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Impact of different *Brachiaria ruziziensis* management practices in a crop-livestock integration system on soil health, soybean physiology, and yields

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ABSTRACT

The utilization of *Brachiaria ruziziensis* (Congo grass) has been consolidated as a strategy to integrate livestock and agriculture (crop-livestock integration system), promoting sustainability and agricultural productivity. However, how different management practices of the forage crop during the off-season affect soil health and soybean physiology remains uncertain. This study aimed to compare conventional soybean cultivation with systems in which soybean is grown under soil cover residues under different *Brachiaria ruziziensis* management practices (free growth, cutting and regrowth of the forage, and grazing in the off-season) in a crop-livestock integration system, and to evaluate how these systems affect chemical and biological properties, cover biomass production, nutrient concentration, soil microclimate, and respiration. Additionally, physiological parameters, plant growth, and soybean yields were assessed. The experiment was conducted on a Quartzarenic Neosol (Entisol) soil using a randomized complete block design with four replicates. The treatments consisted of biomass production: *Brachiaria ruziziensis* in free growth; *Brachiaria ruziziensis* with cutting and regrowth of the forage and *Brachiaria ruziziensis* under grazing in the off-season and an additional treatment of soybean cultivation without soil cover biomass. Results showed that the free growth of *B. ruziziensis* produced the highest soil cover biomass, while *B. ruziziensis* under grazing exhibited higher concentrations of nitrogen, phosphorus, potassium, and sulfur in the soil cover biomass and improved soil chemical attributes. Regardless of management type, systems with soil cover residues demonstrated lower soil temperatures, higher soil moisture, and increased enzymatic activity. Consequently, soybean plants in crop-livestock integration systems exhibited higher chlorophyll indices, resulting in taller plants with greater aboveground biomass production and an average 20.9 % increase in grain yield compared to soybean grown without soil cover residues. These findings highlight that crop-livestock integration systems in a Quartzarenic Neosol (Entisol) soil contribute to reducing mineral fertilizer, favoring the sustainability of agricultural production. Long-term studies to further explore these effects are strongly encouraged.

1. Introduction

Climate change, driven mainly by human activity, has emerged as one of the most urgent global challenges nowadays (Bieluczyk et al., 2024). Climatic events have altered temperatures and precipitation patterns on Earth (Bhatti et al., 2024). Greenhouse gas (GHG) emissions have triggered extreme events such as prolonged droughts and excessive rainfall, aggravating agricultural insecurity (IPCC, 2019). Therefore, the

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academic community has been searching for sustainable and resilient ways to improve agricultural systems to ensure food security while minimizing environmental damage in a scenario of population growth and the challenges posed by environmental pollution in a changing climate (Delandmeter et al., 2024; Feng et al., 2024).

In this context, the crop-livestock integration system is considered a promising strategy, capable of providing various ecosystem services, mitigating climate change (Oliveira et al., 2024), increasing soil health (Bratti et al., 2022), promoting efficient land use (Leal et al., 2024) and diversifying production (Szymczak et al., 2020; Nunes et al., 2021). These systems promote the efficient use of resources (Meunier et al., 2024), and have the potential to retain greater moisture in the soil and reduce its temperature through soil cover (Calonego et al., 2017), promote greater carbon sequestration by plants (Chakraborty et al., 2024), as well as contributing to reducing the use of fertilizers (Dias et al., 2020; Silva et al., 2023) by improving soil fertility and consequently increasing crop yields (Silva et al., 2024a, 2025).

Crop-livestock integration systems are characterized by integrating, in the same area, agricultural and livestock activities in rotation, succession, or intercropping, generating synergistic effects (Cherubin et al., 2023; Chakraborty et al., 2024), being capable of promoting the recovery and increased productivity of pastures (Damian et al., 2023), improving animal performance (Dias et al., 2021), which, in turn, contribute to improvements in soil fertility through the recycling of feces and urine, improving the accumulation of carbon (C) and the availability of nutrients in the soil (Soares et al., 2023; Chakraborty et al., 2024). They also produce soil cover biomass for the no-till system (Silva et al., 2024c). Additionally, benefits to the soil's biological properties have been observed, such as increased microbial activity (Mendes et al., 2021) and weed suppression, reducing the use of pesticides (Jenkins et al., 2024).

It is important to note that the biological properties of the soil when combined with the chemical properties, serve as indicators of soil quality (Carneiro et al., 2024). The chemical properties are related to the storage and supply of nutrients and the biological properties are related to nutrient cycling, which are closely related to crop yields (Serafim et al., 2023; Camargo et al., 2024). Among these indicators, the enzymatic activity of β-glucosidase, acid phosphatase, and arylsulfatase is of great importance for understanding soil health (Mendes et al., 2021), responding to soil management practices much earlier than other changes in soil quality indicators (Chaer et al., 2023).

Among the forage species frequently used in this system in tropical regions, *Brachiaria ruziziensis* (Congo grass) stands out for its good forage production during the off-season, which can meet the nutritional needs of animals (Baptistella et al., 2020), and for providing adequate soil cover for no-till farming (Camargo et al., 2024), in addition to having high nutrient cycling potential for the following crop (Volf et al., 2023; Dias et al., 2021). Thus, the use of *Brachiaria ruziziensis* has been consolidated as a strategy to integrate livestock and agriculture, promoting both the sustainability and productivity of the system as a whole (Leal et al., 2024; Prado et al., 2025). However, defining the management strategy to promote *Brachiaria* as a cover crop is essential for the success of the crop-livestock integration system under no-till farming, whether through grazing (Nunes et al., 2021) or developing the forage solely for soil cover (Silva et al., 2024a).

