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RESEARCH

Soybean-Maize Off-season Double Cropping System as Affected by Maize Intercropping with Ruzigrass and Nitrogen Rate

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Abstract

The soybean-maize off-season double cropping is the main grain production system in Brazil. Maize off-season is most commonly grown sole and without topdressing nitrogen (N) fertilization. When used, N fertilizer is commonly applied at rates lower than 100 kg ha^{-1}. This study aimed to assess the effects of N topdressing rates (0, 60, 120, and 180 kg ha^{-1}) applied to maize off-season grown sole or intercropped with *Urochloa ruziziensis* (Ruzigrass) on maize and soybean grain yields, straw production, partial N balance, and soybean oil and protein contents. The experiment was conducted in Londrina, Paraná, Brazil, in the 2020/2021 and 2021/2022 growing seasons. At N rates above 120 kg ha^{-1}, intercropping with ruzigrass did not affect maize yield. Despite the low N use efficiency of maize off-season, a neutral N balance (i.e. equal to 0) was achieved with 130 kg N ha^{-1} in 2020/2021. Considering the average of the two seasons and doses of N, intercropping of maize increased by 14.4% the straw production and by 8.34% the subsequent soybean yield. The N topdressing of sole maize led to an increase in the yield of soybean grown in succession (1.63 and 3.52 kg ha^{-1} of grains for every 1 kg ha^{-1} of N in 2020/2021 and 2021/2022, respectively). An increase in the N rate applied to maize increased soybean oil content (0.039 g kg^{-1} in 2020/2021 and 0.044 g kg^{-1} in 2021/2022 for each 1 kg N ha^{-1}) and decreased protein content (-0.085 g kg^{-1} in 2020/2021 and -0.088 g kg^{-1} in 2021/2022 for each 1 kg N ha^{-1}) in soybean grains.

Keywords Soybean and maize yield · Straw production · Partial nitrogen balance · Oil and protein content in soybean grains

Introduction

Brazil is currently the world largest producer and exporter of soybean. In 2021/2022, the total agricultural area cultivated with this oilseed reached 41.5 million hectares, with an average yield of 3,026 kg ha^{-1}, representing the main crop of the national agribusiness sector (CONAB, 2023). Maize off-season, sown from January to March, is commonly grown in succession to soybean (Zuffo et al., 2022). In the 2021/2022, maize off-season was grown on 16.4 million hectares, reaching a yield of 5,227 kg ha^{-1}. Soybean and maize off-season yields had a mean annual growth of 43 and 145 kg ha^{-1}, respectively, in the last three decades in Brazil (CONAB, 2023), mainly as a result of genetic improvement and advances in management technologies.

Soybean-maize off-season double cropping system has several advantages, such as intensification of land use, inputs, and labor. However, its continued use also presents some problems: it promotes soil compaction in no-tillage

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system; provides low soil cover from June to October, between maize harvest and soybean sowing; and facilitates infestation by weeds and plant-parasitic nematodes (Garbelini et al., 2020, 2022). In this production system, intercropping of maize off-season and tropical forages is a valuable strategy to improve ground cover, produce grazing pasture, improve soil quality, increase straw production, reduce water erosion, and minimize weed infestation (Borghi et al., 2013; Crusciol et al., 2015; Mateus et al., 2020). A species widely used as a maize intercrop in Brazil is *Urochloa ruziziensis* (R. Germ. & C. M. Evrard), commonly known as ruzigrass (Batista et al., 2019; Sapucay et al., 2020; Zuffo et al., 2022). However, the proper management of maize–tropical forage systems requires some technical adjustments to minimize competition for water, light, and nutrients between species (Pariz et al., 2017). The competition for nitrogen (N) can limit maize yield (Borghi et al., 2014). Therefore, it is necessary to better understand the responses of maize off-season intercropped with tropical forages to different N rates and the effects on soybean in succession under no-tillage system.

Cereals usually present low N use efficiency (about 33% on average) (Raun & Johnson, 1999). In Brazil, maize off-season is generally grown under water deficit conditions, particularly during the grain filling period. This condition may significantly reduce N use efficiency and recovery (Fosu-Mensah & Mensah, 2016). Due to the poor response of maize off-season to N fertilization and the high costs of N fertilizers, many Brazilian farmers do not perform N topdressing of maize off-season (Fuentes et al., 2018). However, a low N supply may lead to depletion of soil N stocks, as the amount of N removed by crops may be higher than the amount entering the system (Roohi et al., 2022). Furthermore, given that soil carbon (C) and N contents are related, systems with a negative N balance suffer a loss of C, which, in the long term, may compromise the sustainability of the production system (Hu et al., 2022).

In the last three decades, the protein content in soybean grains has been reducing at a greater rate than the increase in oil content (Umburanas et al., 2022), raising concern for the industrial sector that produces soybean meal, the main commercial product derived from soybean, due to the difficulty of producing meal with 46% protein (Pope et al., 2023). The protein content in soybean grains is mainly influenced by genetic factors, but there is also a strong association with environmental conditions, especially associated with the availability of N (Chetan et al., 2021). Currently, there is no information on the possibility of increasing the protein content of soybean by applying N in the preceding maize.

Understanding the effects of maize – ruzigrass intercropping and N rates applied to maize by topdressing, as well as their interaction, on soybean-maize off-season double cropping system under no-tillage is fundamental to maximize yields, not only for the isolated crops but also for the system as a whole. The hypothesis of this research is that intercropping of maize off-season and ruzigrass, associated with increasing N rates, increases straw production, maize yield, and subsequent soybean yield in no-tillage system, representing an advancement of management for this production system. The objective of this study was to evaluate the effects of different N rates applied by topdressing to maize off-season grown sole and intercropped with ruzigrass in no-tillage system on grain yields, straw production, partial N balance, and soybean oil and protein contents.

Materials and Methods

Experimental Site, Soil, and Climate

The experiment was conducted in Londrina (23°11′S 51°10′W, 585 m above sea level), Paraná state, Brazil, in the 2020/2021 and 2021/2022 growing seasons (Fig. 1). The climate in the area, according to Köppen classification, is humid subtropical (Cfa), with annual mean temperature of 21 ◦C, mean maximum temperature of 28.5 ºC in February, and mean minimum temperature of 13.3 ºC in July. The soil at the experimental field, according to USDA Soil Taxonomy (Soil Survey & Staff, 2010), is a clayey Rhodic Eutrudox [i.e. *Latossolo Vermelho eutroférrico*, in the Brazilian Soil Classification System] with 710 g clay kg^{-1} soil, 82 g silt kg^{-1} soil, and 208 g sand kg^{-1} soil. Soil chemical properties were determined according to Embrapa (1997): total organic carbon, 18.1 g dm^{-3}; pH in $CaCl_2$, 5.1; Ca, 3.7 $cmol_c$ dm^{-3}; Mg, 1.9 $cmol_c$ dm^{-3}; Al, 0.0 $cmol_c$ dm^{-3}; K, 0.39 $cmol_c$ dm^{-3}; P (Mehlich-1), 28.8 mg dm^{-3}; cation-exchange capacity, 11.1 $cmol_c$ dm^{-3}; and base saturation, 54%. The experimental site has been managed under no-tillage for 20 years. Meteorological data were collected by the experimental weather station at Embrapa Soja, located 400 m far from the experimental site. Figure 1 shows the sequential water balance during the experimental period, estimated using meteorological data and assuming an available water capacity of 75 mm, according to the method described by Thornthwaite and Mather (1955).

