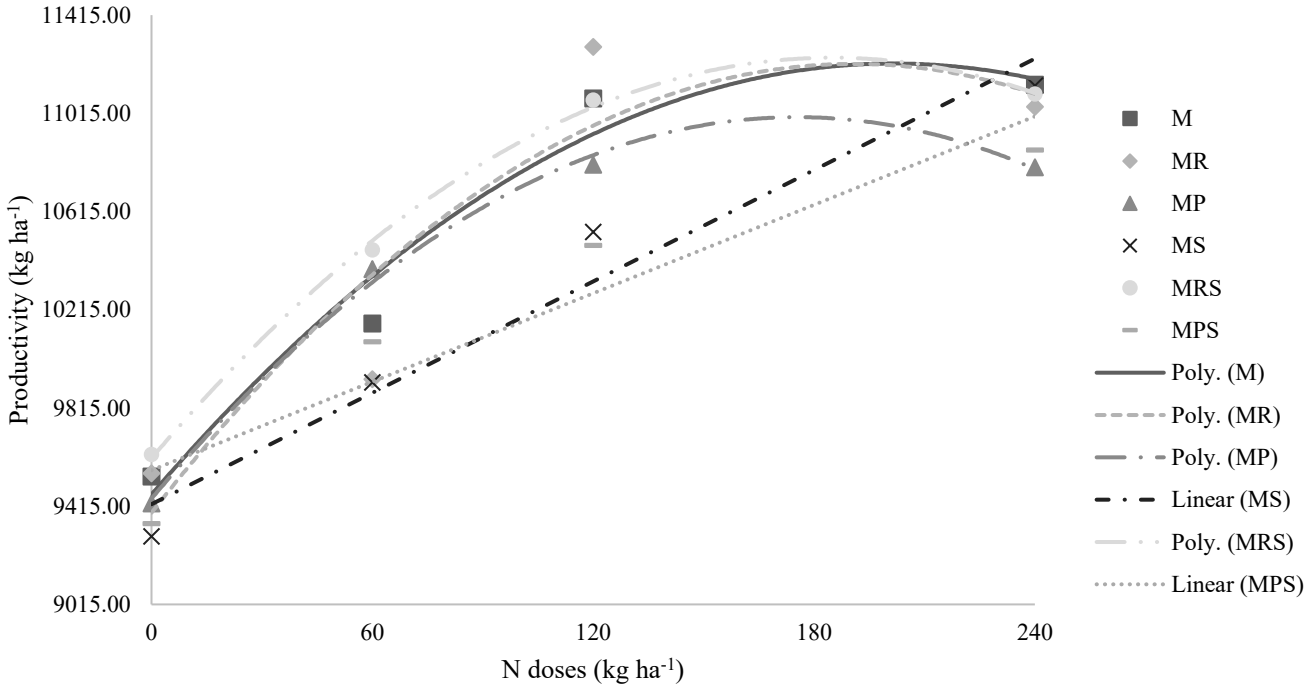
There was a quadratic fit for grain yield (PROD) in the C, CR, CP, and CRS intercropping schemes in response to N doses, while CS and CPS adjusted to the linear model (Fig. 3). The C, CR, and CRS intercropping schemes stood out, indicating an increase in grain yield up to N doses of 201.5 kg ha^{-1}, 191 kg ha^{-1}, and 185 kg ha^{-1}, respectively.

With phosphate

The effect of intercropping (C) was significant only for productivity among the evaluated variables (Table 3). Nitrogen doses (N) were significant in all variables, except for the number of rows per ear (NRE). The interaction between C × N was significant only for grain yield (PROD), demonstrating that the variables respond differently to the N doses supplied.

The significance of N for PH demonstrates the importance of this element, especially when combined with forage crops (Fig. 4A), with maximum efficiency up to a dose of 160 kg ha^{-1} throughout the crop cycle. The quadratic model adjustment for EIH obtained a maximum value at a dose of 100 kg ha^{-1} of N (Fig. 4B).

The linear model was adjusted for stem diameter (SD), indicating that cell expansion and division occurred up to this dose, which favored stem development (Fig. 4C). In Fig. 4D, the N supplied as topdressing showed a positive response with adjustment to the linear model for the variable number of grains per ear (NGE).