Over the last few years, the benefits of crop-livestock integration systems on soil characteristics and crop and animal productivity have been discussed in the scientific community (Muniz et al., 2021; Chakraborty et al., 2024; Prado et al., 2025). However, there is still a gap in knowledge regarding the impact of these systems on the physiological characteristics of plants grown in succession, especially soybeans (Silva et al., 2024c), and how the biochemical and physiological mechanisms in plants grown in these systems are responsible for improving plant development.

Evidence shows that in the crop-livestock integration system, soil moisture is maintained for longer, due to the soil cover residues that protect it from solar radiation (Lal, 2020), allowing growing plants in this system to show greater stomatal conductance, transpiration flow, and consequently better nutrient transport (Buckley, 2019). In addition, due to the greater availability of nutrients, greater chlorophyll biosynthesis and photosynthesis can be expected (Jiang et al., 2024), increasing biomass accumulation, with greater above-ground carbon fixation (Hussain et al., 2021; Silva et al., 2025) and a more efficient photosystem with a higher chlorophyll content (Barreto et al., 2020).

Therefore, this study aimed to compare the conventional method of growing soybeans with regimes in which soybeans are grown on soil residues from different previous management of *Brachiaria ruziziensis* (free growth, cutting and regrowth of the forage, and grazing in the off-season) in a crop-livestock integration system and how these systems affect the chemical and biological properties of the soil, the production of soil cover residues, concentration of nutrients, the microclimate and soil respiration. As well as the physiological parameters, growth, and yield of soybean plants. The hypothesis is that using *Brachiaria ruziziensis* during the off-season will enhance the concentration of nutrients in the ground cover biomass. Additionally, this practice is expected to positively influence the soil's chemical and biological properties as well as improve microclimate conditions. Soybeans grown on grazing residues would result in better soil chemical properties and higher enzyme activity, as well as higher photosynthetic rates, chlorophyll content, above-ground biomass production, and grain yield compared to the other *Brachiaria ruziziensis* management systems.

2. Material and methods

2.1. Experimental site

The study was conducted at Fonseca Farm, located in the rural area of the municipality of Jataí, Goiás, Brazil (17° 54' 00" S and 51° 15' 47" W, at an altitude of 756 m) from March 2021 to February 2022, encompassing two agricultural harvests (Fig. 1). According to the Brazilian soil classification system, the soil in the study area was classified as Quartzarenic Neosol (Santos et al., 2018), Entisol in the USA Keys of Soil Taxonomy (Soil Survey Staff, 2014), with 112; 17; and 871 g kg^{-1} of clay, silt, and sand, respectively. The terrain in this region is gently undulating, suggesting a high potential for the cultivation of plants of significant agronomic interest (Severiano et al., 2013).

The climate of the region, according to the Köppen-Geiger classification (Cardoso et al., 2014), is defined as Megathermal or Tropical Wet (Aw), of the Tropical Savanna subtype, with dry winters and rainy summers. In Fig. 2, it is possible to observe a timeline of the main events that occurred during the experimental period and the climatic conditions. During the experiment, the average annual temperature was 24.1 °C, and the annual precipitation was 1700 mm.

In September, chicken litter was incorporated into the soil at a dose of 4 t ha^{-1} in all the management systems (treatments). For the chemical characterization of the chicken litter, five sub-samples of chicken litter were collected at random to obtain a composite sample, the results of which are shown in Table 1.

2.2. Experimental design and treatments

The experimental design used was randomized complete blocks, with four replications. The treatments consisted of biomass production: *Brachiaria ruziziensis* in free growth; *Brachiaria ruziziensis* with cutting and regrowth of the forage and *Brachiaria ruziziensis* under grazing in the off-season (Fig. 3). As well as an additional treatment of soybeans without cover biomass (Soybean without soil cover treatment).

The area for free-growing *Brachiaria ruziziensis* and *B. ruziziensis* with cutting and regrowth was 2000 m each. The grazing area for the animals was 135 ha and for soybeans without soil cover was 100 ha. The first stage of the research was implemented on March 20, 2021. For the biomass production, *Brachiaria ruziziensis* was sown in all areas after the