Experimental Design and Crop Management

The experimental design was a randomized complete block design with split plots and eight replications. Two maize cultivation systems were evaluated in the main plots: sole maize and maize intercropped with ruzigrass as cover crop. Four N rates were tested in the split plots: 0, 60, 120, and 180 kg ha^{-1}. N fertilizer (ammonium nitrate) was broadcasted

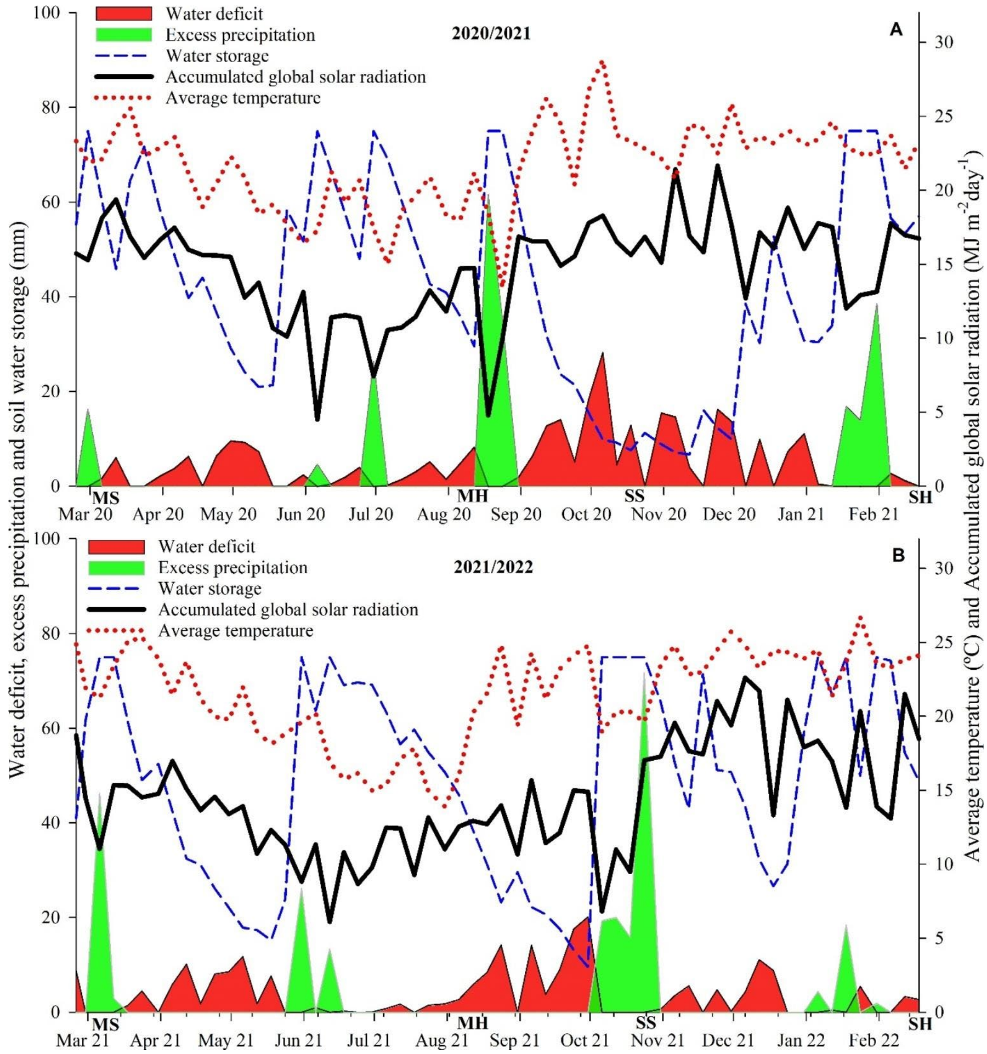

Fig. 1 Sequential water balance measured at 5-day intervals according to the method described by Thornthwaite and Mather (1955) and accumulated global solar radiation in (**a**) 2020/2021 and (**b**) 2021/2022 growing seasons. MS, maize sowing; MH, maize harvest; SS, soybean sowing; SH, soybean harvest

when maize plants were at the V5 stage (Ritchie et al., 1986) following the recommendations of the Paraná State Division of the Brazilian Soil Science Society (NEPAR-SBCS, 2019). Treatments were repeated in the same split plots in the next season. Each experimental unit comprised six 8 m long rows of maize with a spacing of 0.85 m. The four central rows were treated as useful plot area.

The basal fertilizer applied to maize crops consisted of 25 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1}, and 80 kg K_2O ha^{-1}. These rates were based on the results of soil analysis and followed the recommendations of NEPAR-SBCS, 2019. Seeds of the simple maize hybrid P30F53 were sown on March 13, 2020, and March 18, 2021. A seed and fertilizer spreader with a guillotine-type furrowing mechanism was used to open planting rows and apply the fertilizer. Offset double discs were used for sowing. The final plant density was 70 thousand plants ha^{-1}.

Ruzigrass was planted between maize rows, at the 2 cm deep, in the same operation as maize, without fertilization. Figure 2 shows the visual appearance of maize plots with and without ruzigrass. Seeds of ruzigrass were sown using a mechanized system comprising a seed grader and offset double discs set at 5 kg ha^{-1} on a viable seed basis.

Maize seeds were industrially treated with clothianidin (210 mL a.i. 100 kg^{-1} seed) + fludioxonil (3.75 g a.i. 100 kg^{-1} seed). Thiamethoxam (42 g a.i. 60 thousand seeds^{-1}) was used to maximize the control of green-belly stink bugs (*Dichelops furcatus*). Weed control was performed at pre-sowing with glyphosate (1.0 kg a.e. ha^{-1}) and at post-emergence of maize crops (V3 stage) with atrazine (1.75 kg a.i. ha^{-1}). Atrazine was used because it also suppresses ruzigrass growth, reducing competition with maize (Gheno et al., 2021). The insecticide zeta-cypermethrin (105 g a.i. ha^{-1}) was applied when maize plants were at the V3 and V6 stages to control green-belly stink bugs. Maize harvest was carried out in June 25, 2020 and June 29, 2021, when the crop reached harvest maturity.