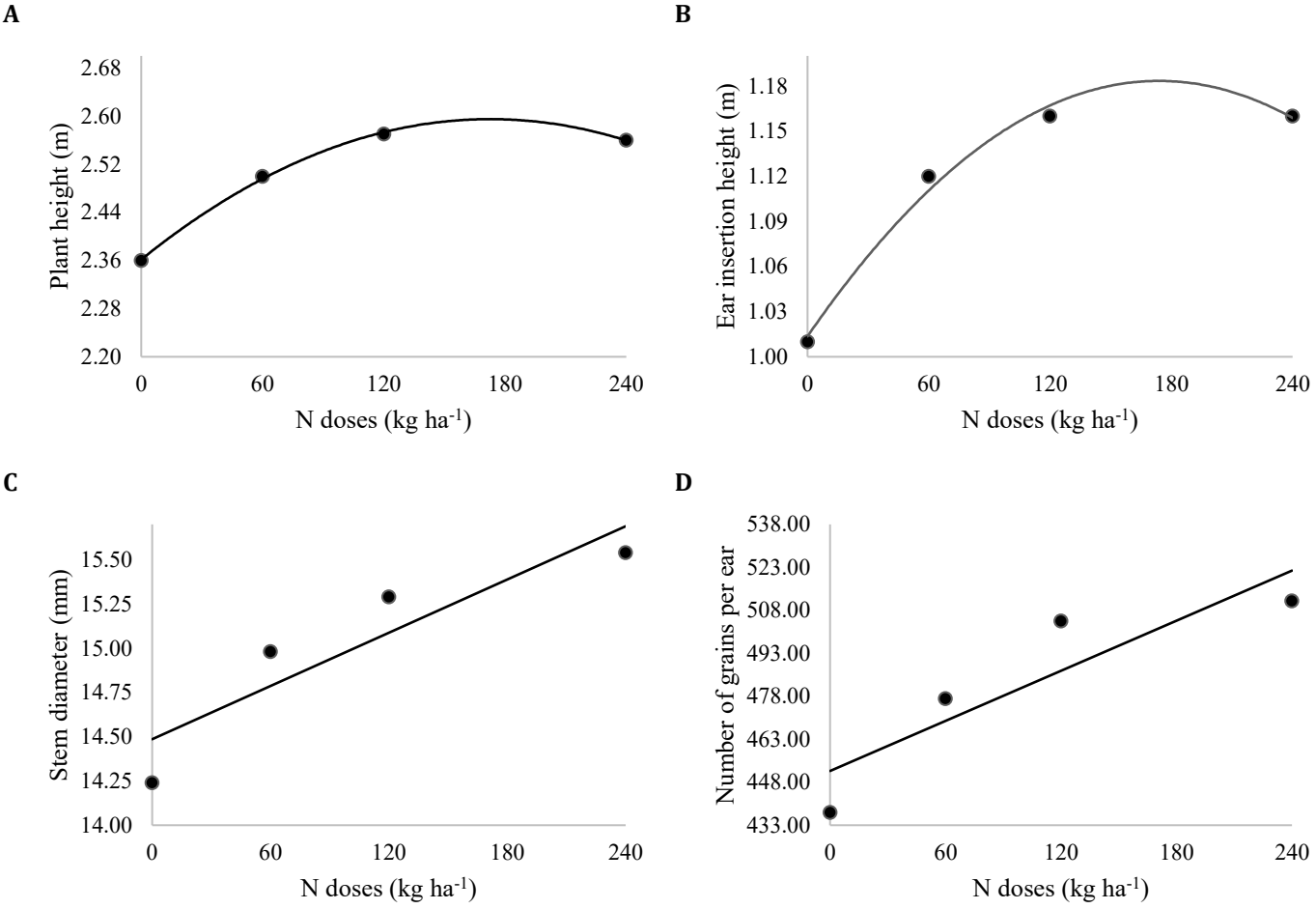
(C) $\hat{Y} = -0.0432x^2 + 17.411x + 9462.6$; $R^2 = 0.9640$
(CR) $\hat{Y} = -0.0503x^2 + 19.17x + 9388.4$; $R^2 = 0.8535$
(CP) $\hat{Y} = -0.0505x^2 + 17.72x + 9445.7$; $R^2 = 0.9962$
(CS) $\hat{Y} = 7.56107x + 9423.02$; $R^2 = 0.961762$
(CRS) $\hat{Y} = -0.0477x^2 + 17.635x + 9610.1$; $R^2 = 0.9982$
(CPS) $\hat{Y} = 6.00332x + 9561.65$; $R^2 = 0.896931$

Fig. 3. Grain productivity (PROD) as a function of intercropping systems: single maize (C); maize + U. ruziziensis (CR); maize + U. brizantha cv. Piatã (CP); maize + *Stylosanthes* (CS); maize + U. ruziziensis + *Stylosanthes* (CRS); maize + U. brizantha + *Stylosanthes* (CPS) and nitrogen topdressing rates, in the area without phosphate. Plot keys: M = C, MR = CR, MP = CP, MS = CS, MRS = CRS and MPS = CPS.

