

Timing of phosphate fertilizer application in off-season corn intercropped with *Urochloa ruziziensis* under Cerrado conditions

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Abstract

The objective was to evaluate the efficiency of anticipating phosphate fertilization on the development and productivity of second-crop maize intercropped with *Urochloa ruziziensis* under Cerrado conditions. The experiment was carried out at the Cerrado Agricultural Research Institute (IPAC), located in the municipality of Rio Verde, Goiás. The experiment was set up in a randomized block design (RBD) in a 5x2 factorial scheme, with 10 treatments: 1) control; 2) conventional fertilization; 3) 100% fertilization in the soybean crop; 4) 100% fertilization in the maize crop; 5) 50% fertilization in the soybean crop and 50% in the maize crop. Each treatment was evaluated with and without consortium with *Urochloa ruziziensis*. The variables evaluated were plant height (PH) (cm); average stem diameter (ASD) (mm); shoot dry mass (SDM) (g plant⁻¹); yield (t ha⁻¹), thousand grain weight (TGW) (g), productivity (YLD) (t ha⁻¹), and shoot dry mass of *Urochloa ruziziensis* (SDM *Urochloa ruziziensis*) (t ha⁻¹). The intercropping and timing of phosphate fertilization did not affect the variables PH, ASD, TGW, and SDM of *Urochloa ruziziensis*. Conventional and 100% fertilization in the soybean was the most recommended for maize. The presence of *Urochloa ruziziensis* inhibited maize development under the conditions of this study.

Keywords: *Zea mays*, fertilization of systems, *Brachiaria*, intercropping.

Época de aplicação de fertilizante fosfatado em milho consorciado com *Urochloa ruziziensis* em condição de Cerrado

Resumo

Objetivou-se avaliar a eficiência da antecipação da adubação fosfatada no desenvolvimento e na produtividade do milho safrinha em consórcio com *Urochloa ruziziensis* em condição de Cerrado. O experimento foi conduzido na Fazenda Experimental do Instituto de Pesquisa Agrícola do Cerrado (IPAC), localizado no município de Rio Verde, Goiás. O experimento foi implantado em delineamento de blocos ao acaso (DBC) em esquema fatorial 5x2, com 10 tratamentos: 1) controle; 2) adubação convencional; 3) adubação 100% na cultura da soja; 4) adubação 100% na cultura do milho; 5) adubação 50% na cultura da soja e 50% na cultura do milho. Cada tratamento foi avaliado com e sem consórcio com *Urochloa ruziziensis*. As variáveis avaliadas foram: altura de plantas (AP) (cm); diâmetro médio do colmo (mm); massa seca da parte aérea (MSPA) (g planta⁻¹); produtividade (t ha⁻¹), peso de mil grãos (PMG) (g); produtividade (PROD) (t ha⁻¹); massa seca da parte aérea da *Urochloa ruziziensis* (MSPA *Urochloa ruziziensis*) (t ha⁻¹). O consórcio e a época de aplicação da adubação fosfatada não influenciaram as variáveis AP, DMC, PMG e MSPA *Urochloa ruziziensis*. A adubação convencional e 100% na cultura da soja foram as mais indicadas para a cultura do milho. A presença da *Urochloa ruziziensis* inibiu o desenvolvimento da cultura do milho nas condições em que este estudo foi conduzido.

Palavras-chave: *Zea mays*; adubação de sistemas; *Brachiaria*; cultivo consorciado.

1. Introduction

Brazil holds a prominent position in corn (*Zea mays*) production, ranking third in the world. Grain corn production in the 2024/2025 crop year, totaling the three harvests, was 138.448.2 million tons, an increase of 19.75% compared to the previous crop year (CONAB, 2026). Among the main strategies used by rural producers to achieve high productivity is fertilization, since it is essential that the plant receives nutrients in adequate quantities so that it can complete its cycle and express its full genetic potential. Therefore, the focus is on phosphate fertilization, which is indispensable in the establishment and maintenance of any agricultural system (Sousa et al., 2016; Li; Gao, 2024).

Phosphorus (P) is among the nutrients that limit grain production in Brazil, especially in the Cerrado region. In these regions, latosol soils, which have a clay fraction rich in oxides, tend to complex phosphorus, restricting agricultural production (Bruand; Reatto, 2022; Valderrama et al., 2011). Although plants need P in smaller quantities compared to other macronutrients, the recommended doses are generally high. This is because the efficiency of phosphorus utilization by the crop is low, due to the high adsorption capacity of P in the soil (Bhat et al., 2024; Han et al., 2022; Luo et al., 2022; Sodré-Filho et al., 2022). As a result, the availability of this nutrient to plants is reduced, and only 10 to 20% of the applied P ends up being absorbed by the plants (Concenço et al., 2012; Khan et al., 2023).

There are management strategies that can be adopted to modify the availability of P in the soil, such as intercropping annual crops with grasses, such as *Urochloa ruziziensis* (Souza et al., 2025; Souza et al., 2024). Sousa et al. (2010) observed that this tropical grass increases P recovery in cropping systems. The increase in P availability promoted by the grass is due to the presence of organic acids, resulting from the degradation of organic matter, which compete with orthophosphate for adsorption sites (Pavinato et al., 2009). Also, the enhanced mineralization of organic P from plant residues will increase the available P in the soil (Erich et al., 2002). Thus, the efficiency of *Urochloa ruziziensis* and *U. decumbens* in acquiring less soluble P in the soil and their nutrient cycling potential are important pieces of information for managing phosphate fertilization in soil with a high capacity for P fixation (Baptistella et al., 2022; Merlin et al., 2013).