Soybean seeds were sown in succession to maize on October 15, 2020, and October 18, 2021, 15 days after desiccation of ruzigrass and weeds with glyphosate (1.5 kg a.e.

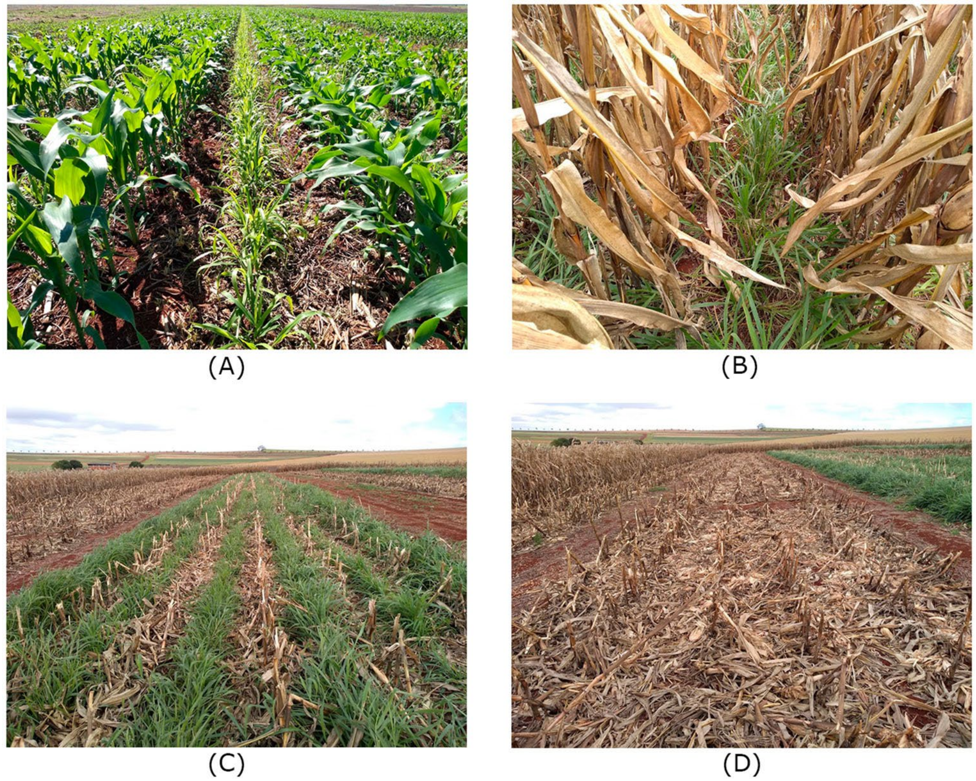

Fig. 2 Maize off-season intercropped with ruzigrass (*Urochloa ruziziensis*) in V5 stage (**A**), harvest maturity (**B**), after harvest (**C**) and sole maize after harvest (**D**)

ha^{-1}). A seed/fertilizer spreader with a guillotine-type furrowing mechanism was used to apply the fertilizer. For soybean sowing, offset double discs were set at 300 thousand seeds ha^{-1}, with a spacing of 0.45 m between rows. The soybean cultivar used was BRS 1003IPRO, an indeterminate growth cultivar that belongs to relative maturity group 6.3 and has a compact plant architecture. Basal fertilization (70 kg P_2O_5 ha^{-1} and 70 kg K_2O ha^{-1}) was carried out at the time of sowing and was chosen based on soil chemical parameters and nutritional recommendations for soybean crops (Oliveira Junior et al., 2020). Additionally, seeds were inoculated with *Bradyrhizobium japonicum* on the sowing day. Weed, pest, and disease management was performed in the same manner throughout the experimental site and followed technical recommendations for the crop (Seixas et al., 2020).

Evaluations

Maize harvest was carried out when grain moisture reached 22%. Grain yield data were adjusted to 13% moisture. Thousand grain weight was determined by measuring the weight of 500 grains harvested from the useful area of each split plot. Number of grains per area was estimated as the ratio of thousand grain weight to the total weight of grains per useful area of split plots. Number of grains per ear was estimated by dividing the number of grains by the number of ears per plot, counted at the time of harvest. At desiccation for the sowing of soybean seeds, maize residues and ruzigrass plants were collected from an area of 1 m^2 in each split plot and used to determine straw production.

In the 2020/2021 growing season, N levels in maize grains and maize and ruzigrass straw were determined by the Kjeldahl method after acid digestion. N exported in grains (kg N ha^{-1}) was calculated using the Eq. 1 (Rocha et al., 2020) and partial N balance (PNB, kg N ha^{-1}) by Eq. 2 (Austin et al., 2019).

$$\text{Nexported} = \text{NCG} \times \text{GY} \tag{1}$$

where NCG is the N content of grains (kg N kg^{-1} grain) and GY is the grain yield (kg ha^{-1}).

$$\text{PNB} = (\text{NR}_t + \text{NR}_s) - \text{NE} \tag{2}$$

where NRt is the N topdressing rate (kg ha^{-1}), NRs is the N rate applied at sowing (30 kg ha^{-1}), and NE is the N exported in grains (kg ha^{-1}).

In both seasons, soybean yield was determined by harvesting three 8 m long rows from each split plot, and values were adjusted to 13% moisture. Oil and protein contents were determined in whole grains by near-infrared reflectance spectroscopy, as described by Heil (2010). Clean whole grains were analyzed using a Thermo Scientific Antaris II system equipped with an integrating sphere at a resolution of 4 cm^{-1}, with an average of 32 scans and background correction at each reading. Mathematical models were used to estimate protein (180 standards, r = 0.97, RMSEC = 0.64) and oil contents (170 standards, r = 0.98, RMSEC = 0.45).

Statistical Analysis

Data from each season were analyzed separately due to the particularities of each growing season. First, the Shapiro–Wilk test was used to assess the normality of residuals and Bartlett's test to test the homogeneity of variances. These tests showed that data transformation was not required, as the dataset met the assumptions for analysis of variance (ANOVA). Then, data were subjected to the F-test ($p \leq 0.05$). When the effects of experimental factors (intercropping and N rate) were significant, the F-test was used for comparison of intercropping levels and polynomial regression for comparison of N rates ($p \leq 0.05$). When interaction effects were significant ($p \leq 0.05$), means of N rates were submitted to regression analysis in each intercropping level (Wei et al., 2012). Additionally, Pearson's linear correlation analysis was performed to identify correlations between variables ($p \leq 0.05$). R software was used for statistical analysis (R Core Team, 2021).

