



Crop diversification in soybean production systems mitigates GHG emissions and enhances soybean yield under no-till management in the Brazilian Cerrado

Jessica Heloiza Coutinho¹ · Saul Ramos de Oliveira¹ · Hilário Junior Almeida¹ · Maria Eloá de Lima¹ · Jorge Luiz Locatelli² · Cimélio Bayer³ · Carlos Eduardo Pellegrino Cerri³ · Luiz Guilherme Santos de Oliveira² · Edicarlos Damacena Souza¹

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Abstract

The aim of this study was to evaluate the impact of crop diversification on the soil emissions of CO₂, CH₄, and N₂O in soybean production systems under no-till management in the Brazilian Cerrado. Five production systems were analyzed: soybean–maize succession (S1); soybean–*Urochloa ruziziensis* succession (S2); soybean–crotalaria succession followed by maize intercropped with *U. ruziziensis* (S3); rotation of soybean and crotalaria followed by soybean and maize intercropped with *U. ruziziensis* for 12 months (S4); rotation of soybean and millet followed by soybean and crotalaria; and finally, maize intercropped with *U. ruziziensis* (S5). The highest greenhouse gas (GHG) emissions occurred during the rainy season, regardless of the production system. For CO₂, between 56% and 65% of the annual emissions occurred during this period. With respect to CH₄, system S3 presented the highest average emission (0.44 kg ha⁻¹), followed by S1 (0.37 kg ha⁻¹) and S5 (0.19 kg ha⁻¹). For N₂O, systems S1 and S2 emitted an average of 0.38 kg ha⁻¹ of N–N₂O during the rainy season, which were 30%, 40%, and 45% greater than those observed in systems S3, S4, and S5, respectively. The more diversified agricultural systems proved to be a strategic and promising alternative for reducing GHG emissions in Cerrado soils, contributing to more sustainable and efficient agriculture.

Keywords Agriculture · *Glycine max* · Global warming potential · Mitigation

✉ Saul Ramos de Oliveira
saul.oliveira.ramos@hotmail.com

¹ Universidade Federal de Rondonópolis-UFR, Rondonópolis, Brazil

² Universidade de São Paulo-USP, São Paulo, Brazil

³ Universidade Federal do Rio Grande do Sul- UFRGS, Porto Alegre, Brazil

1 Introduction

Agriculture plays a crucial role in the provision of food, fiber, and energy and, consequently, in global food security (Charles et al. 2010). Brazil, one of the world's largest grain producers, stands out in the supply of various commodities, ranking among the top producers in the production volume of several products (e.g., soybeans, corn, and coffee) (USDA, 2023). The Cerrado, in particular, is a highly relevant agricultural hub, accounting for approximately 50–70% of the national production of soybeans, corn, and meat (CONAB, 2023; IBGE, 2017). However, as cultivated areas have expanded in the region, associated environmental issues such as greenhouse gas emissions have gained increasing importance. The increasing concentrations of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) in the atmosphere have significantly contributed to the increase in global average temperatures, leading to a range of environmental issues (Paustian et al. 2016). Given Brazil's prominent role in global agriculture, there is growing pressure for the sector to adopt practices that promote sustainability and reduce the environmental impacts associated with large-scale grain production.

Agricultural activity and land use change (LUC) are the main drivers of greenhouse gas (GHG) emissions in Brazil, accounting for approximately 75% of the country's total emissions (SEEG, 2023). The intense conversion of native areas into agricultural land, especially in the Cerrado biome, began in the 1970s when Brazil underwent rapid agricultural expansion. Currently, the Cerrado has the highest land conversion rate in the country, with an estimated 50% loss of its original vegetation cover. This process has not only reduced biodiversity and the ecological resilience of the region but has also triggered substantial changes in the biogeochemical cycles of carbon and nitrogen, leading to increased soil GHG emissions. Among the management factors that influence these emissions, nitrogen fertilization, soil preparation, and the cropping system itself can significantly affect the dynamics of soil GHG emissions (Campanha et al. 2019; Oliveira et al. 2021). Therefore, assessing the impacts of these different factors on GHG emission dynamics is crucial for prioritizing more sustainable agricultural systems and mitigating the negative environmental impacts of Brazil's agricultural sector.

The use of nitrogen fertilizers significantly contributes to increased emissions of N₂O (Gazola et al. 2024) and CH₄, which have global warming potentials 276 and 28 times greater than those of CO₂, respectively. Fortunately, the literature has shown significant advances in understanding how to mitigate emissions resulting from the use of nitrogen fertilizers. The use of inhibitors, for example, has demonstrated considerable potential for reducing N₂O emissions while improving the efficiency of nutrient uptake from fertilization (Liu et al. 2013). The no-till system (NT), known for its benefits in promoting soil aggregation, protecting against degradation and erosion, and increasing soil organic carbon (SOC) stocks (Krauss et al. 2017), has been widely adopted in the Cerrado. The advantages of reduced soil disturbance on GHG emission dynamics have also been explored through various approaches (Li et al. 2023).

Improving soil structure often benefits the diffusion of water and oxygen within the soil, which is essential for preventing anaerobic conditions that favor the denitrification process, one of the main pathways responsible for N₂O emissions. Although reduced soil disturbance can lead to significant improvements in the system, especially compared with conventional

tillage (Li et al. 2023; Maia et al. 2022), adopting no-till practices alone may not be sufficient in certain cases.

The succession between maize (*Zea mays*) and soybean (*Glycine max*), although capable of increasing productivity compared with monocultures, may, under hot climate conditions—such as those in the Brazilian Cerrado lead to a decline in soil health due to limited biomass production and high nutrient export rates. In contrast, compared with nondiversified systems, diversified production systems that rotate commercial crops with cover crops—typically using C4 species with high biomass outputs and large fibrous root systems—contribute to improved long-term soil conditions (Banerjee et al. 2019; Anghinoni et al. 2021; Liebig et al. 2014). In this context, there is a clear and urgent need to reorient agricultural systems toward conservation agriculture that addresses not only productivity and food security goals but also sustainability and climate change mitigation (Anghinoni et al. 2021). Crop diversification and rotation under no-till management offer greater production stability, resilience to climate extremes, and long-term GHG mitigation (Wheeler and Von Braun 2013). This approach supports not only the maintenance of productive capacity but also the enhancement of environmental quality in agricultural systems.

Although several studies have investigated the effects of no-till farming on GHG emissions (Virk et al. 2022; Liu et al. 2023; Gazola et al. 2024), the impact of crop diversification in soybean production systems under no-till, especially in the tropical Cerrado, remains underexplored both in terms of emissions and productivity. This biome presents unique ecological characteristics and faces intense agricultural pressure, making it essential to understand how diversification and crop rotation practices can help mitigate GHG emissions. On this basis, it is assumed that greater diversity and intensity of crop rotations in soybean production may reduce soil GHG emissions. Therefore, the objective of this study was to evaluate the effects of crop rotation and diversification on CO₂, CH₄, and N₂O emissions in soybean production systems managed under no-till in the Cerrado biome.