However, intercropping between annual and forage crops promotes interspecific competition for resources such as water, light, and nutrients, which can result in decreased productivity for both (Carvalho et al., 2011; Toker et al., 2024). According to Fernando & Shrestha (2023), and Jakealitis et al. (2005), competitiveness can be managed through the adoption of cultivation practices such as: spatial arrangement of plants; reduction of row spacing, as in the case of corn, contributing to better use of solar radiation and faster shading of the soil. It is believed that, in wider row spacing, planting *Urochloa* in the corn row can increase competition between species, requiring the use of herbicides in sub-doses to reduce the forage growth rate until it is shaded by the corn.

Regarding competition for nutrients, especially P, the great challenge in grain production is determining the ideal time to carry out phosphate fertilization. The technique of anticipating phosphate fertilization, also known as systems fertilization, has been increasingly discussed and can be defined as anticipating the recommended dose, partially or totally, for the main summer crop, still in the preceding crop, and can be carried out by broadcasting or incorporating (Battisti et al., 2023; Francisco et al., 2007). There is still a lack of studies about the best time to apply P fertilization, that is, whether or not the anticipation of phosphate fertilization will have positive impacts on P dynamics in the soil, as well as on the nutrition and yield of crops used in rotation/succession, which will be essential for the success of this practice in sustainable agricultural production systems.

In view of the above, the objective of this work is to evaluate the efficiency of anticipating phosphate fertilization on the development and productivity of second-crop corn intercropped with *Urochloa ruziziensis* under Cerrado conditions.

2. Materials and Methods

2.1 Climatic, rainfall, and soil chemical conditions

The experiment was carried out at the experimental farm of the Cerrado Agricultural Research Institute (IPAC), located in the municipality of Rio Verde, Goiás, Brazil, with coordinates: South Latitude 17°44'21.99" and West Longitude 50°51'18.11" and an altitude of 740 m. The experimental area had previously been cultivated with soybeans, and this was the second consecutive year of corn cultivation. The municipality is in the Cerrado biome and has an average altitude of 748 m. The region's climate, according to the Köppen classification, is type Aw (Sobrinho et al., 2020). Figure 1 shows the climatological data for the period of the experiment.

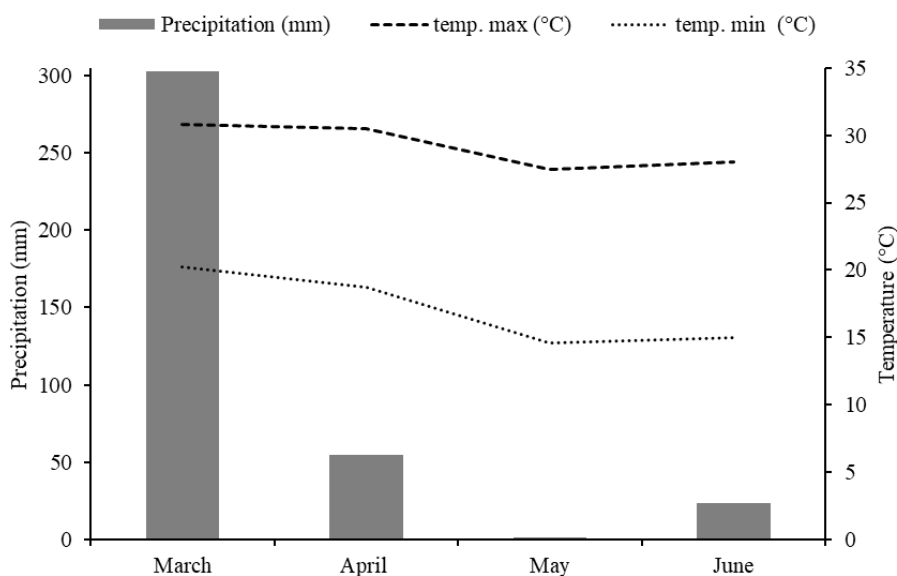


Figure 1. Climatological data for the municipality of Rio Verde-GO during the experimental period. Collected from INMET, 2022.

To make the fertilization recommendation for crop establishment, soil sampling was carried out in two layers (00-20 and 20-40 cm) to characterize the chemical and textural properties (Table 1). The soil is classified as dystrophic Red Latosol. According to soil analysis data, the P levels in the soil solution were found to be classified as very low (Venegas et al., 1999).

Table 1. Chemical and textural attributes of the soil in the 00-20 and 20-40 cm depth layers before the implementation of the experiment to evaluate the timing of phosphate fertilizer application in off-season corn intercropped with *Urochloa ruziziensis* under Cerrado conditions.

Layer	Ca	Mg	Al	H+Al	K
(cm)	cmol _c dm ⁻³				mg dm ⁻³
00-20	1,9	1,1	0,07	5,7	129,5
20-40	1,5	0,8	0,04	5,4	78,0
Layer	P (Mel)	Mn	S	B	Zn
(cm)	mg dm ⁻³				
00-20	3,3	51,7	5,45	0,24	6,0
20-40	0,9	35,3	7,4	0,21	1,9
Layer	Cu	Fe	CTC	m	V
(cm)	mgdm ⁻³		cmol _c dm ⁻³	%	
00-20	5,0	26,0	9,2	2,15	37,6
20-40	5,8	32,0	7,2	1,6	34,4
Layer	M.O.	Argila	Areia	Silte	pH
(cm)	g dm ⁻³				CaCl ₂
00-20	37,1	525,0	287,5	187,5	4,8
20-40	27,6	575,0	275,0	150,0	5,0

Note: Ca: calcium; Mg: magnesium; H+Al: potential acidity; K: potassium; P (Mel): phosphorus in Mehlich; Mn: manganese; S: sulfur; B: boron; Zn: zinc; Cu: copper; Fe: iron; CTC: cation exchange capacity; m: aluminum

saturation; V: base saturation; M.O: organic matter; pH: hydrogen ion potential. Source: Authors, 2026.