Results

Performance of Maize Off-season

In both seasons there was a water deficit during the maize cycle, mainly between April and May, when the crop was in the vegetative stage (Fig. 1). In addition, lower air temperatures occurred in June and July in the 2021/2022 growing season compared to the 2020/2021. In the 2020/2021 season, maize yield was influenced by the intercropping × N rate interaction (Table 1). Intercropped maize had a mean yield increase of 2.9 kg ha^{-1} for every 1 kg ha^{-1} increase in N rate (Fig. 3a). In sole maize, N rate did not influence yield. At N rates of 0 and 60 kg ha^{-1}, the yield of sole maize was higher than that of intercropped maize (Fig. 3a). At higher N rates, there was no effect of intercropping on cereal yields. In the 2021/2022 season, increasing N rates positively influenced maize yield, regardless of intercropping (Table 1). There was a mean yield gain of 1.5 kg ha^{-1} for every 1 kg ha^{-1} increase in N rate (Fig. 3b).

Thousand grain weight was influenced by the intercropping × N rate interaction in 2020/2021 and by N rate in 2021/2022 (Table 1). In both sole and intercropped maize, there was a tendency toward higher grain weight with increasing N rates. However, this effect was more expressive in intercropped maize (Fig. 3c). In the absence of N topdressing, thousand grain weight was higher in sole maize than in intercropped maize. In fertilized plots, there was no influence of intercropping on grain weight. In the 2021/2022 season, there was an increase in thousand grain weight with increasing N rate, regardless of intercropping (Fig. 3d).

In both seasons, there was no effect of intercropping or N rate on number of grains per area (overall mean of 2,684 grains m^{-2} in the first season and 1,329 grains m^{-2} in the second season) and number of grains per ear (overall mean of 338 grains ear^{-1} in the first season and 215 grains ear^{-1} in the second season) (Table 1).

Nitrogen Balance in Maize

Increasing N topdressing rates promoted an increase in the N content of maize grains (Fig. 4a). Maize– ruzigrass intercropping did not affect grain N content (Table 1). The amount of N removed by maize grains increased with increasing N rates by 0.09 kg ha^{-1} for every 1 kg ha^{-1} increase in N rate, regardless of intercropping (Fig. 4b).

The N rates lower than 130 kg ha^{-1} led to a negative N balance in 2020/2021 season (Fig. 4c). In the absence of N topdressing, the N balance was highly negative, about 110 and 130 kg N ha^{-1} in intercropped and sole maize, respectively. The N rate required to achieve a neutral balance (i.e. equal to 0) was slightly higher in sole maize than in intercropped maize because of the higher yield at N rates of 0 and 60 kg ha^{-1} (Fig. 3a). However, at an N rate of 180 kg ha^{-1}, the balance was positive, about 50 kg N ha^{-1}.

Maize and Ruzigrass Straw Production and N Content

The total straw production was influenced by intercropping in both seasons and by N rate in 2020/2021 (Table 1). The amount of residual straw was 1.3 and 1.2 Mg ha^{-1} higher in intercropped maize than in sole maize in 2020/2021 and 2021/2022, respectively (Fig. 5a). In 2020/2021, maize and ruzigrass straw production increased with increasing N rate (Fig. 5b and c). The straw production was high (> 7 Mg ha^{-1}) in all treatments.

The N levels in maize and ruzigrass straw were assessed separately in 2020/2021. The increase in N rate provided an increase in straw N content in both maize and ruzigrass, indicating that directly or indirectly N from fertilization increased N uptake (Fig. 6a and b). However, the N content of maize straw was not affected by intercropping with ruzigrass (Table 1).

Table 1 ANOVA for variables of maize, straw, and soybean, 2020/2021 and 2021/2022 growing seasons

Source	Degree of freedon	MaYi	GrAr	GrEa	ThWe	NGr	NEx	MaSt	ToSt	NSt	SoYi	OiGr	PrGr
	2020/2021												
Replications	7	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Intercropping (I)	1	*	ns	ns	ns	ns	ns	ns	*	ns	**	ns	ns
Nitrogen rates (NR)	3	ns	ns	ns	**	*	*	*	*	**	*	*	**
I x NR	3	*	ns	ns	**	ns	ns	ns	ns	ns	*	ns	ns
CV (%) plot (I)		9.26	15.51	14.21	6.25	10.16	12.94	22.90	23.14	18.75	11.07	4.82	2.87
CV (%) split plot (NR)		6.26	8.95	9.04	3.18	9.74	10.56	14.08	13.62	9.66	9.46	3.08	3.16
	2021/2022												
Replications	7	ns	ns	ns	*	-	-	ns	ns	-	ns	ns	ns
Intercropping (I)	1	ns	ns	ns	ns	-	-	ns	*	-	ns	ns	ns
Nitrogen rates (NR)	3	*	ns	ns	*	-	-	ns	ns	-	*	*	**
I x NR	3	ns	ns	ns	ns	-	-	ns	ns	-	*	ns	ns
CV (%) plot (I)		17.06	29.44	26.11	10.42	-	-	24.15	19.36	-	18.70	5.02	3.61
CV (%) split plot (NR)		13.09	12.49	15.70	9.18	-	-	20.54	18.95	-	10.08	3.51	2.65
	Ruzigrass variables												
		RuSt (2020/2021)			NRu (2020/2021)			RuSt (2021/2022)					
Replications	7		ns			ns			*				
Nitrogen rates (NR)	3		ns			**			ns				
CV (%)			27.30			10.22			20.86				

Variables Maize off-season yield (MaYi), number of maize grains per area (GrAr), number of maize grains per ear (GrEa), Thousand grain weight of maize (ThWe), nitrogen content in the maize grains (NGr), nitrogen exported by maize grains (NEx), maize straw (MaSt), total straw (ToSt), nitrogen content in the maize straw (NSt), soybean yield (SoYi), oil content in the soybean grains (OiGr), protein content in the soybean grains (PrGr), ruzigrass straw (RuSt), nitrogen content in the ruzigrass straw (NRu) ** $p \leq 0.01$ and * $p \leq 0.05$