2 Materials and methods

2.1 Field of study

The study was based on a long-term experiment (14 years) conducted at the research farm under the management of the Mato Grosso Agricultural Research Support Foundation (MT Foundation), located in Itiquira, Mato Grosso, Brazil (17° 09'S, 54° 45'W). The local altitude is 490 m, and the soil is classified as a dystrophic Red Latosol according to the Brazilian Soil Classification System (SiBCS) (Santos et al. 2018) or as Typic Haplustox according to Soil Taxonomy (Soil Survey Staff 2022). The climate of the region was classified as Aw according to Koppen-Geiger (Alvares et al. 2013), with two well-defined seasons: rainy summers, corresponding to the rainy season, and dry winters, corresponding to the dry season. Thus, for this study, the interval from October to March was considered the rainy season since, on average, 80% of the rainfall is concentrated in this period, and the other months constitute the dry season. The average annual rainfall in the region was 1119.20 mm, and the air temperature was between 18.6 and 34.2 °C, according to the climatological patterns recorded during the period evaluated at the automatic meteorological station located in the experimental area (Fig. 1).

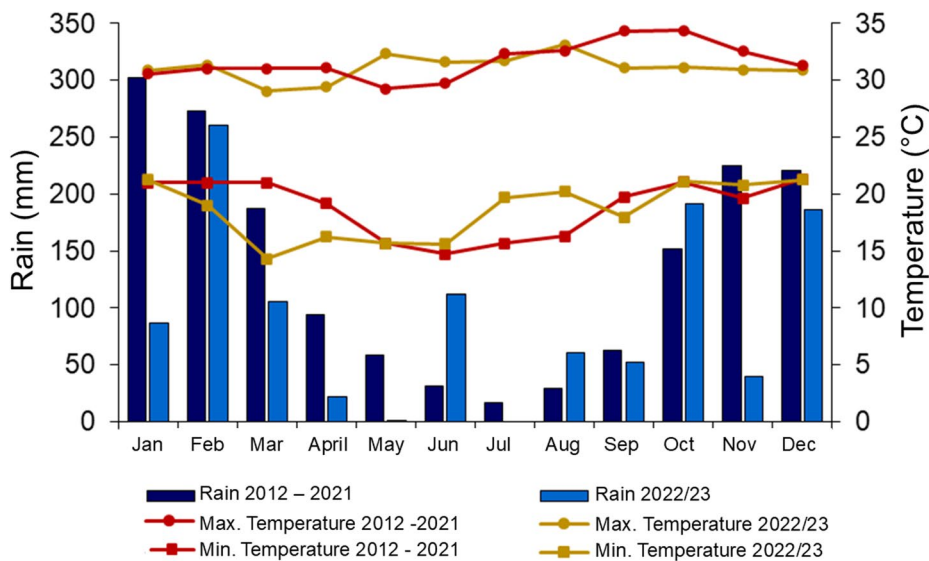


Fig. 1 Rainfall, minimum temperature, and maximum air temperature for the period from 2012 to 2021 and during the evaluation period (2022 to 2023) in the experimental area, Itiquira, Mato Grosso State, Brazil

Prior to the installation of the experiment in 2008, the experimental area was under cultivation of annual crops, especially soybean monoculture for 25 years (1983/1984 to 2007/2008 harvest), with off-seasons including fallow or cover crops, such as pearl millet (*Pennisetum glaucum* (L.), sorghum (*Sorghum bicolor* (L.) Moench), and corn (*Zea mays* L.). In the fall of 2008, the area was prepared using a subsoiler at a depth of 40 cm, a plow with 32-inch discs used for homogenization, and a levelling harrow before sowing the crops.

The experiment consisted of five culture systems arranged in plots of 560 m² (28 × 20 m), with four replications according to a randomized block design. The cropping systems consisted of the succession or rotation of soybean (*Glicine max.*) with commercial crops or cover crops. Over the years of cultivation, the systems have shown increasing levels of crop diversity and agricultural intensification, namely, S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp (*Crotalaria juncea*) followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and pearl millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. Thus, the systems that combined succession (S1 and S2) with crop rotation (S3, S4 and S5) are shown in Fig. 2.

The initial fertility of the soil was high, as indicated in Tables 1 and 2. The initial chemical characterization of the soil was carried out in the year 2021 in the layer 0–10 cm (Table 1), and the physical characterization was carried out in the year 2022. analyzes were carried out pH, base saturation and total organic carbon in layers 0–5, 5–10, 10–20 and 20–30 cm depth from the ground (Table 2) were performed by collecting a composite sample formed by mixing 20 soil subsamples in each plot of the experiment in December 2021. The soil was dried and sieved (2 mm) and then used for laboratory analysis.

PRODUCTION SYSTEM	1		2		3	
	Harvest		Succession		Harvest	
	O	N	D	J	F	M
S1 S: SOYBEAN-CORN						
	<i>G. max</i> – <i>Z. mays</i>		<i>G. max</i> – <i>Z. mays</i>		<i>G. max</i> – <i>Z. mays</i>	
S2 S: SOYBEAN-GRASS						
	<i>G. max</i> – <i>U. ruziziensis</i>		<i>G. max</i> – <i>U. ruziziensis</i>		<i>G. max</i> – <i>U. ruziziensis</i>	
S3 S: SOYBEAN-CROTALARIA/ R: CORN+GRASS						
	<i>G. max</i> – <i>Z. mays</i> + <i>U. ruziziensis</i>		<i>G. max</i> – <i>Z. mays</i> + <i>U. ruziziensis</i>		<i>U. ruziziensis</i>	
S4 S: SOYBEAN-CROTALARIA/ R: CORN+GRASS: SOYBEAN-MILLET/						
	<i>G. max</i> – <i>C. ochroleuca</i>		<i>Z. mays</i> + <i>U. ruziziensis</i>		<i>G. max</i> – <i>C. ochroleuca</i>	
S5 S: SOYBEAN-CROTALARIA/ S: SOYBEAN - CORN+GRASS/ R: GRASS						
	<i>G. max</i> – <i>P. glaucum</i>		<i>G. max</i> – <i>C. ochroleuca</i>		<i>Z. mays</i> + <i>U. ruziziensis</i>	

Fig. 2 Description of the production systems evaluated in a dystrophic red latosol (Typic Haplustox), Itiquira, Mato Grosso State, Brazil. S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*

Table 1 Chemical characterization of the 0–20 cm soil layer in 2021 of the experimental area at the beginning of the experiment in 2008, Itiquira, Mato Grosso State, Brazil

Layer	P	K	Ca	Mg	To the	H+Al	SB	CTC	MO
Cm	mg/kg				cmol/kg			%	%
0–10	23,0	0,35	5,7	2,6	0,0	0,9	8,5	9,4	3,6

P and K were extracted with Mehlich-1; Ca^{2+} , Mg^{2+} and Al^{3+} were extracted with $1.0 \text{ mol L}^{-1} \text{ KCl}$; H+Al was determined by 0.5 mol L^{-1} calcium acetate (pH=7.0); CEC=cation exchange capacity at pH=7.0; and OM=organic matter

2.2 Conducting the experiment and culture treatments

During the evaluation period, the treatments presented the following cultivation order (Fig. 3): S1: corn and soybean succession system; S2: *U. ruziziensis* and soybean succession system; S3: system with rotation with *U. ruziziensis*, which remained for 12 months in the area followed by soybean; S4: rotation system with corn intercropped with *U. ruziziensis*, followed by soybean, followed by pearl millet; and S5: system with rotation of corn intercropped with *U. ruziziensis* followed by soybean, preceded by sunn hemp.