2.2 Soil correction

Soil correction was carried out 17 days before soybean planting in the entire area at a dose of 5 t ha⁻¹ using dolomitic filler limestone with a PRNT of 90%, incorporated into the 00-20 cm layers, to correct acidity and increase base saturation to 60% (Souza; Lobato, 2004). Corrections of potassium and boron levels were carried out on the day of soybean planting, November 4, 2021. 40 kg ha⁻¹ of K₂O was applied in the planting furrow using potassium chloride (KCl) as the source. To correct low boron (B) levels, 1 kg ha⁻¹ of B was broadcast, using boric acid as the source.

2.3 Treatments, experiment implementation, phytosanitary management

The experiment was implemented in a randomized block design (RBD) in a 5x2 factorial scheme, with 10 treatments, four replications, totaling 40 experimental units. Each experimental unit consisted of five rows, spaced 0.50 m apart, 5 m long, and 2.5 m wide, forming a 12.5 m² rectangle. The treatments consisted of different phosphate fertilization strategies in the soybean-corn system: control (without P₂O₅); conventional fertilization (120 kg ha⁻¹ of P₂O₅ in soybean and 80 kg ha⁻¹ in corn); total application in soybean (200 kg ha⁻¹ of P₂O₅); total application in corn (200 kg ha⁻¹ of P₂O₅); and fractional application between crops (100 kg ha⁻¹ of P₂O₅ in soybeans and 100 kg ha⁻¹ in corn). The phosphorus source used was triple superphosphate, applied in the planting furrow. These treatments were evaluated in the presence and absence of intercropping with *U. ruziziensis*.

The corn and *Urochloa ruziziensis* planting was carried out after the soybean harvest on March 3, 2022. The corn was sown mechanically, with the distribution of three seeds per meter, with a row spacing of 0.50 m, using the Morgan® MG 540 PWU hybrid. The *U. ruziziensis* used was from the company Agrosol®, and was sown manually broadcast at a rate of 8 kg ha⁻¹ within each plot.

On March 28, 2022, a post-emergent herbicide application was carried out over the entire area to control weeds, using 5 L ha⁻¹ of atrazine + 0.4 L ha⁻¹ of mesotrione. To control fall armyworm (*Spodoptera frugiperda*), green stink bug (*Diceraeus melacanthus*), and thrips (*Frankliniella williamsi*), 0.3 L ha⁻¹ of Engeo Pleno® (Thiamethoxam + Lambda-cyhalothrin) was applied. Also to control fall armyworm (*Spodoptera frugiperda*), the contact and ingestion insecticide Avatar® (Indoxacarb) was applied at a dose of 0.7 L ha⁻¹.

On March 30th, topdressing fertilization was carried out in all plots, using the 20-00-20 formulation at the recommended dose of 50 kg ha⁻¹ of nitrogen (N) and 50 kg ha⁻¹ of K₂O. Fourteen days after emergence (DAE), when the corn was at the V3 phenological stage, on April 7, 2022, the plant stand assessment was carried out according to the recommendation for the corn variety used, which is 60.000 plants ha⁻¹, and for *U. ruziziensis*, which is 75 plants plot⁻¹.

2.4 Variables evaluated

The variables evaluated were: plant height (PH) (cm); average stem diameter (ASD) (mm); shoot dry mass (SDM) (g plant⁻¹); productivity (PROD) (t ha⁻¹); thousand grain weight (TGW) (g); and shoot dry mass of *U. ruziziensis* (t ha⁻¹) (SDM *U. ruziziensis*). PH was measured at 63 DAE, when the corn crop was in phenological stage R1, using a measuring tape on three plants from each plot, selected at random, and evaluated from the first internode of the plant to the insertion of the last leaf. The average stem diameter (ASD) was measured on the same plants using a digital caliper.

SDM was also determined at 63 DAE, when the corn crop was in phenological stage R1, with three plants per plot collected from the center of each plot. These plants were cut at the stem end, stored in paper bags, and subsequently dried in a forced-air oven at 65 °C for 72 h. To determine the TGW and PROD, a 6 m² area was harvested from the center of each plot on June 29, 2022, at 115 DAE. After harvesting, the material was processed (threshing/cleaning of both manually), stored in paper bags, and placed in a forced-air oven at 65 °C for 72 h to standardize moisture. After this, the grains were weighed using a precision digital scale to estimate PROD. To determine the GMP, 100 grains per plot were counted, which were subsequently weighed to estimate the TWG. After harvesting the grains, in the plots where the corn crop was intercropped with the grass, *U. ruziziensis* was collected to determine the shoot dry mass (MSPA *U. ruziziensis*), using a 1 m² metal square placed in the center of each plot. In the demarcated areas, all plants were cut close to the soil surface, stored in

paperbags, and subsequently dried in a forced-air oven at 65 °C for 72 h.