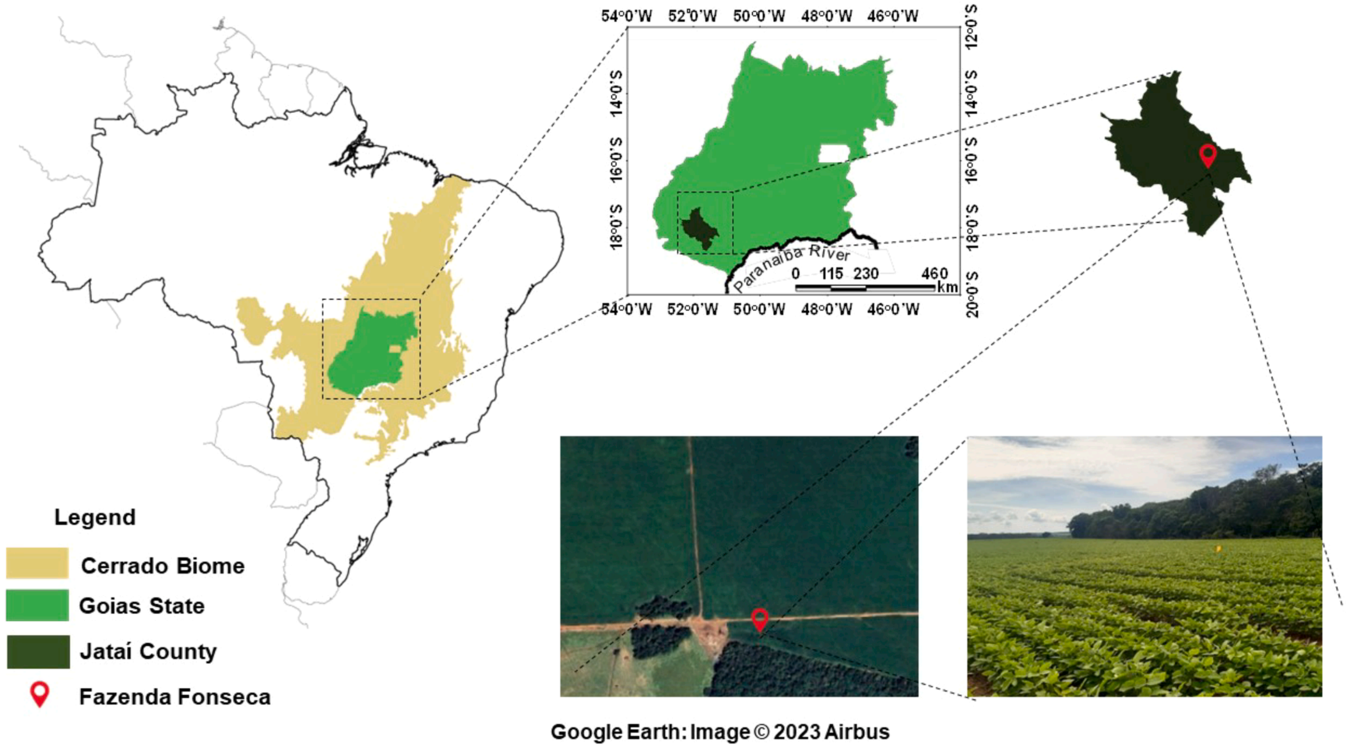

Fig. 1. Experimental area during the experiment in Jataí, Goiás, Brazil.

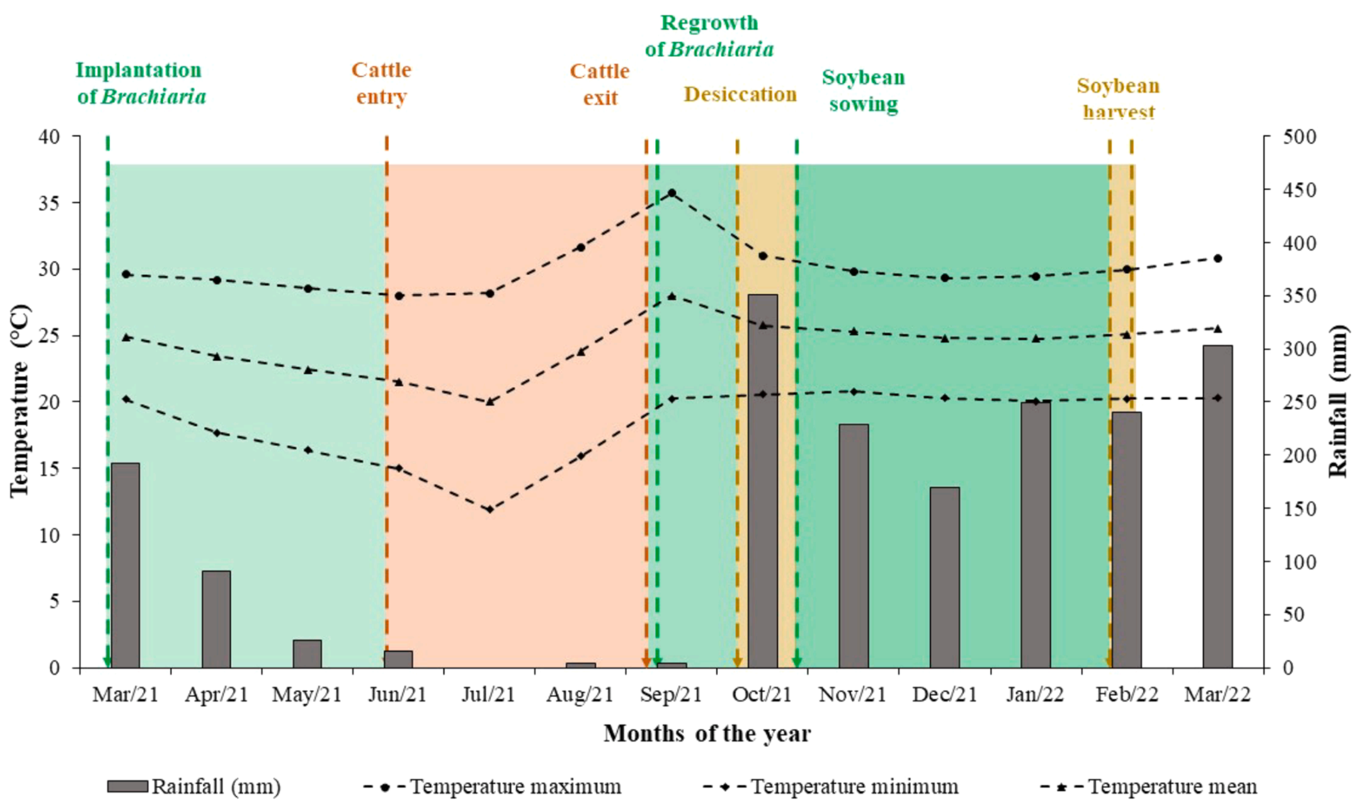

Fig. 2. Monthly rainfall and temperatures recorded during the period from March 2021 to February 2022 in Jataí, Goiás.

soybean harvest. For implementation, 5.0 kg of pure viable *Brachiaria* seeds with a cultural value of 85 % were used and distributed in the areas using lancer equipment. No planting or top dressing was carried out to take advantage of the nutrients in the soil after the soybean harvest.

For the off-season grazing system, in June 2021, after the *Brachiaria ruziziensis* had developed (90 days after sowing - DAS), the animals were introduced to the system. 132 F1 cows were used, with an average age of

Table 1
Chemical characteristics of the chicken litter.