Corn (cultivar DKB 360 PRO3) in S1 was sown on February 26, 2022, received nitrogen fertilization on March 13, 2022 and was harvested on July 13, 2022. The grass (*U. ruziensi-*

Table 2 Characterization of particle size distribution, pH, base saturation, and total organic content in the 0–5, 5–10, 10–20, and 20–30 cm soil layers in 2022 (during the ^{eight years} of the experiment) in Itiquira, Mato Grosso, Brazil

Treatment	Layer	Clay	Silte	Sand	pH	V	COT
	Cm	g kg ⁻¹			H ₂ O	-----(%)-----	
S1	0–5	680	86	235	6,7	92	3,19
	5–10	667	73	261	6,2	65	2,48
	10–20	713	24	263	5,6	37	2,03
	20–30	724	42	234	5,4	32	1,51
S2	0–5	641	97	262	7,0	96	3,92
	5–10	672	73	255	6,4	68	3,92
	10–20	700	58	242	5,9	46	2,44
	20–30	702	68	230	5,6	34	2,14
S3	0–5	647	99	254	5,5	96	4,16
	5–10	699	42	259	5,3	67	2,70
	10–20	689	62	249	5,7	41	2,27
	20–30	694	77	228	5,3	26	1,99
S4	0–5	649	76	275	6,9	94	3,92
	5–10	671	74	255	6,5	67	3,12
	10–20	695	59	246	5,8	37	2,21
	20–30	721	55	224	5,5	33	1,72
S5	0–5	619	93	287	6,9	97	4,29
	5–10	653	109	237	6,1	65	2,70
	10–20	674	83	244	5,5	36	2,25
	20–30	723	55	222	5,3	30	2,05

pH in H₂O; V% = base saturation and TOC = total organic carbon

sis) in S2 was sown on March 21, 2022, and it remained in the system as a cover crop until soybean cultivation. In the S4 and S5 rotation systems, the crops (corn and *U. ruziziensis*) had already been planted since December 22, 2021. The corn harvest in S4 and S5 took place on May 18, 2022. Finally, in all the systems evaluated, soybean sowing, cultivar TMG 2776 IPRO, took place on October 13, 2022, and it was harvested on February 22, 2023 (Fig. 3).

The cover crops were planted with a fine-grained seeder, with the exception of *U. ruziziensis* intercropped with corn. For this purpose, the seeds were previously mixed with fertilizer and subsequently planted in the corn sowing line. A double disc furrower was used for sowing, as well as for soybean sowing. Liming took place on September 6, 2022, at a dose of 2 Mg ha⁻¹ dolomitic limestone on the surface.

For the soybean crop, 45 kg ha⁻¹ of P₂O₅ was applied in the furrow during sowing on October 17, 2022, and 90 kg ha⁻¹ of K₂O in the topdressing was applied to the cast. For maize in rotation, 160 kg of N, 50 kg of P₂O₅ and 50 kg of K₂O were used, and for maize in succession, 100 kg of N, 40 kg of P₂O₅ and 30 kg of K₂O were used. Nitrogen fertilization was divided into two applications, with 40 kg of N applied at sowing, along with P and the rest applied in topdressing, when corn reached vegetative stage V4, together with fertilization with K, as shown in Fig. 3.

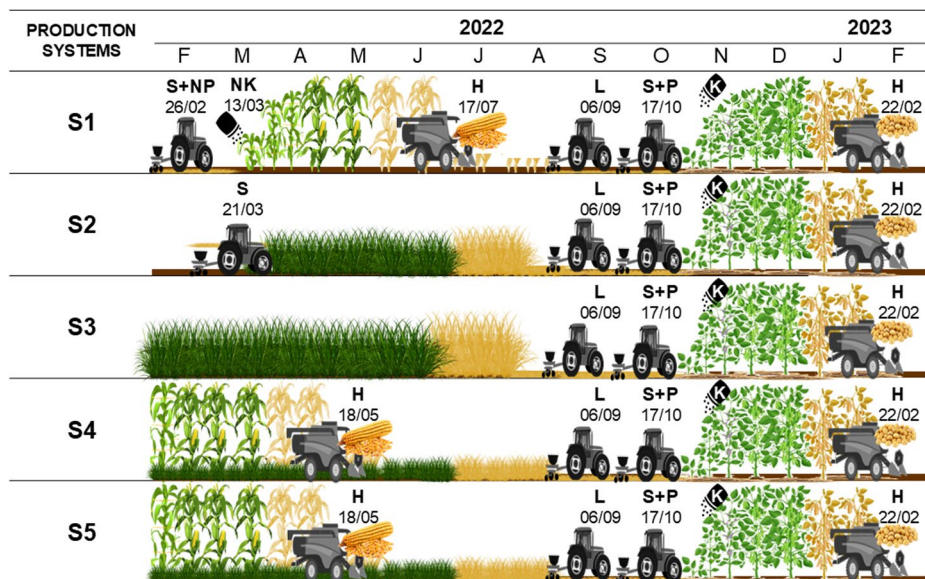


Fig. 3 Evaluated production systems and crop treatments in a dystrophic red latosol (Typic Haplustox), Itiquira, Mato Grosso State, Brazil. S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. S+NP: sowing + nitrogen and phosphate fertilization (40 kg N and 40 kg P₂O₅ ha⁻¹); NK: nitrogen and potassium fertilization (60 kg N and 30 kg K₂O ha⁻¹); H: Harvest; L: liming (2 t ha⁻¹); S+P: Sowing + phosphate fertilization (45 kg P₂O₅ ha⁻¹); K: potassium fertilization (90 kg K₂O ha⁻¹); S: sowing

2.3 Measurement of soil GHG fluxes

The evaluations were carried out between February 26, 2022, and February 22, 2023, maintaining the same treatments and the experimental design established in 2008. Sample collection for the analysis of greenhouse gas fluxes (CO₂, N₂O, and CH₄) began on February 28, 2022, and lasted until February 16, 2023, covering practically the entire period of the experiment.

Manual static cameras were used (Steudler et al. 1991). Each plot received one chamber, totaling four chambers per treatment. The bases were kept in the soil throughout the evaluated period, removed only when it was necessary to carry out management in the area (liming, sowing, harvesting), and were immediately reinstalled after the operations. The sampling periodicity was adjusted according to the seasonality of the rainfall and crop treatments (fertilization, sowing and harvesting). Thus, weekly sampling was carried out in the rainy season, biweekly sampling was carried out in the dry season, and as a result of fertilization, sowing and harvesting, sampling was carried out every two days, at an interval of 15 days. Finally, the flows were determined in 51 collections, of which 33 occurred in the rainy season and 18 occurred in the dry season.