2.5 Statistical analysis

The data obtained were subjected to the *Shapiro-Wilk* normality test at a 5% significance level, confirming the normal distribution of the variables. Analysis of variance was employed, and when significant, *Tukey's* mean comparison test was used at a 5% significance level to evaluate the effect of anticipating phosphate fertilization in intercropping systems or not on all variables analyzed, followed by a comparison of means using the SISVAR statistical software (Ferreira, 2019).

3. Results

3.1 Plant height (PH)

There was no significant interaction between the timing of phosphate fertilization application and intercropping with *U. ruziziensis* for the corn PH variable, nor was there an isolated effect of these factors (Table 2). The observed PH (179.4 cm) was lower than that described for the MG 540 PWU hybrid (235 cm) (Agranda, 2022).

Table 2. Plant height (PH) (cm) of corn subjected to different application times of phosphate fertilization, grown in consortium with *Urochloa ruziziensis*.

	Time of application of P ₂ O ₅				
	Control	Conventional	100% Corn	100% Soybean	50% Soybean 50% Corn
Without <i>Urochloa</i>	170.8	180.6	178.4	183.7	183.4
With <i>Urochloa</i>	177.6	185.1	171.5	182.0	181.4

Note: *control; ** conventional fertilization (120 kg ha⁻¹ of P₂O₅ in soybean and 80 kg ha⁻¹ of P₂O₅ in corn); ***100% fertilization in soybean (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the soybean); ****100% fertilization in corn (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the corn); *****50% fertilization in soybean and 50% in corn (100 kg ha⁻¹ of P₂O₅ in soybean and 100 kg ha⁻¹ of P₂O₅ in corn). *Tukey* test ($p < 0.05$). Average of 4 repetitions. CV = 4.2%. Source: Authors, 2026.

3.2 Average stem diameter (ASD)

For the ASD variable of corn intercropped with *Urochloa ruziziensis*, no significant effect of the phosphate fertilization application times was observed (Table 3). In the present study, the average ASD observed was 16.1 mm. This value is lower than those reported in other studies available in the literature, in which ASD values ranging between 20 and 25 mm were observed (Costa et al. 2012; Godinho; Gasparotto, 2021).

Table 3. Average stem diameter (ASD) (mm) of corn plants subjected to different times of phosphate fertilization application when grown in consortium with *Urochloa ruziziensis*.

	Time of application of P ₂ O ₅				
	Control	Conventional	100% Corn	100% Soybean	50% Soybean 50% Corn
Without <i>Urochloa</i>	16.3	16.0	16.7	15.8	15.7
With <i>Urochloa</i>	17.1	15.8	15.0	16.7	16.5

Note: *control; ** conventional fertilization (120 kg ha⁻¹ of P₂O₅ in soybean and 80 kg ha⁻¹ of P₂O₅ in corn); ***100% fertilization in soybean (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the soybean); ****100% fertilization in corn (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the corn); *****50% fertilization in soybean and 50% in corn (100 kg ha⁻¹ of P₂O₅ in soybean and 100 kg ha⁻¹ of P₂O₅ in corn). *Tukey* test ($p < 0.05$). Average of 4 repetitions. CV= 8,4%.

Source: Authors, 2026.

3.3 Shoot dry mass (SDM)

For the SDM variable, an interaction was observed between the timing of phosphate fertilization application and the corn *U. ruziziensis* intercropping (Figure 2). In the absence of the forage crop, the treatments with conventional fertilization and with 100% phosphate fertilization applied to the soybean crop showed higher SDM values compared to the other treatments, with averages of 14.95 g plant⁻¹ and 16.25 g plant⁻¹, respectively. On the other hand, in the presence of *Urochloa ruziziensis*, conventional fertilization differed from the control treatment (without P₂O₅ application) and the split application strategy (50% corn and 50% soybean), observed values of 15.98 g plant⁻¹, while the control and the 50% corn and 50% soybean treatment presented 15.88 g plant⁻¹ and 15.50 g plant⁻¹, respectively.

Regarding the application times, higher SDM values were observed in the treatments with early conventional fertilization and application of 100% of the fertilization in soybeans, when corn was cultivated without the presence of *U. ruziziensis*, with values of 14.95 g plant⁻¹ and 17.30 g plant⁻¹, respectively. For the control treatments, 100% corn, and 50% corn and 50% soybeans, no influence of the presence or absence of *U. ruziziensis* on the accumulation of SDM by corn plants was observed (Figure 2).