N	P	K	Ca	Mg	S-SO_4	Fe	Mn	Cu	Zn	B
g kg^{-1}						mg kg^{-1}				
42.9	15.0	26.3	128.8	7.2	8.3	772.5	435.9	63.1	136.6	11.5
pH			**D.M**			**OC**			**C/N**	
$CaCl_2$			%			g kg^{-1}				
7.9			83.7			340.1			7.9	

S-SO_4: sulfur sulfate; D.M: dry matter; OC: organic carbon; C/N: carbon/nitrogen ratio

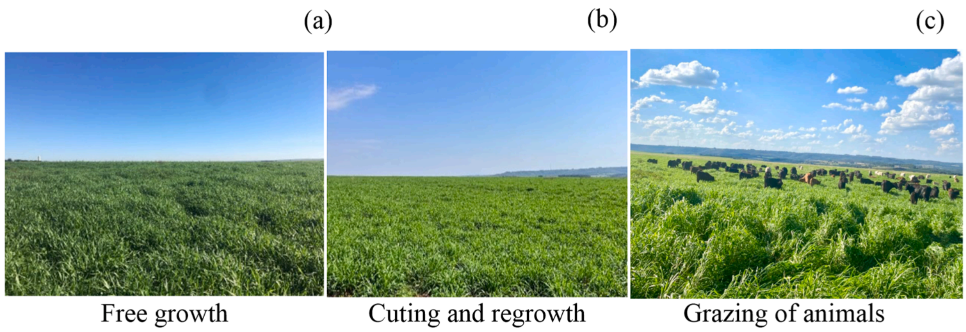

Fig. 3. Demonstration of the treatments (management systems): free growth (a), cutting and regrowth (b) and grazing (c) of *Brachiaria ruziziensis* during the off-season.

36 months. The animals remained in the system for 90 days (off-season), in a continuous grazing system. At the beginning of September 2021, the animals were removed from the area and the forage remained at rest for regrowth. For the cut and regrow system, the forage was cut in August 2021, using a hydraulic brush cutter to cut the forage 15 cm off the ground. For the free-growing system, *Brachiaria ruziziensis* remained in growth from March to October 2021. *Brachiaria ruziziensis* was desiccated in the different cropping systems in October 2021, with glyphosate applied at a dose of 3 L ha^{-1} (480 g L^{-1} of active ingredient).

2.3. Soybean planting in the 2021/2022 season

Soil samples were collected from the 0–20 cm layer to determine the soil's chemical characteristics. Only one analysis was carried out on the total area of the experiment, including all the treatments, according to the results in Table 2.

According to the chemical analysis recommendation, 1.125 tons ha^{-1} of limestone filler (100 % Total Relative Neutralizing Power) was applied for the 2021/2022 harvest. Soybeans were sown in the different cover biomass production management on October 23, 2021, using the IPRO bonus cultivar (this cultivar has a medium to tall plant height and a medium cycle), sown mechanically, with a row spacing of 0.50 m. No phosphate fertilizer was applied at sowing in all the management systems, due to the high levels of phosphorus in the soil (Table 2). Potassium was only applied in the treatment without soil cover biomass, at a dose of 85 kg ha^{-1} of K_2O in the form of potassium chloride. In the treatments with soil cover biomass, no potassium fertilization was applied to take advantage of the cycling of this nutrient through the biomass. The fungicide was applied at 40 and 65 days after sowing - DAS (dose of 0.4 L ha^{-1} of Pyraclostrobin). The soybean development cycle was 120 days, and the harvest took place on February 19, 2022 (Figs. 2 and 4).

2.4. Analyses

2.4.1. Biomass production

To determine soil cover biomass production was used the square method (0.50 × 0.50 m, 0.25 m^2). Measurements were taken 21 days after desiccation of the different biomass production managements of the *B. ruziziensis*. Three squares were placed on the ground in each treatment, and biomass was collected from each area. The plant material was then placed in a forced-air circulation oven at 55°C until it reached a constant weight.

2.4.2. Biomass initial nutrient concentration

After drying, biomass samples were ground using a knife mill with a 1 mm sieve and stored in plastic containers for nutrient concentration determination: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) following the methodology proposed by Malavolta et al. (1997).

2.4.3. Soil microclimate and soil respiration

One soil sample per plot weas collected at 85 days after soybean sowing, using a 20 cm deep soil probe immediately following soil respiration measurements near the polyvinyl chloride (PVC) collars. Samples were placed in sealed plastic bags. Samples were initially weighed to determine fresh weight (FW), then dried in an oven at 70°C until reaching constant weight to measure dry weight (DW). Soil moisture content was calculated using FW and DW values. Surface temperature was measured with an infrared surface thermometer (Testo 835–T1), while soil temperature at 8 cm depth was recorded using a soil thermometer.

Table 2
Chemical characteristics of a Quartzarenic Neosol (Entisol) at a depth of 0–20 cm before soybean planting in the 2021/2022 season.

Season 2021/2022	pH	Ca	Mg	Al	H+Al	K	CEC	P	Zn	B	Cu	V_1	OM
	$CaCl_2$	cmol$_c$ dm^{-3}						mg dm^{-3}				%	g kg^{-1}
	5.3	2.12	1.15	0.01	3.4	0.31	6.98	23.6	1.08	5.3	0.18	51.3	20

CEC: cation exchange capacity; P: Resine; V_1: base saturation; OM: organic matter

Fig. 4. Soybean development on the ground cover biomass of *Brachiaria ruziziensis*.