The samples were collected between 09:00 h and 11:00 h, following the recommendation of Alves et al. (2012), to better represent the average daily flow. From the interior of the chamber, air samples were collected at 0, 15 and 30 min after the chamber was closed with polypropylene syringes (Becton Dickinson Ind. Cirur). A total of 20 ml of BD, which was stored in coolers with ice and transferred to 12 mL glass bottles preevacuated from Labco®, with a double layer of silicone in the caps at an interval of 2–3 h in the laboratory, was transferred to the Department of Soil Science at the Luiz de Queiroz College of Agriculture, University of São Paulo (ESALQ/USP), for analysis of CO₂, N₂O and CH₄ concentrations via gas chromatography via a Shimadzu GC-2014 chromatograph.

2.4 Crop dry matter and soybean yield

Dry mass sampling was carried out at the full flowering stage of cover crops and at the R6 stage of maize. For cover crops, two random samples of 1 m² each were selected per experimental unit, and for maize, five representative plants in each plot were randomly collected; these plants were carefully sectioned close to the ground, transported to the laboratory, and dried in a forced air circulation oven at a constant temperature of 65 °C until the weight of the samples was quantified in relation to their mass.

The soybean grain yield was estimated by harvesting the grain at 2 m in length from two lines demarcated in the experimental unit and expressed in kg ha⁻¹. The harvested grains were cleaned and weighed, and the yields were adjusted to 13% moisture.

2.5 Climate variables

In addition to the soil temperature (0.05 m) determined at each GHG collection, the minimum and maximum air temperature, rainfall, relative humidity and solar radiation data were obtained from the automatic weather station located less than 2 km from the experiment.

2.6 Calculations of greenhouse gas fluxes and global warming potential

Gas concentrations were obtained, and daily emissions were calculated from the average value of the four chambers of each treatment. The daily flows were determined via linear regression as a function of the sampling time (Hutchinson and Livingston 1993), and the accumulated emissions were estimated via linear interpolation between the means of the daily flows (Oliveira et al. 2021). Thus, the emission of gases in the annual period was obtained. Owing to the seasonality of regional rainfall, emissions were also analyzed for the interval of the rainy (rainy) and dry seasons and expressed in Mg ha⁻¹ of C-CO₂ and kg ha⁻¹ C-CH₄ and N-N₂O.

The partial global warming potential (pGWP) was calculated by multiplying the seasonal emissions of CH₄ and N₂O by their respective cumulative forcings over 100 years and adding the two values:

$$pGWP = CH_4 \times 28 + N_2O \times 276$$

where pGWP is the partial global warming potential (kg CO₂ eq ha⁻¹), and CH₄ and N₂O are the seasonal emissions of the two gases (kg ha⁻¹).

Finally, yield-scaled GHG emissions, emissions of GHG in relation to the unit of productivity, were calculated as the ratio between pGWP yield and soybean yield:

$$Y_{pGWAP} = pGWAP/GY$$

where pGWP is the partial global warming potential ($\text{kg CO}_2 \text{ eq kg}^{-1}$) and the grain yield GY (kg ha^{-1}).

2.7 Statistical analysis

GHG emissions were analyzed to determine the effects of crop system, season (drought and rain), and their interaction. In addition, the accumulated annual gas emission and the accumulated production of Dry mass (DM) grain yield (PGS) and emission intensity (IEN) were analyzed. The results were analyzed for homogeneity of the residuals (Shapiro–Wilk) and variance (Box Cox), transformed when necessary, and subjected to analysis of variance at the 0.05 level. When significant, the difference between means was evaluated by Tukey's test at the level of 0.05 via R software, version 4.3.

3 Results

3.1 Climatic seasonality during crop development

The total rainfall recorded between March 2022 and February 2023 was 1119.20 mm (Fig. 4). Of this total, 78% (871.6 mm) occurred during the rainy season, whereas 22% occurred during the dry season. Although the rainy season presented a considerable volume, the distribution of rainfall was irregular, with periods of drought that lasted more than ten consecutive days. In June, sporadic rainfall totaled 112 mm, contributing to the observed climate variability. During the rainy season, solar radiation increased significantly, with a peak incidence in November. The average daily temperatures showed little variation throughout the experimental period, ranging between 21.7 and 26.7 °C, whereas the soil temperature oscillated between 27.3 and 36.2 °C, indicating a lower variability (Fig. 4).

3.2 Fluxes of CO₂, CH₄ and N₂O gases in the soil

The GHG fluxes ranged from 167 to 3065 $\mu\text{g m}^{-2} \text{ day}^{-1}$ for C-CO₂, -6589 to 1529 $\mu\text{g m}^{-2} \text{ day}^{-1}$ for C-CH₄ and -61 to 2328 $\mu\text{g m}^{-2} \text{ day}^{-1}$ for N-N₂O (Fig. 5). The CO₂ fluxes varied over time, with recorded maxima of 2369, 3065, 1999, 1893 and 2868 $\mu\text{g m}^{-2} \text{ day}^{-1}$ and minimums of 281.167, 461, 258 and 285 $\mu\text{g m}^{-2} \text{ day}^{-1}$ in the S1, S2, S3, S4 and S5 systems, respectively. Notably, in S1, the fluxes of all gases increased after nitrogen fertilization in off-season corn (02/26/2022 and 03/13/2022) and in all systems after soybean sowing (09/13/2022). The flows subsequently decreased and largely stabilized, with minimum values occurring during the dry season.

In general, CH₄ fluxes showed positive peaks (efflux) during soybean cultivation in the rainy season (Fig. 5). These peaks ranged from 1214, 1053, 1529, 782 and 942 $\mu\text{g m}^{-2} \text{ day}^{-1}$

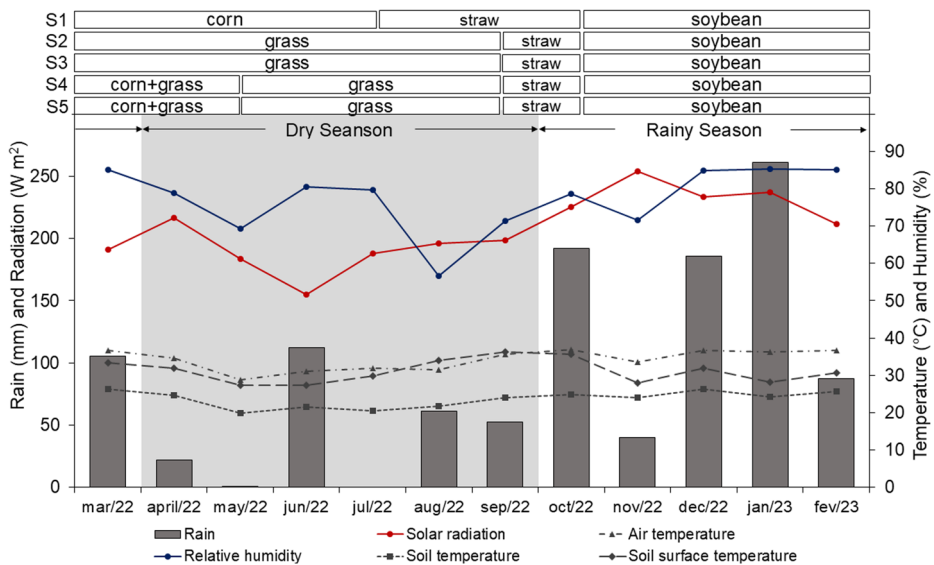


Fig. 4 Accumulated rainfall, solar radiation, air and soil temperature, and relative humidity in the experimental area in the rainy and dry seasons during the 2022/2023 agricultural year, Itaquira, Mato Grosso, Brazil. S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*

in the rainy season and reached minimum values of -6589, -1359, -955, -600 and -952 $\mu\text{g m}^{-2} \text{ day}^{-1}$ (inflow) in the dry season and in S1, S2, S3, S4 and S5, respectively.