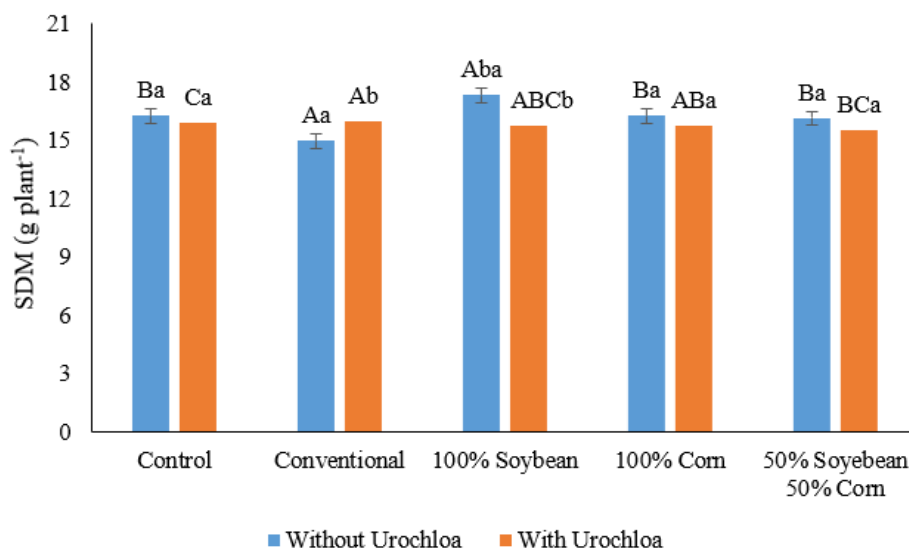


Figure 2. Shoot dry mass (SDM) (g plant⁻¹) of maize plants subjected to different application times of phosphate fertilization, grown in consortium with *Urochloa ruziziensis*. Tukey test ($p < 0.05$). Means followed by uppercase letters indicate the differences between fertilization times with or without *Urochloa ruziziensis*, while lowercase letters indicate differences between the presence or absence of *Urochloa ruziziensis*. Mean of 4 repetitions. CV= 6.7%. Standard error: 4.5%. Source: Authors, 2026.

3.4 Productivity (PROD)

For the variable PROD, no significant interaction was observed between the application times of phosphate fertilization and the intercropping with *U. ruziziensis*. However, when considering the factors in isolation, a significant effect was observed for both the application times and the intercropping. Regardless of the treatment, the observed PROD was lower than that reported in the literature, due to the irregular distribution and low volume of rainfall during the experimental period. Regarding the application times, it was observed that only the management with conventional fertilization differed from the control treatment (without P₂O₅ application). Except for the control, the other application strategies showed similar averages, with an average productivity of 2338.25 kg ha⁻¹ (Figure 3).

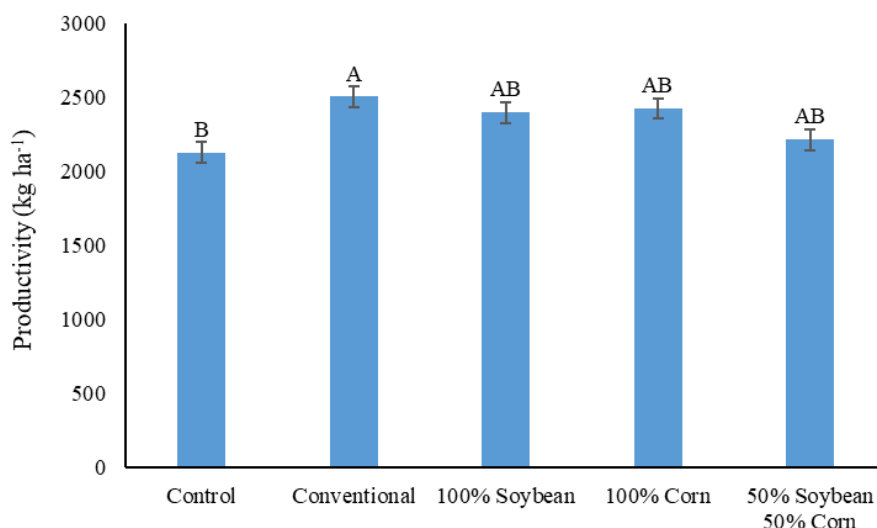


Figure 3. Productivity (PROD) (kg ha⁻¹) of corn plants subjected to different application times of phosphate fertilization, grown in consortium with *Urochloa ruziziensis*. Means followed by the same letter do not differ from each other. Tukey test ($p < 0.05$). Mean of 8 observations. CV = 8.9%. Standard error:46.6%. Source: Authors, 2026.

When evaluating the intercropping of corn and *Urochloa ruziziensis*, a statistically significant difference was observed for the PROD variable. Corn plants grown without *Urochloa ruziziensis* showed higher productivity, reaching 2556 kg ha⁻¹, compared to plants grown in intercropping with the forage grass, which showed a productivity of 2118 kg ha⁻¹ (Figure 4).

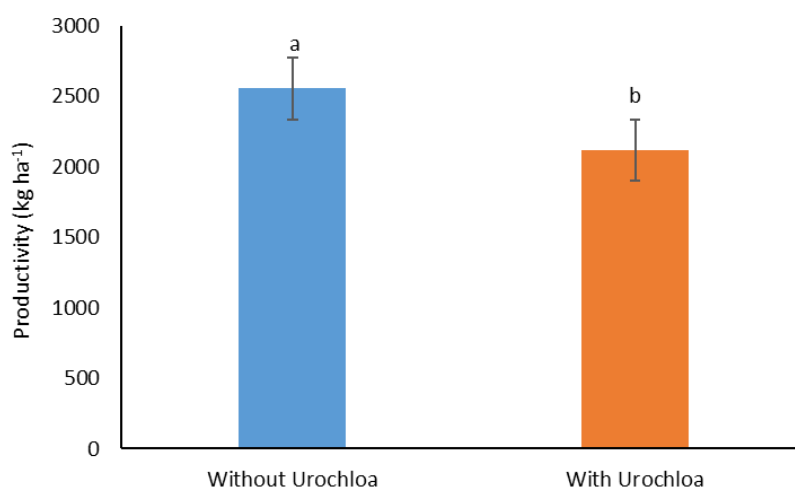


Figure 4. Productivity (PROD) (kg ha⁻¹) of corn plants subjected to intercropping or not with *Urochloa ruziziensis* under Cerrado conditions. Means followed by the same letter do not differ from each other. Tukey test ($p < 0.05$). Mean of 20 observations. CV = 8.9%. Standard error:46.6%. Source: Authors, 2026.