Soil respiration was measured using a soil CO_2 Flux System LI-8100A (LI-COR, NE, USA) with a manually operated 20 cm diameter chamber was employed. Measurements were conducted between 8 am and 11 am, consistent with Gonzalez-Meler et al. (2017). PVC collars, 20 cm in diameter, were installed centrally in each plot between soybean rows devoid of plants. Each collar was inserted 5 cm below ground level and extended 5 cm above ground level.

2.4.4. Soil chemical analysis and soil enzymatic activity analysis

After soybean harvest, soil chemical properties (macro and micronutrients) in the 0.0–0.1 m layer were evaluated using a composite sample of 10 subsamples per replication for each treatment, collected with an auger-type soil sampler. Soil samples were analyzed for pH; exchangeable levels of P, Ca, Mg, and K; H+Al content; CEC at pH 7.0; levels of Cu, Fe, Mn, and Zn; and total organic carbon, following Van Raij et al. (2001). The content of organic matter (OM) and total N in the soil were determined using the Near Infrared (NIR) method. There were also, soil samples were collected to assess soil health through enzymatic activity analysis following Mendes et al. (2020) and Mendes et al. (2021). At a depth of 0–10 cm, one composite sample per replication was collected for each treatment, with each sample composed of 10 subsamples collected using an auger-type soil sampler. Soil enzyme activities: β-glucosidase associated with the carbon cycle, arylsulfatase associated with the sulfur cycle, and acid phosphatase associated with the phosphorus cycle were evaluated using methods described by Tabatabai (1994). Soil samples were prepared according to the FERTBIO soil sampling concept as described in Mendes et al. (2019).

2.4.5. Soybean leaf gas exchange

The gas exchange: net photosynthesis rate (A), the stomatal conductance (g_s), and the transpiration rate (E) in the central region of expanded leaves were measured using a portable infrared gas analyzer LI-6800 (LI-COR, NE, USA). Measurements were conducted between 8 am and 11 am, 85 days after soybean sowing. The constant conditions of radiation (2000 s), CO_2 concentration (400 ppm), and leaf temperature (25 °C) were used for gas exchange measurements. The leaves were maintained inside the chamber until the parameters stabilized.

2.4.6. Soybean chlorophyll index, growth, and grain yield

The leaf chlorophyll concentration index of soybean plants was estimated using a CCM-200 Chlorophyll Meter (OPTI-SCIENCE, HUDSON, NH, USA) at midday and 85 days after soybean sowing. Measurements were conducted on ten expanded central leaflets (trifoliate leaves) on the adaxial leaf surface per plot. At 105 days after soybean sowing, was measured the height (m) and aboveground biomass of the soybean plants. Plants were harvested from one linear meter in each plot containing all the aboveground plant material (stems, leaves, and pods). The soybean harvest was carried out manually at ground level. Plant material was dried in a stove until the dry weight stabilized, and was calculated the kg of soybean biomass per hectare. Grain yield was determined on February 19, 2022 (120 days after sowing), with values expressed in kg ha^{-1}.

2.5. Statistical analyses

Data were checked for normality and homogeneity. Data were analyzed using one-way ANOVA, followed by Tukey's test ($P < 0.05$). For multivariate analyses, it was used the R-3.1.1 software (R Core Team, 2014), incorporating packages such as "tidyverse" for database manipulation, "stats" for analysis, and "factoextra" for graphical representation, facilitating these analytical processes.

3. Results

3.1. Soil organic residues, biomass initial nutrient concentration, soil respiration, soil temperature, and soil moisture

It was observed that the production of soil cover residues was higher by 24.5 % when the forage was grown without the influence of grazing or cutting management (Fig. 5). N concentration was higher in the grazing of animals treatment, followed by the cut and regrowth treatment and free growth produced without management (Fig. 6a). For P, K, and S concentrations, the highest values were observed when the soil cover residues were produced in the post-grazing treatment, followed by managed and not-managed grass (Figs. 6b, 6c, 6f). There was no statistical difference between treatments for Ca and Mg concentration (Figs. 6d, 6e).

Soil respiration, soil surface temperature, and soil temperature measured 5 cm depth were higher in the conventional soybean cultivation method (Figs. 7a, 7b, 7c). However, soil moisture was lower in the treatment without soil plant residues covering the soil (Fig. 7d).

3.2. Soil chemical analysis and soil enzymatic activity analysis

The lowest soil pH values were observed in the post-grazing and soybean without soil cover treatments (Table 3). For P, O.M. content,

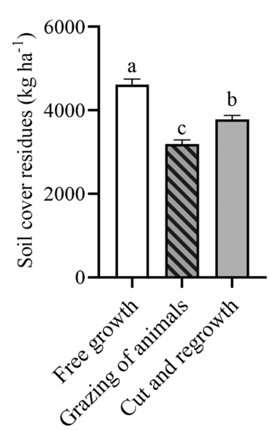

Fig. 5. Production of soil cover residues resulted from previous crops under different cultivation methods. Bars shows the average value, and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences ($P < 0.05$) between averages.