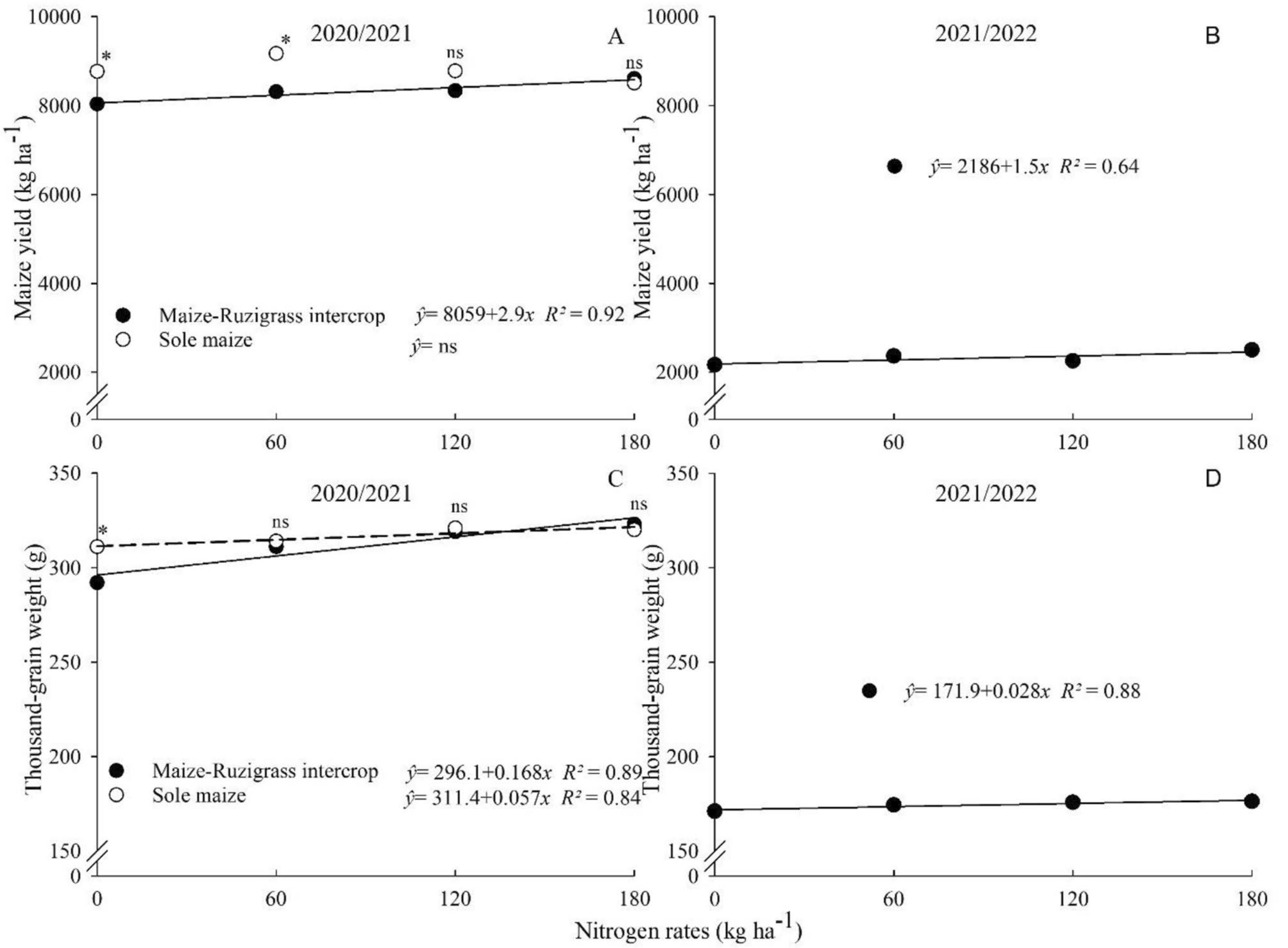

Fig. 3 Maize off-season yield as a function of nitrogen rate and intercropping with ruzigrass (*Urochloa ruziziensis*) in the 2020/2021 (**A**) and 2021/2022 (**B**) growing seasons. Thousand grain weight of maize off-season as a function of nitrogen rate and intercropping with ruzigrass in the 2020/2021 (**C**) and 2021/2022 (**D**) growing seasons. ns, not significant; * significant difference between maize- ruzigrass intercrop and sole maize ($p \leq 0.05$)

Yield and Grain Oil and Protein Contents of Soybean Grown in Succession to Maize

In both soybean growing seasons, there was a water deficit in November and December, when the crop was in the vegetative phase and pod formation (Fig. 1). However, during the grain filling there was adequate water availability. In both seasons, soybean yield was influenced by the interaction effects of maize intercropping and N topdressing rate (Table 1). Soybean yield increased by 1.63 and 3.52 kg ha^{-1} for every 1 kg ha^{-1} increase in N rate in preceding sole maize in 2020/2021 and 2021/2022, respectively (Fig. 7a and b). Soybean yield was not influenced by N fertilization of preceding maize–ruzigrass intercrop.

In 2020/2021, grain yield was higher in soybean grown in succession to intercropped maize than in succession to sole maize for all N topdressing rates (Fig. 7a). However, in 2021/2022, an increase in the yield of soybean grown in succession to intercropped maize was only observed for unfertilized plots (Fig. 7b). The greatest impacts of maize–ruzigrass intercropping on soybean yield were observed in the absence of N topdressing in maize.

In both seasons, there was a consistent effect of N topdressing rate applied to preceding maize on soybean oil and protein contents (Fig. 7c, d, e, and f). However, there was no effect of maize–ruzigrass intercropping or of the interaction between N rate and intercropping (Table 1). In both seasons, soybean oil content increased with the increment of N rate in preceding maize. An inverse trend was observed for protein content, which decreased with increasing N rate in maize. The rates of increase in oil content and reduction of protein content in soybean as a function of N rate in maize were similar in both seasons, namely, for oil, 0.039 g kg^{-1} in 2020/2021 and 0.044 g kg^{-1} in 2021/2022 for each 1 kg N ha^{-1} and, for protein, -0.085 g kg^{-1} in 2020/2021 and -0.088 g kg^{-1} in 2021/2022 for each 1 kg N ha^{-1}.

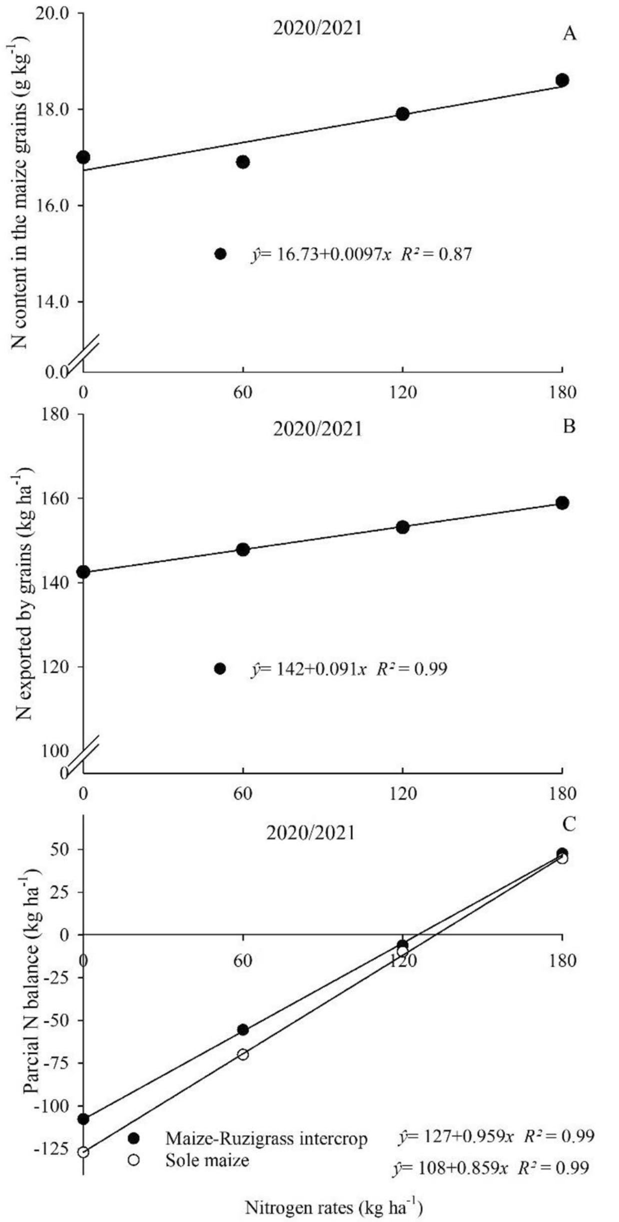

Fig. 4 Grain nitrogen content (**A**), N exported in grains (**B**), and Partial nitrogen balance (**C**) of maize off-season as a function of N rate in the 2020/2021 growing season