The soil N₂O fluxes, in turn, showed maximum peaks of 2328, 639, 953, 590 and 648 $\mu\text{g m}^{-2} \text{ day}^{-1}$ and minimums of -6, -4, -23, -61 and -30 $\mu\text{g m}^{-2} \text{ day}^{-1}$ in systems S1, S2, S3, S4 and S5, respectively (Fig. 5). In particular, N₂O fluxes in the S1 cropping system increased significantly after nitrogen fertilization, with peaks recorded at 17 days after fertilization. Although all the systems presented multiple peaks of N₂O emissions during soybean cultivation, indicating high volatility, the fluxes in S4 and S5 remained consistently lower than those in the other systems throughout the study period.

3.3 Effects of climate seasonality and production system on greenhouse gas emissions

For GHG emissions, a significant interaction was observed between the seasons of the year and the production systems evaluated for the three gases evaluated (C-CO₂; $P=0.005$; C-CH₄; $P<0.001$; N₂O; $P<0.001$). In addition, differences were found in cumulative emissions (annual) and N₂O emission intensity (IEN) between production systems. The results revealed that the accumulated emission of CO₂ was impacted by the cropping system, with the S2 system presenting the highest emissions, with 5.0 Mg ha⁻¹ for the total period evaluated (Fig. 6B). The other systems presented average emissions of 3.0 Mg ha⁻¹. When comparing the general averages of the two seasons, we found that the rainy season presented CO₂ emis-

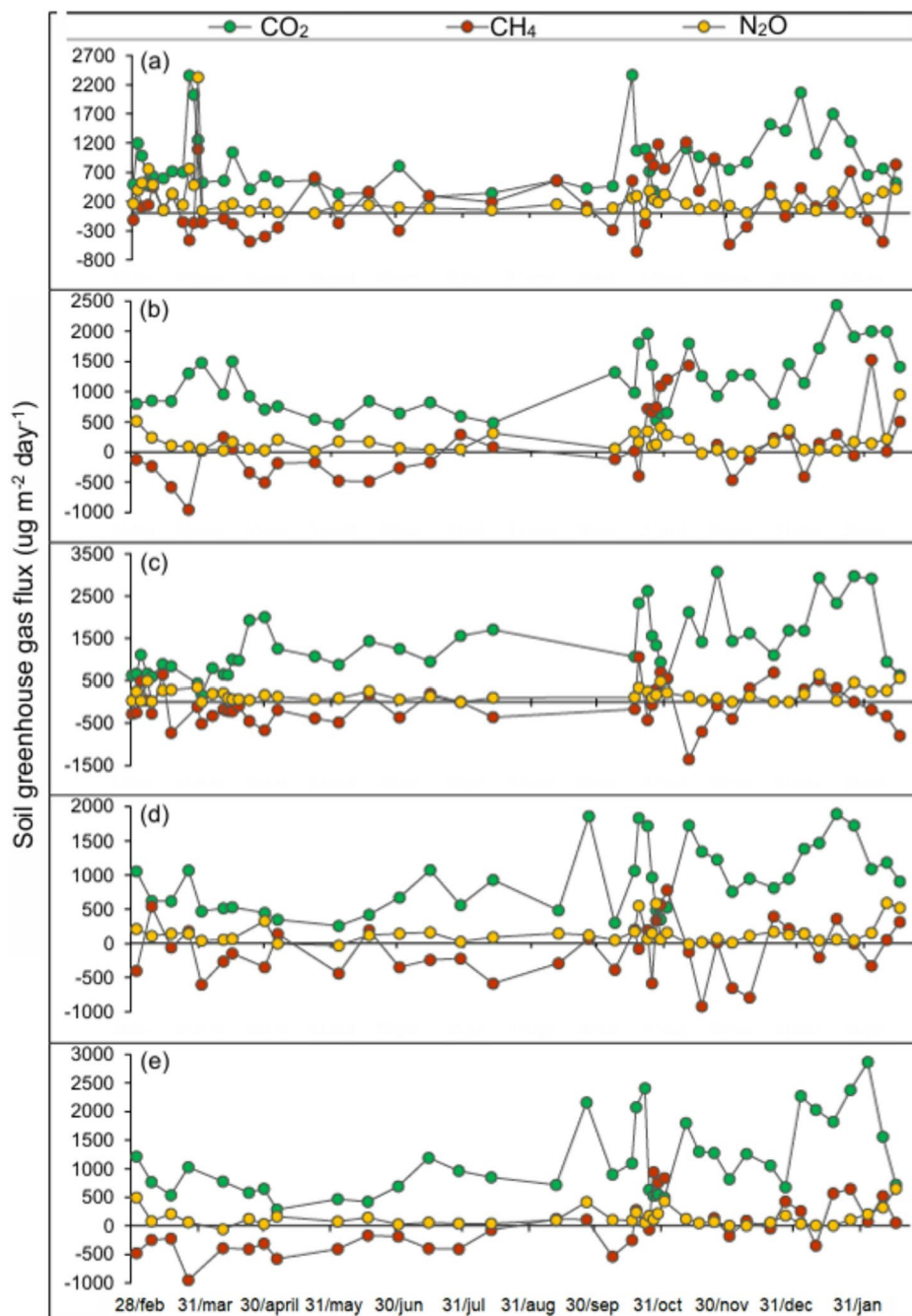


Fig. 5 Daily fluxes of CO₂, CH₄ and N₂O in µg m⁻² day⁻¹ in different production systems in a dystrophic red latosol (Typic Haplustox), Itiquira, Mato Grosso State, Brazil. **(a)** S1: soybean and corn succession system; **(b)** S2: soybean and *Urochloa ruziziensis* succession system; **(c)** S3: soybean and sunn hemp succession system followed by corn intercropped with *U. ruziziensis* that remains for 12 months; **(d)** S4: succession system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; **(e)** S5: soybean and pearl millet succession system, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*