3.5 Thousand grain weight (TGW)

For the variable TGW, the results did not indicate a significant interaction between the timing of phosphate fertilization application and intercropping with *U. ruziziensis* (Table 4). Furthermore, when analyzing the factors in isolation, no statistically significant differences were observed for TGW in function of fertilization application timing or the forage presence in the system.

Table 4. Thousand-grain weight (TGW) (g) of corn plants subjected to different application times of phosphate fertilization, grown in consortium with *Urochloa ruziziensis*.

	Time of application of P ₂ O ₅				
	Control	Conventional	100% Corn	100% Soybean	50% Soybean 50% Corn
Without <i>Urochloa</i>	285.0	341.2	355.5	294.0	276.0
With <i>Urochloa</i>	257.2	310.7	289.5	304.7	267.2

Note: *control; ** conventional fertilization (120 kg ha⁻¹ of P₂O₅ in soybean and 80 kg ha⁻¹ of P₂O₅ in corn); *** 100% fertilization in soybean (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the soybean); **** 100% fertilization in corn (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the corn); ***** 50% fertilization in soybean and 50% in corn (100 kg ha⁻¹ of P₂O₅ in soybean and 100 kg ha⁻¹ of P₂O₅ in corn). Tukey test ($p < 0.05$). Average of 4 repetitions. CV= 5,4%. Source: Authors, 2026.

3.6 Shoot dry mass of *Urochloa ruziziensis* (SDM *U. ruziziensis*)

For the variable SDM *U. ruziziensis*, the results did not indicate a significant interaction between the timing of phosphate fertilization application and intercropping with the forage (Table 5). Similarly, when the factors were analyzed in isolation, no statistically significant differences were found for SDM *U. ruziziensis*. In the present study, an average value of 3.1 t ha⁻¹ was observed for this variable. According to the recommendations of Agrosol®, the company responsible for the *U. ruziziensis* used during the experimental period, the expected production is approximately 10 t ha⁻¹ year⁻¹ (Agrosol, 2024), which corresponds to about 3.3 t ha⁻¹ in the evaluated period. Thus, the values obtained in this study were close to the levels indicated by the company.

Table 5. Shoot dry mass of *Urochloa ruziziensis* (SDM *U. ruziziensis*) (t ha⁻¹) subjected to different times of phosphate fertilization application.

	Time of application of P ₂ O ₅				
	Control	Conventional	100% Corn	100% Soybean	50% Soybean 50% Corn
Without <i>Urochloa</i>	0.0*	0.0*	0.0*	0.0*	0.0*
With <i>Urochloa</i>	2.9	3.2	3.2	3.0	3.3

Note: *control; ** conventional fertilization (120 kg ha⁻¹ of P₂O₅ in soybean and 80 kg ha⁻¹ of P₂O₅ in corn); *** 100% fertilization in soybean (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the soybean); **** 100% fertilization in corn (200 kg ha⁻¹ of P₂O₅, the sum of what would be done in soybean and corn was applied to the corn); ***** 50% fertilization in soybean and 50% in corn (100 kg ha⁻¹ of P₂O₅ in soybean and 100 kg ha⁻¹ of P₂O₅ in corn). Tukey test ($p < 0.05$). Average of 4 repetitions. CV= 7,4%. Source: Authors, 2026.

4. Discussion

The lack of statistical significance for the interaction between the timing of phosphate fertilization application and intercropping with *U. ruziziensis*, as well as for the isolated effects of these factors on PH, can be explained by water limitation throughout the crop cycle. Accumulated rainfall was 382 mm, a value lower than the water demand of corn, estimated at approximately 600 mm (Magalhães; Durães, 2008). Under these conditions, water deficit possibly acted as the predominant limiting factor for vegetative growth, restricting the potential for plant height expression and, consequently, minimizing the effects of the evaluated management practices. Water deficit significantly alters the P dynamics in the soil, reducing its mobility and availability in the soil solution, since the transport of this nutrient occurs predominantly by diffusion.

Decreased soil moisture compromises the diffusive flow of P to the rhizosphere, reducing its absorption by plants. Consequently, essential physiological processes related to energy production, cell expansion, and plant growth

are limited, resulting in less biomass accumulation and reduced PH. Recent studies demonstrate that water stress conditions reduce P availability, restricting root growth and significantly decreasing the development of crops such as maize, highlighting the strong interaction between water availability and phosphate nutrition in the agronomic performance of plants (Loftus et al., 2025; Mahmood et al., 2025; Santoro et al., 2024). Similar results were reported by Makino et al. (2019), who, when studying the intercropping of corn with *U. brizantha* cv. BRS Paiguás also did not observe statistical differences for the PH variable, indicating that the presence of the grass did not interfere with the corn height growth.

However, Quaresma et al. (2013), evaluating the intercropping of corn and *U. brizantha*, found a significant difference for PH when a dose of 150 kg ha⁻¹ of P₂O₅ was applied, using NPK 04-30-16 fertilizer as a source. As discussed by the authors, this result is related to the function of phosphorus in plant metabolism, since this nutrient participates in fundamental processes such as respiration and photosynthesis. Adequate P supply favors the synthesis of nucleic acids and proteins, promoting greater plant height development. In intercropping systems, this characteristic is considered relevant because it can directly influence harvesting operations. Smaller plants can compromise the efficiency of mechanized harvesting, mainly due to the possible obstruction of the cutting platform caused by the presence of *U. brizantha*.