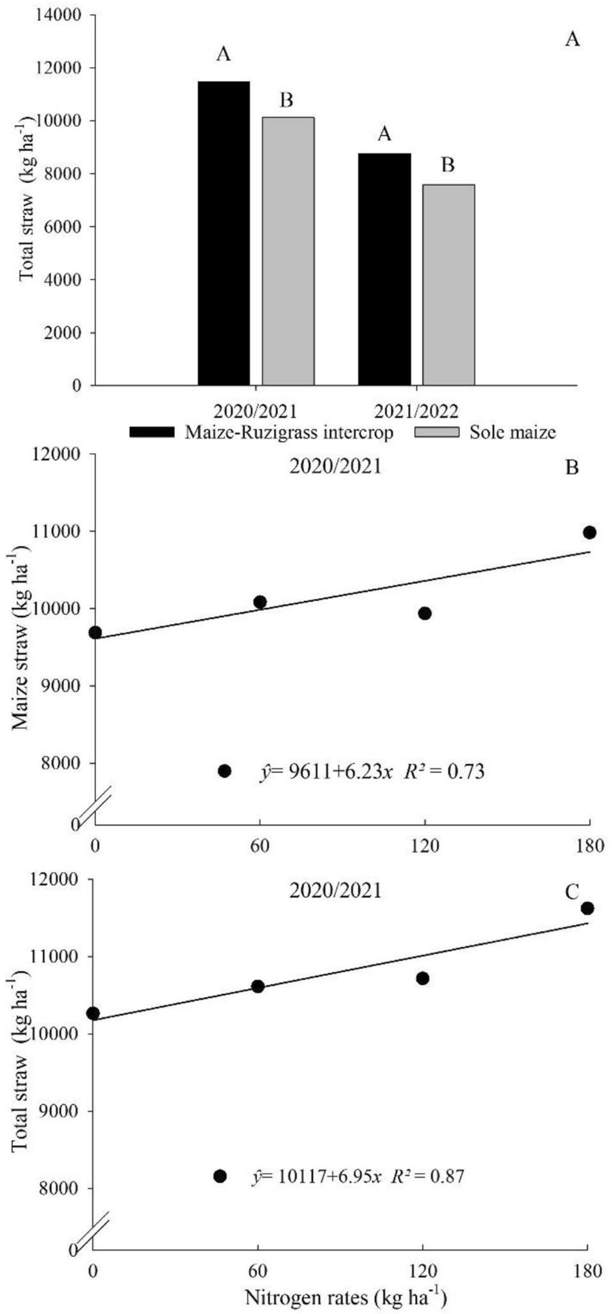

Fig. 5 Total straw production by sole maize and maize intercropped with ruzigrass (*Urochloa ruziziensis*) preceding soybean in 2020/2021 and 2021/2022 growing seasons (**A**). Production of straw by maize (**B**) and maize and ruzigrass (*Urochloa ruziziensis*) (**C**) preceding soybean as a function of nitrogen topdressing rates in the 2020/2021 growing season

Discussion

In the first growing season, maize yields were higher than 8,000 kg ha^{-1}, despite the water deficit in April and May 2020 (Fig. 1), being above the national average (4,050 kg ha^{-1}) (CONAB, 2023). In the 2021/2022 season, yield was strongly affected by the water deficit from March to June, frost in June, and maize leafhopper attack (*Dalbulus maidis*), the main biotic stress of maize in this season in Brazil (Foresti et al., 2022). Given these issues, the average yield in 2021/2022 ranged from 2,200 to 2,500 kg ha^{-1}, being lower than the national average (5,230 kg ha^{-1}) (CONAB, 2023).

When intercropped, ruzigrass can compete with maize for water, light, and nutrients, reducing the cereal yield

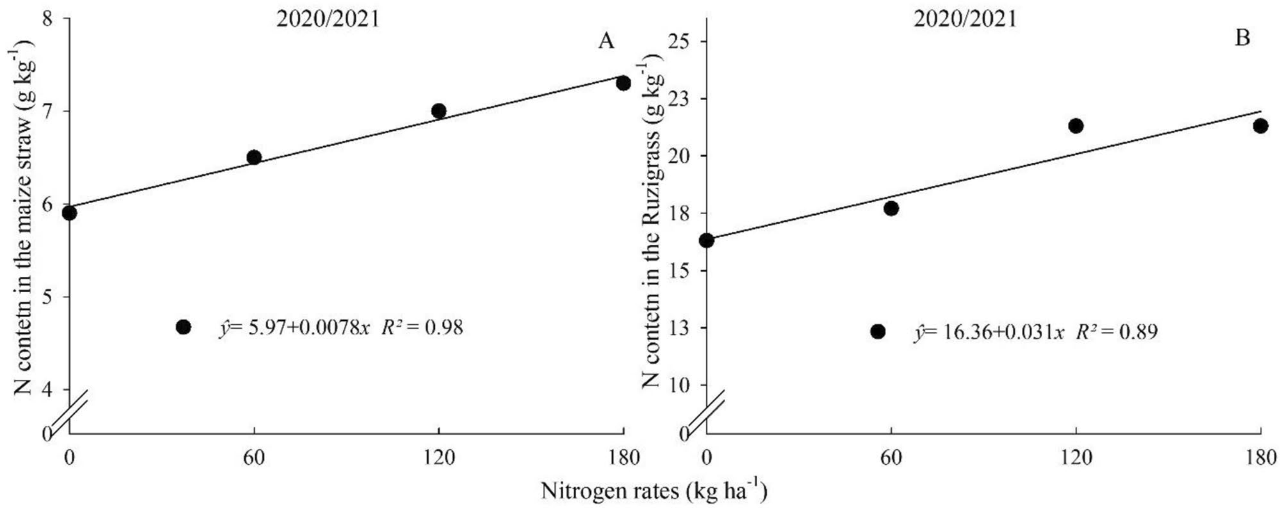

Fig. 6 Nitrogen content of maize (**A**) and ruzigrass (*Urochloa ruziziensis*) (**B**) straw in intercrop systems preceding soybean as a function of N topdressing rate in 2020/2021 growing season

(Silva et al., 2020). During 2020/2021, in the two treatments with the lowest N rates, ruzigrass significantly decreased maize yield, despite being sown between maize rows and being suppressed by atrazine at the beginning of tillering. This result indicated the need to associate other herbicides with atrazine, such as mesotrione (Martins et al., 2019), to increase the suppression of ruzigrass, especially in the absence of N topdressing. However, at N rates of 120 and 180 kg ha^{-1}, there was no difference in yield between sole and intercropped maize. This result indicates that N availability is determinant of interspecific competition between maize and ruzigrass, as reported by Zuffo et al. (2022). In 2021/2022, the effect of ruzigrass on maize grain production was not observed because the prolonged water deficit significantly limited yield, reducing the effects of treatments on cereal yield.