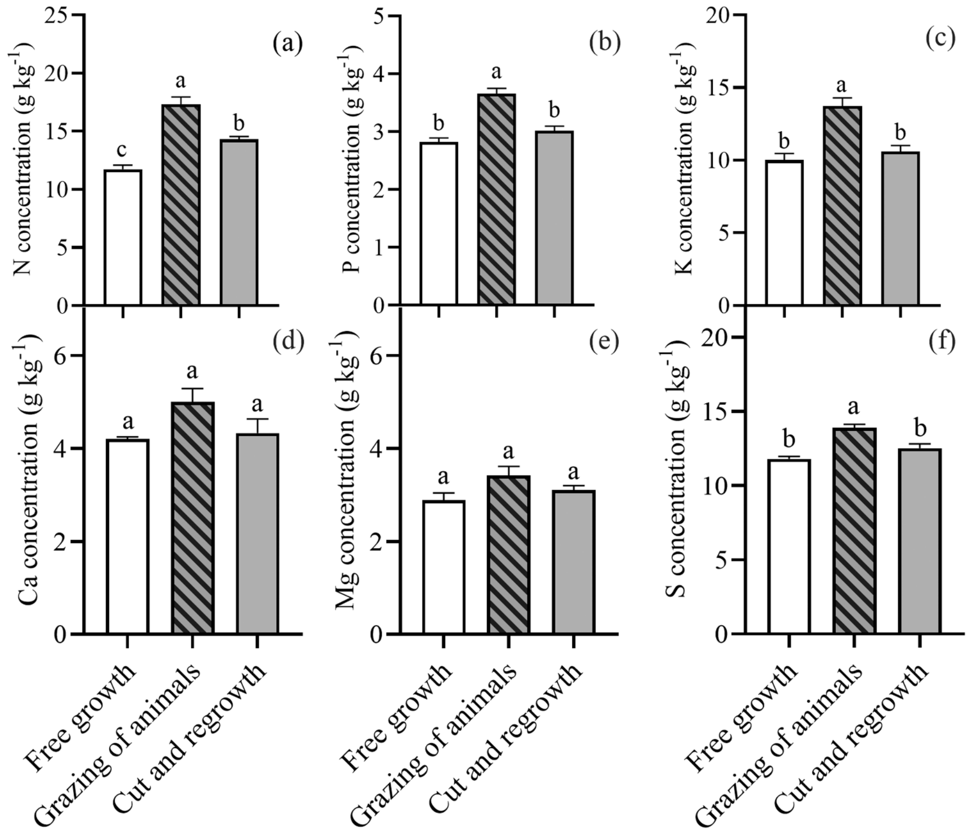

Fig. 6. N = nitrogen (a), P = phosphorus (b), K = potassium (C), Ca = calcium (d), Mg = magnesium (e) and S = sulphur (f) concentration in the plant residues resulted from previous crops under different cultivation methods. Bars shows the average value and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences (P < 0.05) between averages.

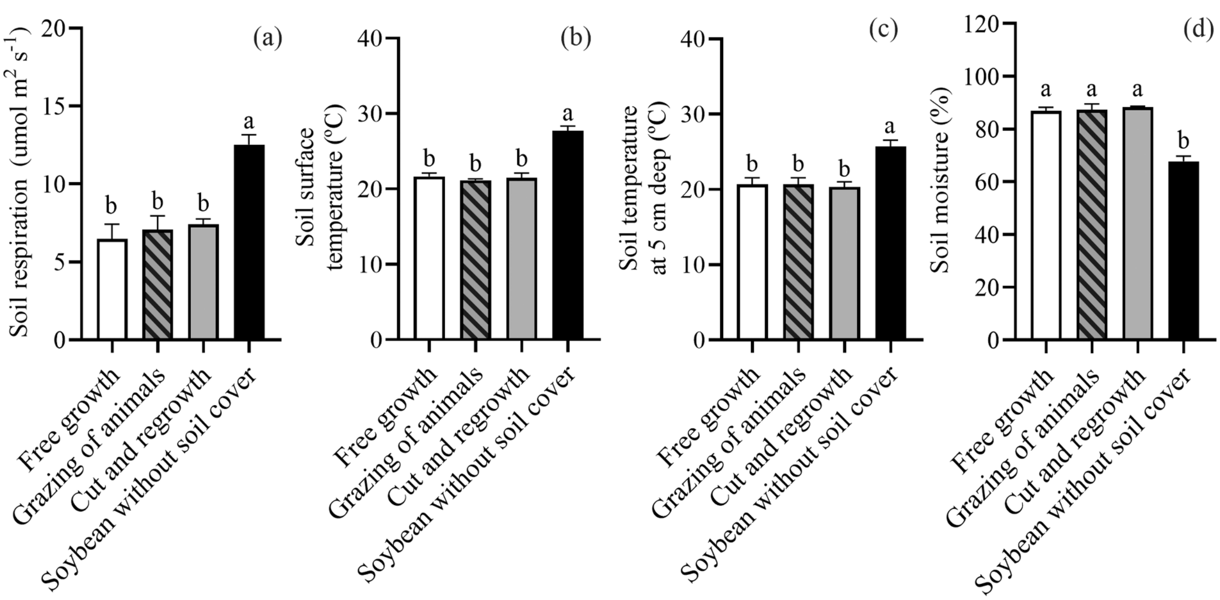

Fig. 7. Soil characteristics: soil respiration (a), soil surface temperature (b), soil temperature at 5 cm deep (c), soil moisture (d) observed in each treatment. Bars shows the average value, and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences (P < 0.05) between averages.

and K, the highest values were found in the post-grazing treatment, followed by treatments with soil cover regardless of management practices, and lastly in soybean without soil cover (Table 3). For Ca and TOC, the highest values were observed in the free growth and post-grazing soil cover treatments, while the lowest value was recorded in the conventional soybean cultivation method. Mg did not differ between treatments.

For H+Al, the highest value was observed in the post-grazing soil cover treatment, and the lowest value was observed in the traditional soybean cultivation method. The TN percentage was highest in the post-

Table 3
Soil chemical analysis of each treatment at the end of the experimental period.