Regarding the timing of phosphate fertilization application, Silva et al. (2021) evaluated the anticipation of fertilization in the development of corn in an area managed for 37 years under a no-till system and found no statistical differences for PH. According to the authors, this behavior may be associated with both the genetic material used and the history of soil management. Prolonged maintenance of the no-till system favors the accumulation of organic matter, increasing the cation exchange capacity (CEC) of the soil and contributing to greater availability of nutrients, especially phosphorus, which can favor crop development.

These results, lower than those found in the literature for the ASD variable, can be explained by the water deficit during the experimental period, directly affecting the P dynamics in the soil. Therefore, a reduction in ASD is observed, since stem growth depends on adequate energy supply and maintenance of cell turgor. Furthermore, water deficiency promotes anatomical changes in the vascular tissues of maize, reducing stem thickening and compromising its structural resistance. Recent studies demonstrate that the simultaneous limitation of water and P intensifies the reduction in vegetative growth and directly affects morphological characteristics of the stem, including its diameter, due to less tissue formation and reduced accumulation of structural biomass (Liu et al., 2024; Mahmood et al., 2025).

Makino et al. (2019), when evaluating the intercropping of corn and *U. brizantha* cv. BRS Paiguás found a statistically significant difference for the ASD variable, observing that corn plants grown in intercropping had thinner stalks. According to the authors, this result may be related to the interspecific competition established between the crop and the grass, which can delay the normal development of the corn and result in a smaller stalk thickness. As highlighted by Kappes et al. (2011), ASD has a direct relationship with productivity, since stalks with a larger diameter have a greater capacity to store photoassimilates, which subsequently contribute to grain filling.

Regarding the timing of phosphate fertilization application, Silva et al. (2021), when evaluating the anticipation of fertilization in the development of corn in an area managed for 37 years under a no-till system (without soil disturbance), observed higher ASD values when fertilization was carried out 30 days before planting, using NPK 08-28-16 fertilizer as the source, at a dose corresponding to 100 kg ha⁻¹ of P₂O₅. According to the authors, this result may be associated with the greater spacing between plants adopted in the experiment (45 cm), which reduced interspecific competition for resources such as water, light, and nutrients, favoring the vegetative development of the crop.

The higher SDM values observed in treatments with conventional fertilization and with 100% of the P₂O₅ dose applied to soybeans can be explained by the greater availability and better P synchronization in the soil-plant system, which favors its absorption by corn during phases of higher demand. P plays a central role in energy metabolism and cell expansion, so its adequate supply is directly related to the accumulation of shoot biomass. Furthermore, these results highlight the importance of P in the initial establishment of the crop, especially in the early stages of root system development, when absorption efficiency is still limited (Elhaissofi et al., 2022; Khan et al., 2023; Zhanget al., 2016; Yadav et al., 2021).

Thus, a deficiency of this nutrient in early stages can restrict crop growth and compromise dry matter production throughout the cycle (Wen et al., 2017; Liu, 2021). On the other hand, the reduction in SDM in treatments with lower P input or split application may be associated with nutritional limitations during critical stages of maize growth. Furthermore, the presence of *U. ruziziensis* can intensify competition for resources, especially under

conditions of lower P availability, further reducing maize growth. In intercropping systems, this competition can limit the efficiency of P use and result in lower SDM accumulation (Brooker et al., 2015; Li et al., 2018).

Riferte (2021), when evaluating the effects of early fertilization in maize cultivation, also found that SDM was not influenced by this practice. According to the author, this behavior may be related to the preceding crop used in the experimental area, black oats, recognized for their ability to recycle phosphorus, a characteristic like that observed in *U. ruziziensis*. In this context, the mineralization of black oat crop residues may have contributed to making adequate amounts of nutrients available to the maize, favoring the SDM accumulation. Similar results were reported by Silva et al. (2021), who, when evaluating the early application of phosphate fertilization in maize cultivation, also observed no differences in SDM when the application was carried out 15 or 30 days before sowing.

The significant effect observed for both application times and intercropping with *U. ruziziensis* on the PROD variable indicates the possibility of applying 100% of the phosphate fertilizer to the soybean crop, aiming to reduce the need for supplementation of this nutrient at the beginning of corn development. This strategy has the potential to optimize fertilization management, contributing to the reduction of operational costs associated with fertilization, especially those related to the use of labor and machinery. However, Silva et al. (2021), when evaluating the anticipation of phosphate fertilization for maize cultivation, did not find differences in yield when the fertilizer was applied broadcast 30 days before sowing, compared to application in the planting furrow. According to the authors, this behavior may be related to the shorter period of P exposure in the soil, which reduces losses due to the adsorption of this nutrient. Similar results were reported by Peron et al. (2019), who, when evaluating the effect of anticipating fertilization in maize cultivation using the fertilizer formulated 09-28-17 + 0.5 Zn at a dose of 500 kg ha⁻¹, also observed that productivity was not influenced by the early application of fertilization.

In addition to the water deficit, the presence of *U. ruziziensis* negatively influenced corn PROD, which may be related to possible allelopathic effects or competition between species for resources that are essential to plant development, such as water, light, and nutrients. Studies conducted by Arf et al. (2018) indicate that intercropping can result in reduced corn PROD under certain conditions. The discrepancies observed in the literature regarding the effects of intercropping between corn and grasses, such as *U. ruziziensis*, are mainly associated with variations in edaphoclimatic conditions, the management adopted, and the cultivation practices used.