Table 3. Summary of the analysis of variance for plant height (PH), ear insertion height (EIH), stem diameter (SD), number of rows per ear (NRE), number of grains per ear (NGE), and grain yield (PROD), evaluated in a split-plot design (intercropping = main plots; N rates = sub-plots), in the area with rock phosphate in the 2021/2022 growing season.

SV	DF	PH	EIH	SD	NRE	NGE	PROD
Block	3	0.04^{ns}	0.01^{ns}	0.56^{ns}	0.06^{ns}	4809.70^{ns}	2550^{ns}
C	5	0.04^{ns}	0.00^{ns}	0.88^{ns}	0.18^{ns}	1734.90^{ns}	229914***
Error a	15	0.02	0.00	1.96	0.42	1553.00	15360
N	3	0.21***	0.12***	7.66**	0.21^{ns}	26881.90***	9274277***
C × N	15	0.02^{ns}	0.00^{ns}	0.86^{ns}	0.38^{ns}	2051.30^{ns}	38162***
Error b	54	0.01	0.00	1.76	0.42	1704.20	9455
CV1 (%)		6.28	9.33	4.63	8.17	1.20	1.19
CV2 (%)		6.56	8.85	4.62	8.56	0.94	0.93

*, **, ***: significant at 5%, 1%, and 0.1% probability, respectively; ^{ns}: not significant; SV: source of variation; CV: coefficient of variation; DF: degrees of freedom.



(A) $\hat{Y} = -1E-05x^2 + 0.0026x + 2.3657$; $R^2 = 0.9963$
(B) $\hat{Y} = -1E-05x^2 + 0.002x + 1.0138$; $R^2 = 0.9886$
(C) $\hat{Y} = 0.00501429x + 14.486$; $R^2 = 0.831001$
(D) $\hat{Y} = 0.291362x + 451.932$; $R^2 = 0.795895$

Fig. 4. Plant height (A), ear insertion height (B), stem diameter (C) and number of grains per ear (D) for maize crop managed with N doses in the area with phosphate.

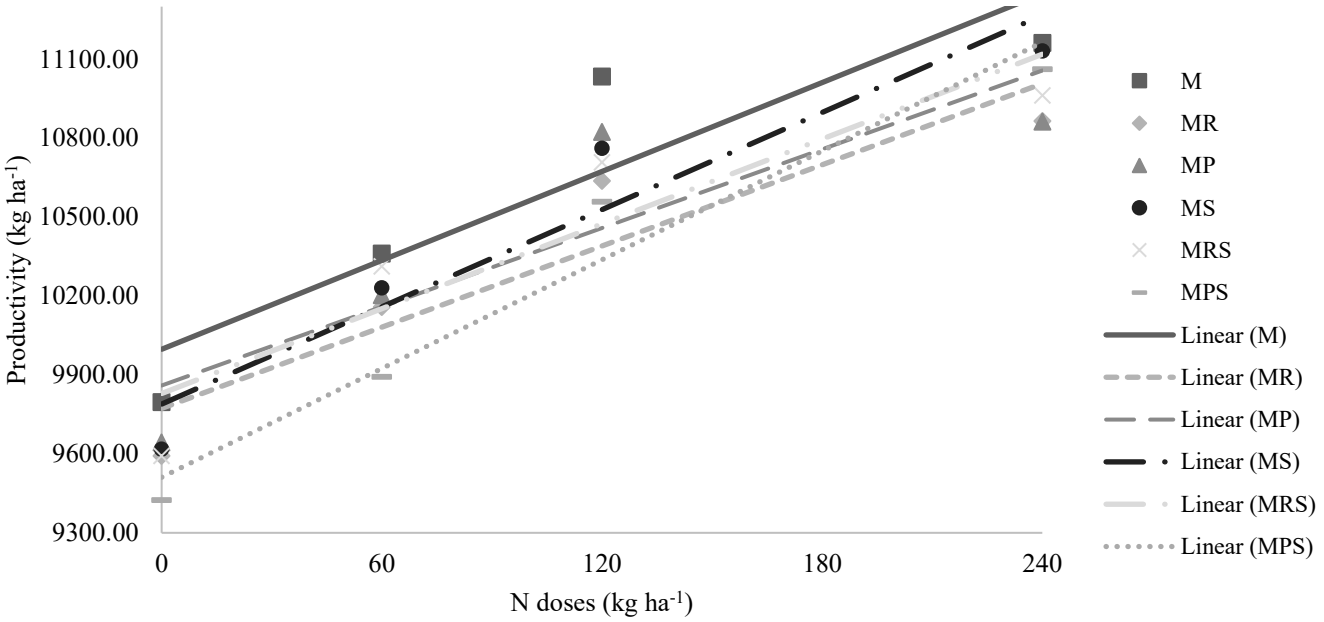
In Table 4, regarding the interaction of corn intercropping with forage crops and N doses as topdressing, intercropping modality C showed higher PROD when compared to the other intercropping systems statistically, regardless of the N dose. However, there was no difference in the maximum dose supplied of 240 kg ha^{-1} for intercropping systems C, CS, and CRS.