Parameter	Free growth	Grazing of animals	Cut and Regrowth	Soybean without soil cover
pH ($CaCl_2$)	6.1 ± 0.03 ab	5.8 ± 0.18 b	6.5 ± 0.06 a	5.9 ± 0.03 b
P (mg dm^{-3})	24.2 ± 0.8 b	28.4 ± 0.6 a	24 ± 0.9 b	7.2 ± 0.7c
OM (g dm^{-3})	24.4 ± 0.4 b	28.9 ± 0.3 a	22.2 ± 0.7 b	17.1 ± 1.1 c
TOC (g dm^{-3})	22.8 ± 0.4 a	27.57 ± 1.91 a	27.20 ± 1.18 a	12.10 ± 1.25 b
K (cmolc dm^{-3})	0.4 ± 0.01 b	0.52 ± 0.01 a	0.43 ± 0.01 b	0.18 ± 0.01 c
Ca (cmolc dm^{-3})	1.7 ± 0.12 a	1.7 ± 0.09 a	1.3 ± 0.18 ab	0.9 ± 0.06 b
Mg (cmolc dm^{-3})	1.35 ± 0.03 a	1.52 ± 0.02 a	1.34 ± 0.05 a	1.49 ± 0.07 a
H + Al (cmolc dm^{-3})	0.97 ± 0.03 b	1.15 ± 0.03 a	0.94 ± 0.03 b	0.81 ± 0.02 c
TN (%)	0.18 ± 0.01 b	0.23 ± 0.01 a	0.15 ± 0.01 b	0.14 ± 0.01 b
CEC (cmolc dm^{-3})	4.4 ± 0.2 ab	4.9 ± 0.1 a	4 ± 0.2 bc	3.4 ± 0.1c
SB (cmolc dm^{-3})	3 ± 0.1 ab	3.4 ± 0.1 a	2.7 ± 0.2 b	1.9 ± 0.1c
V_1 (%)	69.3 ± 0.5 a	69 ± 0.7 a	67 ± 1.1 a	56 ± 1.1 b

P (Mehlich), OM = organic matter, TN = total nitrogen, CEC = cation exchange capacity, SB = sum of bases, V_1 = Base saturation, TOC = total organic carbon. Average ± standard error of the mean. n = 4. Different letters between columns within the same row indicate statistical differences between means.

grazing treatment (Table 3). The lowest cation exchange capacity was observed in the Soybean without soil cover, followed by the cut and regrowth treatment. This same pattern was also observed in the sum of bases. For the base saturation the highest values were observed in the free growth and post-grazing soil cover treatments, while the lowest value was recorded in the conventional soybean cultivation method.

It was observed that all soil enzymes were modified by treatments (Fig. 8). For the treatments with soil cover, no statistical differences were observed, however, an increase of 20.42, 38.07 and 30.68 % in the content of β-glucosidase, acid phosphatase, and arylsulfatase, respectively in relation to the method of conventional cultivation of soybeans, which presented the lowest values, was observed (Fig. 8).

3.3. Soybean leaf gas exchange, chlorophyll index, growth and grain yield

Leaf gas exchange of soybean plants was not modified by any treatment (Fig. 9). Soybean chlorophyll index was lower in the conventional soybean cultivation method (Fig. 10a), while no differences were observed between the other treatments (Fig. 10a). Plant height was smaller in the conventional soybean cultivation, followed by cut and regrowth treatment, whilst the highest values were observed in the free growth and grazing of animals treatments (Fig. 10b). The aboveground biomass productivity of soybean plants was higher in the grazing of animals treatment, followed by soil cover produced with or without management. As expected, the lower aboveground biomass productivity was observed in the conventional soybean method (Fig. 10c). The different methods of soil cover showed the highest yields of soybeans with an increase of 21.39, 22.50 and 19 % for the system of free growth, grazing of animals cover and cut and regrowth, respectively, compared to the conventional cultivation method which showed the lowest grain yield (Fig. 10d).

3.4. Multivariate analysis

Correlation analysis (Fig. 11) revealed the formation of two variable groups. Group 1 consists of Tsurface (soil surface temperature), Rsoil (soil respiration), and Tsoil (soil temperature at 5 cm depth), while Group 2 includes the remaining variables: OM (organic matter), TOC (total organic carbon content), β.glucosidase (β-glucosidase content), Phosphatase (acid phosphatase content), Arylsulfatase (arylsulfatase content), Bsoybean (soybean aerial biomass), Bheight (soybean plant height), Chlorophyll (soybean chlorophyll index), Biomass (soil cover biomass), Msoil (soil moisture), N, P, K, Ca, Mg, S and Yield (grain yield soybean). Most variables within each group showed high positive correlations ($r \geq 0.7$) with each other and high negative correlations ($r \geq 0.7$) with the variables from the other group, except for Biomass, which showed a positive moderate correlation ($|0.30 < r < 0.70|$) with OM, and Tsoil, which showed a negative moderate correlation with OM and Phosphatase.

Principal component analysis (PCA) allowed a graphical understanding of the interrelationships between the parameters using the first and second principal components (Fig. 12). It was observed that the first and second components together explained 92 % of the total data variation. The first principal component (based on the observed shift along the horizontal axis) explained 88.7 % of the total data variation, showing a high positive correlation with OM, TOC, β-glucosidase, Phosphatase, Arylsulfatase, Biomass, Msoil, N, P, K, Ca, Mg, S, Bsoybean,