The emergence dynamics of the species can also influence the performance of the intercropping system. In general, *U. ruziziensis* seeds exhibit slower emergence, which provides an initial advantage to corn during the early stages of development, especially between V3 and V4, mainly in systems with simultaneous sowing (Canisares et al., 2021; Kumar et al., 2015). Furthermore, climate plays a determining role in forage growth, with tropical conditions tending to favor the development of *Urochloa*, especially due to temperatures that are more suitable for the species growth at the end of the agricultural season (Baptistella et al., 2020; Uzayisenga et al., 2021).

Another relevant factor is the greater tolerance of *U. ruziziensis* to periods of water deficit, attributed to its vigorous root system, which can confer a competitive advantage over maize in environments with irregular rainfall distribution (Cheruiyot et al., 2018; Silva et al., 2022; Pizarro et al., 2013). Under these conditions, intercropping systems tend to exhibit lower corn grain productivity and higher grass biomass production, a characteristic that may be interesting for management strategies aimed at maintaining soil cover or forage production in integrated agricultural systems (Bybee-Finley; Ryan, 2018; Glaze-Corcoran et al., 2020; Silva et al., 2022).

The lack of statistical significance for the TGW variable can be explained by the fact that this is one of the production components least influenced by management practices, being strongly determined by genotype, nutrient availability, and climatic conditions during the grain filling period. Therefore, satisfactory values for this variable are directly related to adequate absorption and assimilation of nutrients by plants, especially nitrogen (Ohland et al., 2005). Corroborating with Dickmann et al. (2022), who, when evaluating the effect of phosphate fertilization on summer corn grown in consortium with *U. brizantha* cv. Marandu also found no statistical difference for the TGW variable.

On the other hand, Quaresma et al. (2013), when evaluating the intercropping of maize and *Urochloa brizantha*, observed higher values of phosphorus production TGW in intercropped plants when using the recommendation of 150 kg ha⁻¹ of P₂O₅. According to the authors, this result may be related to the high capacity of *Urochloa* grasses to absorb, recycle, and make P available in the system through straw decomposition and intense root activity. In this context, *U. ruziziensis* may act in maintaining the P dynamics in the soil, contributing to greater efficiency in the use of the nutrient by maize without compromising grain filling, which helps to explain the absence of negative effects on TWG observed in the present study.

Regarding the timing of phosphate fertilization application, Silva et al. (2021), when evaluating the anticipation of fertilization in corn cultivation, using the 08-28-16 formulated fertilizer at a dose of 350 kg ha⁻¹ applied 30 days before planting, also did not observe significant differences for TGW. According to the authors, this behavior indicates that this productive component shows low sensitivity to the temporal management of P, especially when the nutrient availability in the soil is adequate, which can be explained by the high efficiency of corn in maintaining grain filling even under different fertilization strategies.

The lack of statistical significance for the interaction between the timing of phosphate fertilization application and intercropping with *U. ruziziensis*, as well as for the isolated effects of these factors on the SDM *U. ruziziensis* variable, can be explained by the sampling timing, which occurred after the corn harvest. During this period, the drying and senescence process of the crop leaves began, favoring greater light incidence in the area and, consequently, greater accumulation of dry matter by *U. ruziziensis*.

Although the present study did not include a formal economic analysis, the agronomic results suggest that applying 100% of the phosphate fertilizer during soybean establishment may provide important operational and economic advantages over conventional fertilization. Since grain yield obtained with early phosphorus application was statistically similar to that observed under conventional fertilization, concentrating phosphorus fertilization in the soybean crop has the potential to reduce production costs while maintaining maize productivity.

From an operational perspective, anticipating phosphate fertilization may eliminate one fertilizer application during maize sowing, reducing machinery use, fuel consumption, labor demand, and operational time. Such reductions are particularly relevant in large-scale production systems, where the optimization of field operations directly affects production efficiency and profitability. Recent studies have emphasized that improving phosphorus use efficiency should be accompanied by economic optimization, since excessive fertilizer application increases production costs without proportional yield gains (Luo et al., 2024; Singh et al., 2023).

Furthermore, efficient phosphorus management has become increasingly important because phosphate fertilizers represent one of the most expensive inputs in grain production systems. Sustainable phosphorus stewardship aims not only to maximize crop productivity but also to improve resource-use efficiency, reduce environmental impacts, and increase farm profitability (Walsh et al., 2023).

Although the present results indicate that early phosphate fertilization is agronomically feasible, a complete economic assessment is still necessary before recommending its large-scale adoption. Future studies should include production cost analyses based on fertilizer price, machinery operation costs, fuel consumption, labor requirements, gross revenue, net profit, benefit-cost ratio, return on investment, and production cost per kilogram of grain. Economic indicators of this nature have long been recognized as essential for determining the real viability of phosphorus fertilization strategies in maize production systems (Prado; Fernandes, 2001).

5. Conclusions

Conventional fertilization and the application of 100% of the phosphorus fertilizer during soybean establishment proved to be viable strategies without compromising maize productivity under the conditions of this study. The presence of *Urochloa ruziziensis* reduced maize development and grain yield. Considering that early phosphorus application may reduce field operations during maize establishment, future studies should incorporate comprehensive economic analyses to determine the cost-effectiveness and profitability of this management strategy under different production systems.

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7. Authors' Contributions

Werleis Alves Diniz: conceptualization, investigation, methodology, data curation, formal analysis, visualization, writing – original draft. *José Milton Alves*: supervision, methodology, validation, formal analysis, writing – review & editing. *Thais Gonçalves Veloso Gouveia*: conceptualization, project administration, resources, funding acquisition, supervision, validation, writing – review & editing.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

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