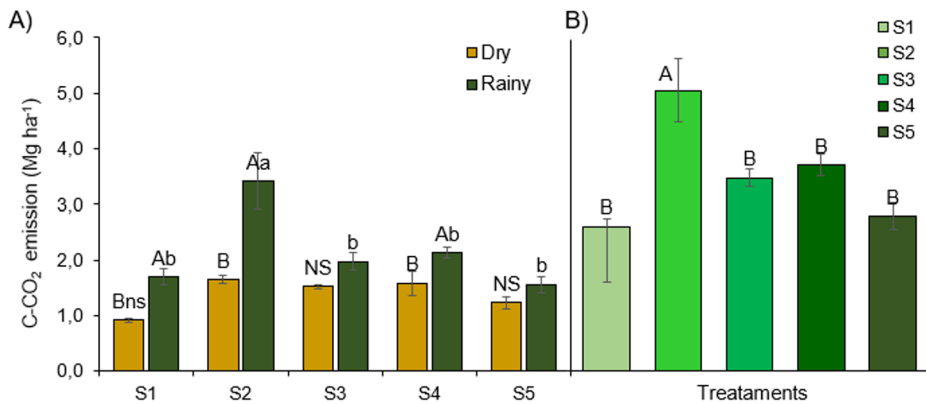


Fig. 6 C-CO₂ emissions per season (dry and rainy) (A) and accumulation during the evaluated period (B) in different soybean production systems in a dystrophic red latosol (Typic Haplustox), Itaquira, Mato Grosso, Brazil. Means followed by the same lowercase letter in the same column do not differ according to the Tukey test ($P < 0.05$). S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. Lowercase letters indicate significant differences among production systems within the same season according to Tukey's test ($p < 0.05$). Uppercase letters indicate significant differences between seasons (dry vs. rainy) within the same production system ($p < 0.05$). Values are means $\pm$ SE

sions that were approximately 57% higher than those of the dry season. The analysis of the interaction between the factors indicated that CO₂ emissions in the S1, S2 and S5 systems were higher in the rainy season than in the dry season (Fig. 6A). Approximately 65%, 67%, 56%, 57% and 56% of CO₂ emissions occurred during the rainy season in systems S1, S2, S3, S4 and S5, respectively. In particular, the S2 system presented CO₂ emission of 3.4 Mg ha⁻¹ during the rainy season, a value 46% higher than the average of the other systems, while no significant difference was observed between the systems during the dry season (Fig. 6A).

In general, CH₄ emissions were positive (efflux) during the rainy season, with an average of 0.15 kg ha⁻¹ C-CH₄, whereas in the dry season, the soil acted as a sink (inflow) of CH₄, with an average of -0.26 kg ha⁻¹ C-CH₄. A comparison of the accumulated CH₄ emissions between the systems revealed that the emissions were greater in S1 and S3, with 0.56 and 0.21 Mg ha⁻¹ C-CH₄, respectively. On the other hand, the S2, S4 and S5 systems mitigated CH₄ emissions, as indicated by the negative flow values, indicating the consumption of CH₄ by microorganisms in the soil (Fig. 7B).

When the magnitude of C-CH₄ emissions between the dry and rainy seasons was evaluated, only the S2 system did not present a significant difference (Fig. 7A). On the other hand, at both stations, this system effectively mitigated C-CH₄ emissions. During the rainy season, the S3 system presented average CH₄ emissions that were 16, 143, 111 and 57% higher than those of the S1, S2, S4 and S5 systems, respectively. The S2 and S4 systems remained CH₄ sinks, with inflows of 0.19 and 0.05 kg ha⁻¹ of C-CH₄, respectively (Fig. 7A). During the dry season, the S1 system resulted in 0.20 kg ha⁻¹ of C-CH₄, which was 150, 116, 230 and 274% higher than those of the S2, S3, S4 and S5 systems, which acted as CH₄ sinks, as indicated by the observed inflow values (Fig. 7A).

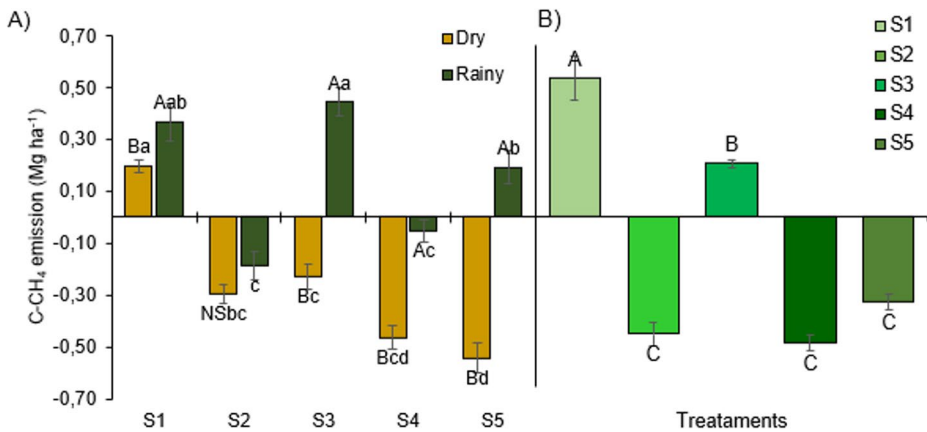


Fig. 7 C-CH₄ emissions per season (dry and rainy) (A) and accumulation during the evaluated period (B) in different soybean production systems in a dystrophic red latosol (Typic Haplustox), Itiquira, Mato Grosso, Brazil. Means followed by the same lowercase letter in the same column do not differ according to the Tukey test ($P < 0.05$). S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. Lowercase letters indicate significant differences among production systems within the same season according to Tukey's test ($p < 0.05$). Uppercase letters indicate significant differences between seasons (dry vs. rainy) within the same production system ($p < 0.05$). Values are means $\pm$ SE

N₂O emissions were highest in the rainy season, with an average of 0.29 kg ha⁻¹ N-N₂O. When the accumulated emissions of N₂O were evaluated, the highest emissions occurred in the S1, S2 and S3 systems, with values of approximately 0.55, 0.52 and 0.51 kg ha⁻¹, respectively. On the other hand, the S4 and S5 systems presented an average of 0.40 kg ha⁻¹ of N-N₂O, which was statistically lower than that observed in the S1 system (Fig. 8B). Among the stations, only the S1 and S2 systems presented significantly higher N-N₂O emissions in the rainy season, with values that were 131 and 171% higher than those reported in the dry season, respectively. N-N₂O emissions during the rainy season were greater in the S1 and S2 systems than in the S3, S4 and S5 systems by 30, 40 and 45%, respectively (Fig. 8). During the dry period, the S3 system recorded the highest N-N₂O emissions among the systems, with values 33, 42, 29 and 25% higher than those of the S1, S2, S4 and S5 systems, respectively (Fig. 8A).

Considering the pGWPs of the systems, a significant difference was observed between the treatments. Compared with the other systems, the S4 and S5 systems presented lower pGWPs, with values of 1558 and 155 kg ha⁻¹ of CO₂, respectively (Fig. 9). In contrast, the S1 and S3 systems emitted the highest amounts of CO₂, at 260 and 228 kg ha⁻¹, respectively (Fig. 9).

3.4 Dry mass (DM) and soybean grain yield (PGS) of the production systems

The S3 system had the lowest PGS, with a reduction of approximately 5% in relation to the other systems, which did not present significant differences between them (Table 3).