Table 4. Unfolding of the significant interaction of the analysis of variance regarding consortia for grain productivity (PROD, t ha^{-1}) as a function of N doses for corn intercropped with forage crops, in an area with phosphate in the 2021/2022 growing season.

Doses of N (kg ha^{-1})	C	CR	CP	CS	CRS	CPS
0	9.80 a	9.60 ab	9.64 a	9.62 ab	9.60 ab	9.42 b
60	10.36 a	10.16 a	10.20 a	10.23 a	10.31 a	9.89 b
120	11.03 a	10.64 bc	10.82 ab	10.76 bc	10.71 bc	10.56 c
240	11.16 a	10.86 b	10.86 b	11.13 a	10.96 ab	11.06 ab

Means followed by the same letters in the rows do not differ from each other by Tukey's test at 5% probability. C: single maize; CR: maize + U. ruziziensis; CP: maize + U. brizantha cv. Piatã; CS: maize + *Stylosanthes*; CRS: maize + U. ruziziensis + *Stylosanthes*; CPS: maize + U. brizantha + *Stylosanthes*.

The relationship between intercropping and nitrogen doses favored grain productivity in maize cultivation. All intercropping modalities fit the linear model, with C and CS standing out (Fig. 5), suggesting that in these intercropping systems the plants made better use of nitrogen.



(C) $\hat{Y} = 5.63194x + 9997.63$; $R^2 = 0.828822$
(CR) $\hat{Y} = 5.14344x + 9773.03$; $R^2 = 0.874369$
(CP) $\hat{Y} = 4.98863x + 9859.88$; $R^2 = 0.780627$
(CS) $\hat{Y} = 6.15827x + 9789.26$; $R^2 = 0.917232$
(CRS) $\hat{Y} = 5.3739x + 9829.47$; $R^2 = 0.849543$
(CPS) $\hat{Y} = 6.88937x + 9511.07$; $R^2 = 0.956711$

Fig. 5. Grain productivity (PROD) as a function of intercropping systems: single maize (C); maize + U. ruziziensis (CR); maize + U. brizantha cv. Piatã (CP); maize + *Stylosanthes* (CS); maize + U. ruziziensis + *Stylosanthes* (CRS); maize + U. brizantha + *Stylosanthes* (CPS) and nitrogen topdressing rates, in the area treated with phosphate. Plot keys: M = C, MR = CR, MP = CP, MS = CS, MRS = CRS and MPS = CPS.

Discussion

Corn, when intercropped with brachiaria grasses, can be influenced by the speed of establishment of the forage and the increased competition for environmental resources, which may harm the development and productivity of the crop (Pariz et al., 2011). This fact corroborates Silva et al. (2015), who state that the emergence of brachiaria together with corn may have contributed to greater competitive capacity and an 8% reduction in productivity.

It is important to note that *Stylosanthes* cv. Campo Grande was sown one day after corn (October 7, 2021), whereas *Urochloa* species were sown 14 days later. This delay was intended to reduce early competition from the aggressively growing *Urochloa* during corn establishment (Silva et al., 2015; Pariz et al., 2011). In contrast, *Stylosanthes*, a legume with slower initial growth, was sown earlier to ensure adequate establishment before canopy closure. This differential timing may have contributed to the better performance of the CS (corn + *Stylosanthes*) system, as *Stylosanthes* likely established without intense competition, while the 14-day delay for *Urochloa* may not have fully eliminated competitive pressure. The influence of forage sowing timing on crop–forage competition warrants further investigation.

In addition to competition, the management of nitrogen fertilization of corn intercropped with brachiaria is an important parameter that must meet the demand of the intercropped species without harming the productivity of either, since they are highly demanding in this element (Costa et al., 2012). The results observed in both the area without phosphate (P) and the area with P show that the intercropping did not negatively influence grain productivity. This indicates that competition between the species did not interfere with the absorption of water, light, and nutrients, and that the climatic conditions (Fig. 6) were favorable, contributing to plant development.