The N is the nutrient most absorbed by maize and its availability is crucial for achieving high yields (Braos et al., 2022; Coelho et al., 2022). However, in the present study, the response of maize yield to increasing N rates was low. In 2020/2021, there was a response of maize yield to N rates only when intercropped with ruzigrass, possibly because of the interspecific competition for the nutrient. In Brazil, maize off-season is subjected to several stresses, especially water deficit, which limits crop responses to increased N supply (Sapucay et al., 2020; Simão et al., 2020). Fuentes et al. (2018) tested N rates ranging from 0 to120 kg N ha^{-1} in maize season and maize off-season in Brazil. There was an increase of 9.2 kg ha^{-1} in grain yield for each 1 kg N ha^{-1} in the season and of only 2.5 kg grain ha^{-1} for each 1 kg N ha^{-1} in the off-season. In our study, we found an increment of 2.9 kg grain ha^{-1} for each 1 kg N ha^{-1} in 2020/2021 in intercropped maize and 1.5 kg grain ha^{-1} for each 1 kg N ha^{-1} in 2021/2022.

The differences in maize yield between N treatments were mainly attributed to the variations in thousand grain weight, given that number of grains per area and number of grains per ear were not influenced by treatments. In maize off-season fertilized with increasing N topdressing rates, Bueno et al. (2020) found that grain weight was strongly correlated with grain yield.

In 2020/2021, intercropping reduced grain weight in treatments without N topdressing. In 2021/2022, there was no effect of ruzigrass on maize grain weight. The current study shows that competition for N is determinant in the effect of intercrop ruzigrass and that grain weight is the yield component most affected by competition. Therefore, N topdressing is important in maize–ruzigrass intercrop systems, as it reduces the impact of competition on cereal yield and increases grass biomass production, which can be used as ground cover or fodder after maize harvest (Crusciol et al., 2020; Mateus et al., 2020).

The experiment results showed that partial N balance can be highly negative at low N rates when maize yields are high (> 8 Mg ha^{-1}), as observed in 2020/2021. In Brazil, maize off-season commonly receives < 100 kg ha^{-1} or no N fertilization due to the low response of the crop to the nutrient (Fuentes et al., 2018; Sapucay et al., 2020). In soybean, the partial N balance ranges from − 10 to 40 kg N ha^{-1}, considering the N content of shoot and roots (up to 0.3 m) and the contribution of biological N fixation (70–80%) to total N content (Kehoe et al., 2022). Thus, soybean-maize off-season doble cropping system in Brazil commonly have a negative N balance. Reduction of soil N stocks can compromise soil physical, chemical, and biological quality over

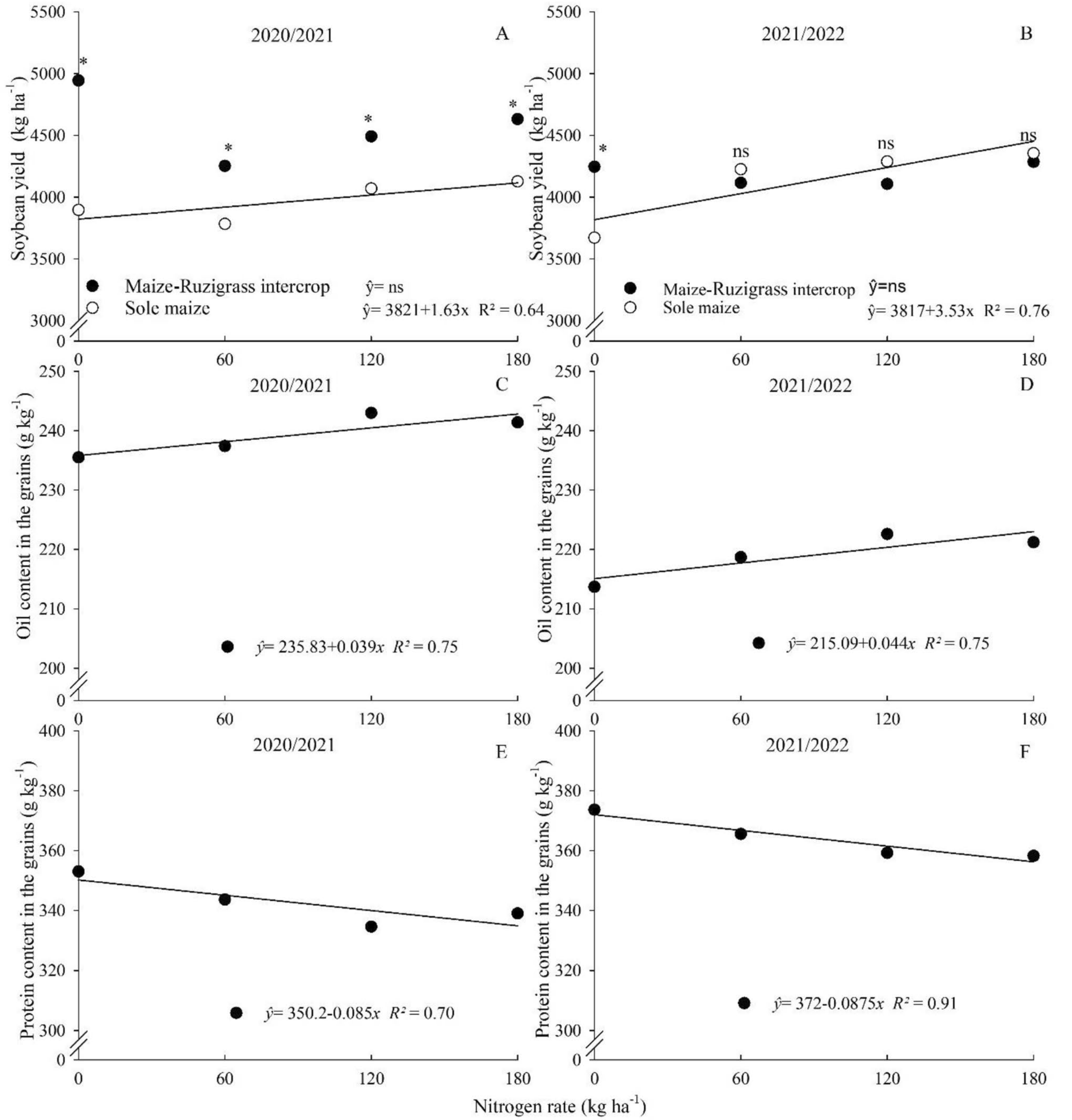

Fig. 7 Soybean yield (**A** and **B**), Grain oil (**C** and **D**) and protein (**E** and **F**) contents of soybean grown in succession to maize off-season fertilized with different N topdressing rates in 2020/2021 and 2021/2022 growing seasons