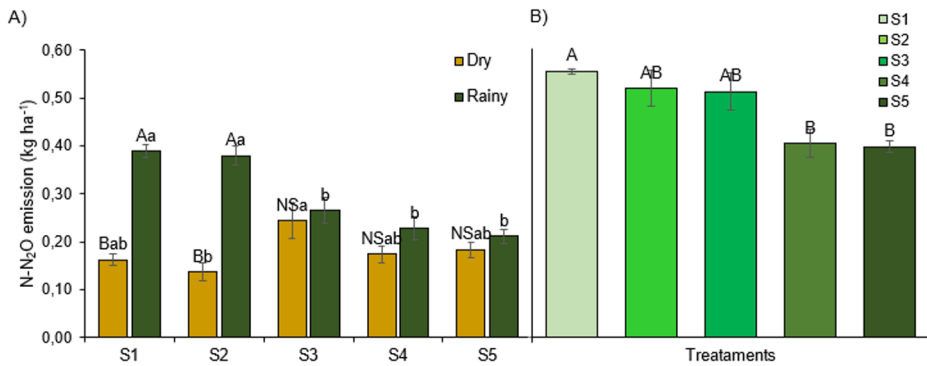


Fig. 8 N-N₂O emissions by season (dry and rainy) (A) and accumulation during the evaluated period (B) in different soybean production systems in a dystrophic red oxisol (Typic Haplustox), Itiquira, Mato Grosso State, Brazil. Means followed by the same lowercase letter in the same column do not differ according to the Tukey test ($P < 0.05$). S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. Lowercase letters indicate significant differences among production systems within the same season according to Tukey's test ($p < 0.05$). Uppercase letters indicate significant differences between seasons (dry vs. rainy) within the same production system ($p < 0.05$). Values are means $\pm$ SE

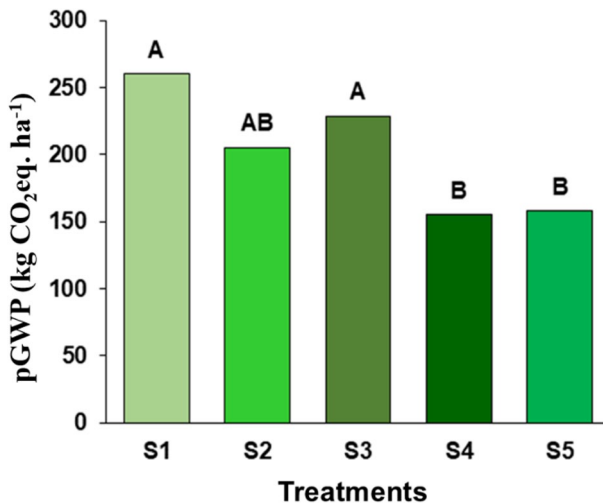


Fig. 9 Partial global warming potential in different soybean production systems in a dystrophic red oxisol (Typic Haplustox), Itiquira, Mato Grosso State, Brazil. Means followed by the same lowercase letter in the same column do not differ according to the Tukey test ($P < 0.05$). S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with rotation of soybean and millet, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*

Table 3 Grain yield of corn (PGM) at the 2021/22 harvest, soybean (PGS) at the 2022/2023 harvest and dry matter production (DM) at the 2021/2022 harvest in different production systems in a dystrophic Red Latosol (Typic Haplustox) in the Brazilian Cerrado

Production System	PGM kg ha ⁻¹	PGS	DM Mg ha ⁻¹
S1	4124 b	4091,42 a	8,06 c
S2	-	4028,67 ab	10,00 bc
S3	-	3909,55 b	22,87 a
S4	10,844 a	4086,14 a	14,23 b
S5	10,504 a	4132,36 a	14,22 b
Media	5094,55	4049,63	13,88
CV (%)	179,0	1,61	17,31

Means followed by the same lowercase letter in the same column do not differ according to the Tukey test ($P < 0.05$). S1: soybean and corn succession system; S2: soybean and *Urochloa ruziziensis* succession system; S3: system with rotation of soybean and sunn hemp followed by corn intercropped with *U. ruziziensis* that remains for 12 months in the planting area; S4: rotation system with soybean and sunn hemp, followed by soybean and corn intercropped with *U. ruziziensis*; and S5: system with soybean and pearl millet rotation, followed by soybean and sunn hemp and, finally, corn intercropped with *U. ruziziensis*. *Dry matter in S4 and S5 is the sum of corn plants (resteva) plus *Urochloa ruziziensis*, and the DM accumulation of previous crops must be taken into account in all systems

However, in terms of DM productivity at the 2021/2022 harvest, the S1 and S2 systems had the highest MS2022/20,223 yields, and the S3 system had the highest productivity, being approximately 65, 56, 38 and 38% higher than those of the S1, S2, S4 and S5 systems, respectively, which did not differ (Table 3). These results indicate that the highest yields were achieved with DM yields ranging between 8.1 and 14.23 Mg ha⁻¹, whereas the lowest DM yield was recorded in S3, with a value of 22.9 Mg ha⁻¹.

With respect to the corn yield in the treatments in which it was cultivated (S1, S4 and S5) during the 2022/23 harvest, the systems under crop rotation, such as S4 and S5, presented significantly greater yields than did the soybean/corn successional system (S1). The corn yields in the S4 and S5 systems were approximately 163% higher than those observed in the S1 system (Table 3).

4 Discussion

This study demonstrated that soil acted as a significant source of CO₂ in all the systems evaluated, with relatively high emissions during the rainy season. The higher emissions associated with the rainy season are related to the greater activity of microorganisms in the soil. The increase in soil moisture, associated with the relatively high temperatures recorded during this period, are factors that condition the increase in microbial activity, impacting the oxidation of soil organic matter and biomass added by the cultivated plant component. The results corroborate the literature indicating that soils in tropical regions, which are subjected to high temperatures and irregular precipitation, are highly vulnerable to CO₂ emissions due to the acceleration of microbial activity (Davidson and Janssens 2006). The soil temperatures, ranging from 19 to 35 °C, were adequate to promote maximum soil microbial activity, with reductions outside this range (Moreira and Siqueira, 2006).

These results confirm that the growth phase of crops, especially soybean, intensifies CO₂ emissions. The rainy season results in the highest growth rates of the plant component, which consequently promotes an increase in the rates of biomass (C) addition to the soil, either at the end of the cycle with the senescence process or through the addition of rhizodeposits that occur throughout the crop cycle (Cotrufo and Lavalée 2022). Additionally, higher growth rates of plant components are expected to lead to increased root respiration, a process that contributes significantly to increased soil biological activity and the release of CO₂ (Rigon et al., 2018; Hatfield and Parkin 2012). Research indicates that up to 50% of emissions in agricultural systems are derived from root respiration during periods of high metabolic demand for crops (Feng et al. 2013; Sainju and Singh 2008; Wilson and Al-Kaisi 2008). The lower accumulated emissions of CO₂ in the S3, S4 and S5 systems than in the succession systems (S1 and S2) may be associated with the frequent presence of cover crops. The presence of cover crops promotes an increase in organic matter in the soil, which affects the stability of soil aggregates (Shakoor et al. 2021; Breil et al. 2023). The addition of carbon, mainly through low-molecular-weight compounds, is one of the effective mechanisms for the aggregation process. Organic compounds of low molecular weight act as condensation nuclei, which start to form associations with the mineral fraction of the soil, which can generate stable aggregates (Lal 2015). Similarly, the addition of more complex organic compounds (e.g., roots) also contributes to the formation of stable macroaggregates. Macroaggregates are mostly formed through biotic action, either by roots or organisms (the action of hyphae or macrofauna) (Li et al. 2024). In summary, the formation of stable aggregates can increase the C sequestration rate and consequently reduce CO₂ emissions. Additionally, the presence of cover crops in the system can benefit the soil microbial community (Lange et al. 2015). A greater diversity of organic compounds added via the plant component associated with a diverse microbial community can contribute positively to increasing the efficiency of metabolization of the organic fraction by microorganisms, increasing the efficiency of substrate use and thus reducing CO₂ emissions (Cotrufo and Lavalée, 2022).