However, a critical methodological limitation must be acknowledged: weed control was not uniform across treatments. Atrazine was applied only to single corn plots, while intercropped plots received no herbicide. This differential weed management may have contributed to the observed differences in grain yield between cropping systems. Single corn plots benefited from chemical weed suppression, whereas intercropped plots faced potential competition from weeds in addition to competition from the forage species. Therefore, the yield advantages observed for single corn and the CS intercropping system should be interpreted with caution, as they may partially reflect differences in weed pressure rather than the intrinsic effects of intercropping alone.

N in topdressing, when applied in high doses, favors the yield response of the corn crop. However, excessive fertilization can cause environmental impacts. Aiming to reduce this process, remote monitoring techniques have been used, such as vegetation indices (VIs), which assist in decision-making regarding the appropriate amount of N that should be supplied to a crop according to the nutritional needs of the crop (Santana et al., 2021). This occurs due to the sensitivity that VIs have

in detecting the "green" of the vegetation (Xue and Su, 2017), and nitrogen fertilization plays a fundamental role in this process.

N has a greater influence on the agronomic characteristics of corn plants. Topdressing fertilization favors initial growth, indicating that, regardless of the cropping system, plant height may be lower when N is not available (Patel et al., 2019). Increasing the doses supplied provides greater plant height, ear insertion, and stem diameter, highlighting the importance of this nutrient in plant growth and development (Pedrazzi et al., 2016). Thus, high doses may be necessary when grain-producing crops and forage species are intercropped to meet the demand for adequate plant growth, since both have C4 metabolism (Borghi and Crusciol, 2007).

Considered a constituent of chlorophyll, N plays a direct role in the photosynthetic process, which influences cell expansion and division, promoting greater plant height, ear insertion, and stem diameter (Goes et al., 2014). However, researchers indicate that the best strategy is to look for plants that have lower EIH (Pizolato Neto et al., 2016), since a high ratio between EIH and PH promotes greater displacement of the plant's center of gravity, which can lead to greater stem breakage (Kappes et al., 2013b).

The response to N in this study was superior to that observed by the authors Goes et al. (2014) and Torres et al. (2014), in the areas studied for the morphological and production components. These results may be related to the cropping system, since the presence of straw on the soil surface from previous crops contributes to the greater availability of residual N obtained through the mineralization of plant residues, reducing the amount of N required by the corn crop in integrated systems. This may also be related to the type of soil.

Soils in the Brazilian Cerrado region have low levels of organic matter, requiring the application of high doses of N for the corn crop. Therefore, high doses of nitrogen (N), in addition to keeping the plant well-nourished, favor the growth of the leaf area, since it is a constituent of molecules vital to the plant in all metabolic processes, especially chlorophyll, which is responsible for photosynthesis. This process prolongs the duration of the grain filling period. However, the concentration of foliar N and the higher productivity of the crop also indicate that fertilization with N should be carried out at the appropriate time and dose, favoring its uptake by the plant and the production of heavier grains (Silva et al., 2005).

The response to PH and SD observed in this study is important considering the translocation and accumulation capacity of nutrients to the ears during the grain filling phase. However, SD only showed significant results in the area with phosphate, where the corn intercropping with forage species did not interfere with stalk development, indicating homogeneity among the species. Possibly there were plants with thicker stalks, which ensures greater resistance to lodging due to climatic conditions and breakage during harvesting, making translocation more efficient, reflecting in productivity (Costa et al., 2012). This occurs because stalks with a larger diameter provide the plant with a greater capacity to store photoassimilates, which contributes to grain filling (Kappes et al., 2011). Authors highlight the influence on SD growth with the supply of N (Kappes et al., 2013b; Pedrazzi et al., 2016).

Increasing doses of N promote increased productivity in terms of the number of rows per ear and the number of grains per row (Sichocki et al., 2014). However, the variable number of rows per ear is more associated with the genetics of the cultivars than with the management practices employed in the crop (Besen et al., 2018). Due to this, the variable NRE did not respond to the management employed in the crop. However, for the variable NGE, management with N provides a significant improvement in ear characteristics, promoting an increase in grain weight (Li et al., 2020), in addition to favoring plant growth and development, it also increases grain productivity. Grain productivity is directly related to these variables, as N promotes an increase in the number of ovules formed per row, favoring the production of photoassimilates, which reduces grain abortion, resulting in an increase in production components (Gazola et al., 2014).