time, as soil C and N contents are strongly related (Abrar et al., 2021). Systems that have greater N removal than N input may cause loss of C in soil. Furthermore, N depletion can reduce biomass production and yield over time, degrading the soil and limiting the profitability of the production system (Bayer et al., 2006). Therefore, it is relevant to evaluate the production system as a whole to determine the recommended N rates for maize, including the benefits of N fertilization in maize off-season on soybean in succession. Considering the negative side effects of mineral N fertilization, it is important to study the effects of organic sources of N and, especially the use of leguminous species intercropped with maize off-season, such as showy rattlebox

(*Crotalaria spectabilis*), in order to incorporate N into the soil (Sapucay et al., 2020).

One of the pillars of no tillage system is sowing in straw-covered soil, with minimal soil mobilization (Balbinot Junior et al., 2017; Franchini et al., 2012; Yokoyama et al., 2022). Straw reduces water erosion, soil temperature peaks, evaporation, and weed emergence, essential factors for the success of soybean crop (Balbinot Junior et al., 2020; Schick et al., 2000). In both seasons, intercropping provided higher straw production than sole maize, being 13.3% higher in 2020/2021 and 15.4% higher in 2021/2022, proving our hypothesis. In a study conducted at three localities in Mato Grosso do Sul State, Brazil, Ceccon et al. (2013) observed that maize intercropped with ruzigrass produced, on average, 18% more straw than sole maize. In soybean-maize off-season double cropping system, straw production by off-season crop is crucial, given that soybean produces low amounts of straw (<4 Mg ha^{-1}). Furthermore, soybean straw decay rapidly due to its low C:N ratio (Ferreira et al., 2016).

In 2020/2021, straw production by maize and maize and ruzigrass increased with increasing N rates, but N topdressing did not influence ruzigrass straw production. This finding indicates that N fertilization favored more maize than ruzigrass growth. Crusciol et al. (2020) found a significant effect of N fertilization in maize intercropped with forage on total straw production and, consequently, on the sustainability of production systems in tropical regions. The increase in total straw production, associated with high straw N content resulting from increasing N rates in maize, favor nutrient cycling in the soybean-maize off-season system, providing benefits to soybean production (Werner et al., 2020). In 2021/2022, increasing N rates did not influence maize or ruzigrass straw production, probably due to the longer water deficit, limiting the use of N by the crop (Ullah et al., 2019).

In 2020/2021, intercropping maize and ruzigrass increased soybean yield compared with sole maize at the four N rates (mean increment of 611 kg grain ha^{-1}), thus confirming our hypothesis. There was also an increment of 573 kg grain ha^{-1} at the zero N rate in 2021/2022. Ceccon et al. (2013) reported a significant increase in soybean yield in succession to maize intercropped with ruzigrass as compared with sole maize (mean increment of 367 kg ha^{-1}). This positive effect of intercropping on subsequent soybean is related to the higher production of root and straw biomass, enhancing soil physical properties and promoting nutrient cycling (Mendonça et al., 2015). These results demonstrate the potential of intercropping in improving soybean-maize off-season system in Brazil, thereby increasing the efficiency of land use (Mateus et al., 2020).

Research studies carried out by Hungria et al. (2006) and Yokoyama et al. (2022) have shown that mineral N fertilization is not able to provide gains in soybean yield in Brazil. However, the present work showed that the use of increasing N topdressing rates in sole maize provided an increase in subsequent soybean yield. This beneficial effect is probably related to the greater production of shoot and root biomass by maize under higher N rates (Coelho et al., 2020), improving soil physical quality and increasing nutrient cycling (Mendonça et al., 2015). In addition, as shown in the present study, N fertilization in maize increased the N content in the straw, enhancing the availability of this nutrient to soybeans in succession, mineralized gradually (Tian et al., 2019). Thus, N rate recommendations for maize grown off-season should consider the possible beneficial effect on subsequent soybean. Whereas, when maize was intercropped with ruzigrass, no benefits of N fertilization in maize were detected on soybean yield in succession. This result was consistently observed in both growing seasons. In this case, probably the benefits of ruziziensis in the soil, such as high root growth and increased soil coverage, were more expressive for soybean than the N in the preceding maize. Moreover, N release by ruzigrass straw (Tanaka et al., 2019), even without N topdressing fertilization, contributes to the N nutrition of soybeans in succession.

Increasing N topdressing rates in sole maize and maize–ruzigrass caused an increase in subsequent soybean oil content and a reduction in protein content. Chetan et al. (2021) and Wijewardana et al. (2019) have shown that there is a negative correlation between soybean protein and oil contents. No previous study demonstrated the effect of N fertilization in maize off-season on the oil and protein contents of subsequent soybean. Initially, we expected an increase in protein content in soybean grains with the increase in N doses in the preceding maize, but the result was the opposite. It is possible that protein was diluted and its reduction was compensated by an increase in yield resulting from high N rates in maize. Conversely, there was an increase in oil production per area derived from the combination of increased yield and grain oil content in response to increasing N fertilization in maize. Furthermore, intercropping did not affect subsequent soybean oil or protein contents.

Conclusions

The present study demonstrated the benefits of intercropping maize and ruzigrass, including an increase in straw production and subsequent soybean yield. N topdressing in sole maize led to an increase in subsequent soybean yield. Increasing N rates in maize off-season, regardless of intercropping, led to an increase in oil content and a reduction in protein content. In this context, intercropping maize off-season and ruzigrass and applying N in topdressing are important practices for the improvement and sustainability of soybean-maize off-season cropping system in Brazil.

Author Contributions Alvadi Antonio Balbinot Junior: conceptualization, study design, methodology, data acquisition, supervision, statistical analysis, writing – original draft preparation. Antonio Eduardo Coelho: conceptualization, study design, methodology, data acquisition, graphic design. Luis Sangoi: visualization, writing – original draft preparation. Henrique Debiasi: conceptualization, study design, data acquisition, visualization. Julio Cezar Franchini: conceptualization, data acquisition, visualization. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Consent for Publication All the authors have given their consent for the publication of this manuscript.

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