In the rainy season, the soil acted as a source of CH₄ in S1, S3 and S4, whereas in the dry season, only S1 maintained positive emissions. The negative values recorded in other systems highlight the capacity of soils under diverse management practices to act as CH₄ sinks. In general, approximately 80% of the methane produced via methanogenesis is estimated to be oxidized in the soil before it reaches the surface via methanotrophic microorganisms (Serrano-Silva et al. 2014). This behavior can be intensified by the presence of cover crops, such as grasses, which promote greater soil aeration and create favorable microclimates for methanotrophic microorganisms (Szafranek-Nakoneczna et al. 2019). These results are in agreement with studies that associate CH₄ fluxes with the proportions of methanogenic and methanotrophic microorganisms, which are determined by the availability of oxygen and organic substrates (Neto et al. 2011). Diversification through the presence of cover crops can contribute to the maintenance of the community of methanotrophic microorganisms, thus reducing the possibility of gas emissions. On the other hand, the higher emission of CH₄ in S3 in the rainy season may be associated with higher soil moisture, possibly due to the greater addition of DM (Table 3). The maintenance of soil moisture associated with high-intensity precipitation events can contribute to the formation of anaerobic microsites in the soil, which favor the redox conditions necessary for the production of gas (Neto et al. 2011).

The higher emission of CH₄ in the S1 system, even in the dry season, may be associated with nitrogen fertilization in corn, which may affect the methanotrophic process in the soil. The presence of ammonium (NH₄⁺) in large quantities can inhibit the oxidation of CH₄, promoting an increase in emissions. Methanotrophic microorganisms can use NH₄⁺ (Acton and Baggs, 2011; Reay and Nedwell 2004) to replace CH₄. This behavior reinforces the need for management strategies that balance the use of agricultural inputs and the mitigation of GHG emissions (Israel et al. 2020). Similarly, the addition of large quantities of mineral nitrogen is also directly associated with increased N₂O emissions, especially in the S1 system. In addition to the effect of the addition of mineral N, the N₂O fluxes exhibited uniform behavior between the systems, with higher emissions in the rainy season, highlighting the role of precipitation in stimulating denitrification. Intense precipitation events can lead to the formation of anaerobic sites, which trigger the denitrification process. On the other hand, the impact of management with cover crops on N₂O emissions was evident, with more diversified systems, such as S4 and S5, resulting in lower accumulated emissions. As observed for CH₄, cover crops may effectively contribute to the improvement of soil physical quality. Greater structuring through the formation of stable aggregates contributes to better soil aeration, reducing the occurrence of anaerobic sites. In addition, the continuous presence of cover crops contributes to increasing the efficiency of nitrogen use in the soil, thus reducing the proportion of the substrate used in the denitrification process (Blanco-Canqui and Ruis 2020).

From a practical standpoint, these findings indicate that agricultural areas in the Brazilian Cerrado can significantly reduce GHG emissions by prioritizing diversified no-till systems incorporating high-biomass cover crops. Regional agricultural programs could incorporate these results by promoting crop-rotation schemes that emphasize C4 grasses and by regulating nitrogen fertilization to minimize ammonium-driven inhibition of methane oxidation. Additionally, extension services could use these indicators to develop technical recommendations for optimizing soil moisture management in high-rainfall periods, reducing the formation of anaerobic microsites that drive CH₄ and N₂O emissions. Such strategies align with ongoing regional initiatives focused on low-carbon agriculture and can support more sustainable land-use policies in the Cerrado. The pGWP is a relevant metric for evaluating the efficiency of production systems. The S4 and S5 systems, which combine rotation with greater crop diversity, presented the lowest pGWPs, indicating greater potential to mitigate global warming. These results show that diversified agricultural systems promote a reduction in environmental impact without compromising crop productivity. These patterns reinforce the need for regional management policies that encourage diversified cropping arrangements as part of mitigation strategies. Incorporating cover crops into local conservation-agriculture guidelines could improve nitrogen-use efficiency and prevent emissions peaks during the rainy season. Public incentives could also target the adoption of management systems (S4 and S5) that showed superior performance in reducing GHG emissions.

In terms of DM and PGS productivity (Table 3), the S3 system presented the highest DM productivity in the 2021/22 harvest for only *U. ruziziensis*. This finding reinforces the importance of adjusting agricultural management to balance biomass inputs and the productive performance of subsequent crops. Studies suggest that for high yields, at least 11.5 Mg ha⁻¹ year⁻¹ of DM is necessary. However, excess biomass in the soil can compromise the establishment of crops due to mechanical difficulties in planting (Aratani Pires et al. 2008, 2006). Therefore, crop residue management strategies are essential for optimizing the

relationship between DM and PGS, ensuring benefits in both nutrient cycling and soil protection. Ultimately, the results demonstrate that the combination of crop rotation and diversification practices is an effective approach to minimize GHG emissions and increase the sustainability of agricultural production in the Brazilian Cerrado. However, species choice and crop management play critical roles in the success of these strategies. Future studies should explore how different crop combinations and levels of intensification affect emission dynamics in tropical systems, particularly considering climate change and global agricultural sustainability demands (Duku et al. 2018).

5 Conclusion

The results indicate that the evaluation period (dry or rainy season) played a central role, with higher emissions observed during the rainy season. At a regional scale, these findings provide actionable guidance for environmental and agricultural agencies in the Cerrado. Policies that support diversified no-till systems, particularly those incorporating high-residue cover crops, may effectively reduce GHG emissions while maintaining productivity. Including such practices in regional low-carbon agriculture programs could help mitigate climate impacts and improve the resilience of production systems under increasingly variable rainfall patterns. On the other hand, diversified systems demonstrated greater mitigation potential during the dry season. Crop diversification and rotation reduced accumulated CO₂ and N₂O emissions, in addition to increasing CH₄ absorption, indicating its effectiveness in mitigating greenhouse gas (GHG) emissions in no-till systems. The reduction in N₂O emissions and the increase in CH₄ influx in the most diverse systems are possibly associated with improved soil physical quality and more efficient use of fertilizers, especially nitrogen applied via mineral fertilization. These results highlight the potential of diversifying agricultural systems to reduce GHG emissions and promote low-carbon production practices in tropical regions.

Author Contribution Jessica Heloiza Coutinho: Data curation, formal analyses, Investigation, Writing – Original draft. Saul Ramos de Oliveira: Conceptualization, Supervision, Funding acquisition, Methodology. Hilário Junior Almeida: Formal analyses, Methodology. Jorge Luiz Locatelli: Formal analyses, Investigation, Methodology. Cimélio Bayer: Formal analyses, Investigation, Methodology. Maria Eloá de Lima: Formal analyses, Investigation, Methodology. Carlos Eduardo Pellegrino Cerri: Data curation, formal analyses. Luiz Guilherme Santos de Oliveira: Data curation, formal analyses, Investigation. Edicarlos Damacena Souza: Data curation, formal analyses, Investigation.

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Data Availability The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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