Corn intercropped with forage species of the genus *Urochloa* does not interfere with production components and productivity when compared to single-crop corn (Garcia et al., 2013). Nitrogen fertilization in corn cultivation provides a 28% increase in grain production and a 37% increase in dry phytomass production, achieved at a dose of 240 kg ha^{-1} (Araújo et al., 2004). This occurs because N fertilization improves grain productivity, thus increasing crop productivity. For this reason, N supply is essential for profitable corn production, in addition to reducing losses to the environment when recommendations are made according to the crop's needs (Morris et al., 2018).

It is important to note that this study was designed to evaluate agronomic performance, not economic viability. While statistically significant yield differences were observed among treatments, the economic trade-offs—such as the cost of additional N fertilizer at 240 kg ha^{-1} versus 120 kg ha^{-1}, and the costs of establishing and managing forage species—were not assessed. Therefore, the results should be interpreted primarily as agronomic responses, and future research should include economic analyses to support decision-making by farmers in the Brazilian Cerrado.

It is important to emphasize that intercropping can be considered a viable alternative to increase sustainability (Garcia et al., 2013; Ceccon et al., 2013). In addition to providing greater economic profitability to the producer by optimizing forage production in the same area as the grain-producing crop, generating economic and environmental sustainability (Richetti, 2013), improving the physical characteristics of the soil, minimizing degradation and loss of nutrients. In this study, in both areas, there was an increase in grain productivity with the application of N doses, highlighting the C and CS intercropping modalities, reflecting higher productivity when compared to the other intercropping systems.

The response patterns between the areas with and without rock phosphate were broadly similar, as observed in the regression models and productivity trends (Figs. 3 and 5). However, because the areas with and without rock phosphate were established as independent experiments rather than randomized treatments within a single design, a formal statistical

comparison of the effect of rock phosphate could not be performed. Therefore, the observed similarity in responses should be interpreted descriptively, and no formal conclusion can be drawn regarding the effect of rock phosphate on grain productivity. Future studies should incorporate phosphate as a randomized factor within a combined experimental design to enable formal inference on its effects.

Materials and methods

Location of the experiments

Two experiments were conducted in the experimental field of the Federal University of Mato Grosso do Sul, Chapadão do Sul campus - MS, (18°46'13.4" S and 52°37'19.8" W and average altitude of 819 m), during the 2021/2022 growing season. The region's climate, according to the Köppen classification, is tropical humid (Aw), with a rainy season in summer and a dry season in winter, with average precipitation, temperature and relative humidity of 1,850 mm; 24.1 °C and 64.8%, respectively. The climatic data, referring to average maximum, average, and minimum temperatures and rainfall collected in the experimental area during the research, are presented in Fig. 6. During the experiment, the total accumulated rainfall was 1,385.5 mm, with good water distribution, meeting the crop's demand, which varies from 400 to 700 mm in its complete cycle (Andrade et al., 2006).

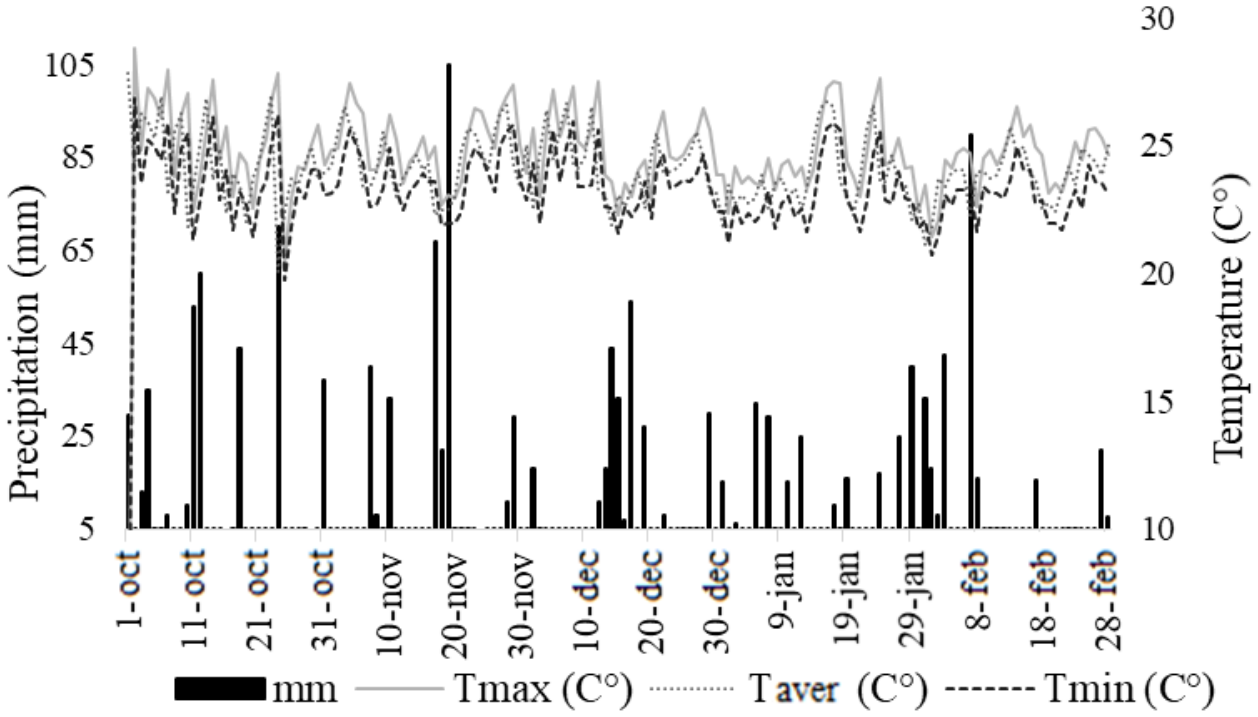


Fig. 6. Rainfall and average maximum, average, and minimum temperatures during the experiment.

The soil in the region, based on the Brazilian Soil Classification System (Embrapa, 2018), was classified as a Dystrophic Red Latosol with a clayey texture. Prior to setting up the experiment to characterize the experimental area, soil sampling was carried out at depths of 0.0-0.20 and 0.20-0.40 m (Table 5). Fertilization and liming recommendations were made based on soil analysis through calculation, and the liming requirements for corn sowing.

Table 5. Chemical and granulometric characteristics of the soil in the experimental area prior to the installation of the experiment in the 0.0-0.20 and 0.20-0.40 m layers, respectively.

Depth	pH	P	K	Ca	Mg	Al	H+Al	SB	t	T	V	m	Clay	Silt	Sand	MO
m	$CaCl_2$	mg dm^{-3}		cmolc dm^{-3}							%					
0.0–0.20	4.9	13.2	67	2.9	0.7	0.08	5.7	3.77	3.85	9.47	39.8	2.1	48.5	5.00	46.5	2.75
0.20–0.40	4.8	5.5	35	1.7	0.4	0.15	5.2	2.19	2.34	7.39	29.6	6.4	48.5	2.50	49.0	1.93

pH = hydrogen ion potential, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Al = aluminum, H+Al = hydrogen + aluminum, SB = sum of bases, t = effective cation exchange capacity, T = cation exchange capacity, V = base saturation, m = aluminum saturation, MO = organic matter.

Experimental design and conduct

For the implementation of the experiments, conventional soil preparation was carried out with plowing on 09/14/2021, followed by harrowing and immediately after liming, a second leveling harrowing was performed. On 09/16/2021, liming was carried out with the application of 2.13 ton ha^{-1} of limestone, with PRNT (Relative Total Neutralizing Power) of 90% composed of 31% calcium oxide (CaO) and 21% magnesium oxide (MgO), aiming to raise the base saturation to 60%. In

experiment 2, rock phosphate (P) was applied on 09/30/2021 with the application of 2 ton ha^{-1} and incorporated with a leveling harrow, using natural phosphate extracted in the municipality of Taipas - TO.

Corn was mechanically sown on 10/06/2021 using the X30R520VYH cultivar, with a distribution of 3.5 seeds per meter. Base fertilization was carried out together with sowing, with urea as the nitrogen (N) source and potassium chloride (KCl) as the potassium source, containing 11 kg of N; 160 kg of triple superphosphate and 56.4 kg of K_2O. *Stylosanthes* cv. Campo Grande was sown manually on 10/07/2021 at 3 kg ha^{-1}, while *Urochloa* brizantha cv. Piatã and *Urochloa* ruziziensis were sown 14 days after planting (DAP) of the crop, totaling 4 kg ha^{-1} in both areas.

The experiments were arranged in a split-plot design in randomized blocks, with four replications. The main plots consisted of six intercropping systems: single corn (C); corn + *Urochloa* ruziziensis (CR); corn + *Urochloa* brizantha cv. Piatã (CP); corn + *Stylosanthes* cv. Campo Grande (CS); corn + *Urochloa* brizantha cv. Piatã + *Stylosanthes* cv. Campo Grande (CPS); and corn + *Urochloa* ruziziensis + *Stylosanthes* cv. Campo Grande (CRS). The sub-plots consisted of four N doses: 0, 60, 120, and 240 kg ha^{-1} of N, respectively. Each plot consisted of 12 sowing rows with a spacing of 0.50 m and a length of 14 m, totaling an area of 84 m^2. Topdressing fertilization occurred at the V4 stage, with N doses applied in split plots and 40 kg ha^{-1} of K_2O, using KCl as a source, with application performed manually in both experiments.

It is important to note that the areas with and without rock phosphate were established as independent adjacent experiments, not as randomized treatments within a single combined design. Therefore, comparisons between the two areas are descriptive and do not allow formal statistical inference on the effect of rock phosphate. The results are presented separately for each area.

Phytosanitary management

The crop's phytosanitary management was carried out according to the technical recommendations for the crop. For weed control, 2 L ha^{-1} of Atrazine (500 g L^{-1}) was applied only in the single corn plots in post-emergence. Atrazine was not applied to the intercropped plots to avoid potential phytotoxicity to the forage species (*Urochloa* spp. and *Stylosanthes*), which are known to be sensitive to this herbicide. This differential weed management was adopted based on standard agronomic recommendations for corn-forage intercropping systems, where chemical weed control is often restricted to single-crop areas. However, it is important to acknowledge that this creates a confounding factor: the single corn plots benefited from chemical weed control, while the intercropped plots relied solely on the competitive suppression of weeds by the forage species (i.e., no chemical control was applied). Consequently, comparisons between single corn and intercropped treatments should be interpreted with caution, as the effects of intercropping on corn yield are confounded with differential weed management. Pest and disease control was carried out with the application of 400 ml ha^{-1} of Zeta-Cypermethrin (200 g L^{-1}); 0.4 L ha^{-1} of Picoxystrobin (200 g L^{-1}); and 1 L ha^{-1} of the mixture of beta-cyfluthrin (12.5 g L^{-1}) + imidacloprid (100 g L^{-1}), during the vegetative period of the crop.

Agronomic evaluations

At 130 DAP (days after planting), the morphological components of corn plants at the wet grain stage (R5) were evaluated with the following assessments:

a) plant height (PH, m), measured at physiological maturity in five randomly selected plants in the usable area of the plot, using a graduated ruler, taking as a reference the distance between the soil surface and the apex of the plant;

b) ear insertion height (EIH, m), measured in five plants in the plot using a graduated ruler from the soil surface to the insertion of the first ear in an ascending direction;

c) stem diameter (SD, mm), measured with a digital caliper at the internode below the ear, in five plants per plot.

The production components were:

d) number of rows per ear (NRE), performing a manual count of rows in five ears collected in the usable area;

e) number of grains per ear (NGE), obtained by counting grains in five rows and calculated by multiplying the number of rows by the number of ears and grains in the row;

f) grain yield (PROD, kg ha^{-1}), obtained by weighing the grains harvested in the useful area of the plot, corrected to 13% moisture.

Statistical analysis

The results for the morphological and production components were subjected to analysis of variance (ANOVA) following the split-plot model, where intercropping systems were considered the main plot factor and N rates the sub-plot factor. When significant values were found by the F-test, the means of the qualitative factors (intercropping systems) were compared using Tukey's test at 5% probability. For the quantitative factor (N doses), polynomial regression equations were fitted between the N doses and the dependent variables, seeking the model that best expressed this relationship. All analyses were performed using the Rbio software (Bhering, 2017).

Conclusion

Among the cropping systems evaluated, single corn (C) and corn + *Stylosanthes* (CS) showed the highest grain productivity at the maximum N dose of 240 kg ha^{-1}. However, these comparisons should be interpreted with caution, as single corn plots

received chemical weed control while intercropped plots did not. The yield advantage of single corn may be partially attributable to differential weed management rather than the absence of intercropping alone.

Increasing N doses positively influences morphological components up to a dose of 160 kg ha^{-1} of N, and production components up to a dose of 240 kg ha^{-1}.

The response patterns to nitrogen fertilization were similar between the areas with and without rock phosphate. However, as the areas were not combined in a single statistical model, a formal inference on the effect of rock phosphate could not be made. Further studies with randomized phosphate treatments are needed to evaluate its agronomic contribution.

Intercropping corn with *Stylosanthes* (CS) is recommended as the best option to combine high grain productivity under the conditions of this study, with N doses close to 240 kg ha^{-1} to maximize corn grain yield. However, further studies including forage biomass evaluation are needed to fully assess the sustainability benefits of these intercropping systems.

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