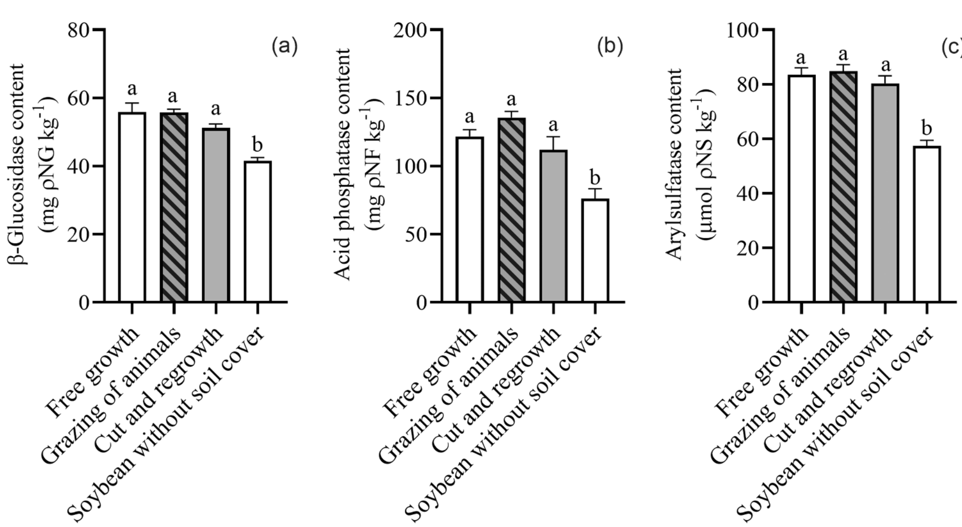

Fig. 8. β-glucosidase content (a), Acid phosphatase content (b) and Arylsulfatase content (c) in each treatment. Bars shows the average value and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences ($P < 0.05$) between averages.

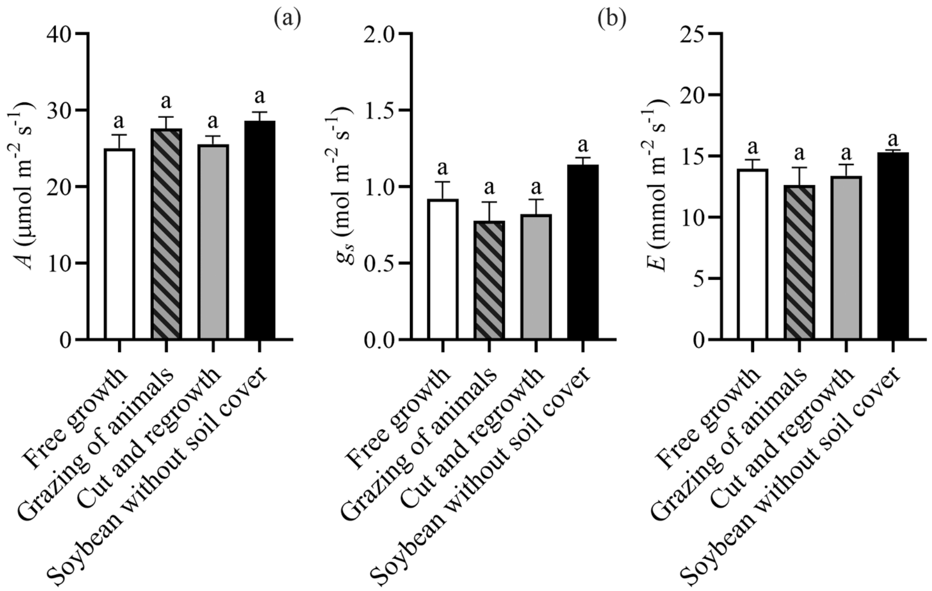

Fig. 9. Leaf gas exchange: A = Net photosynthesis rate (a), g_s = Stomatal conductance (b), E = Leaf transpiration rate (c) of soybean plants cultivated on plant residues resulted from previous crops under different cultivation methods. Bars shows the average value and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences (P < 0.05) between averages.

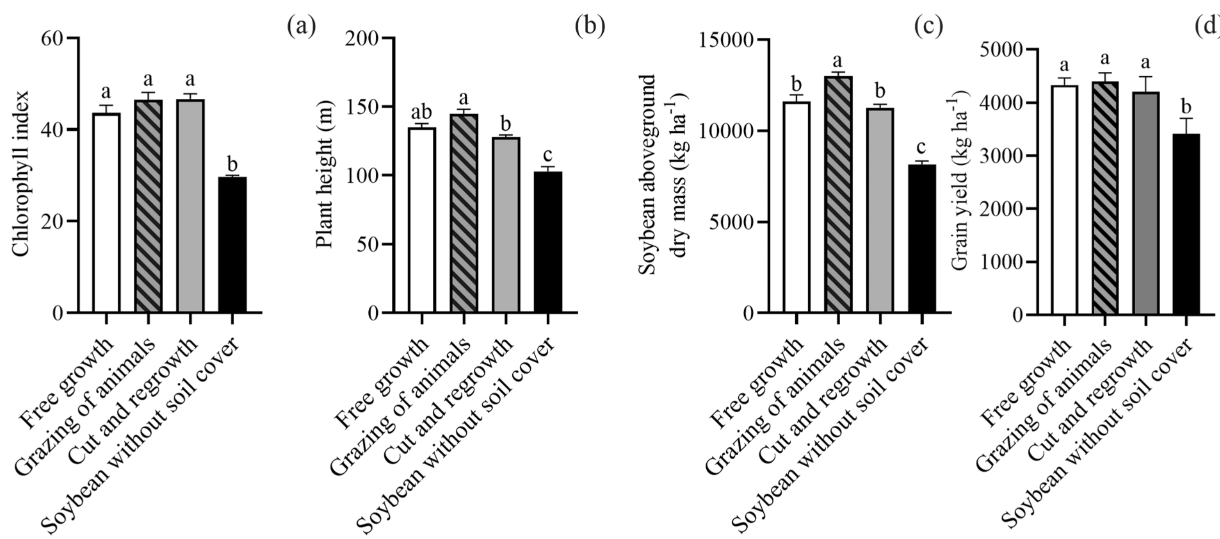

Fig. 10. Chlorophyll index (a), Plant height (b), Soybean aboveground dry mass (c) and Grain yield (d) of soybean plants cultivated on plant residues resulted from previous crops under different cultivation methods. Bars shows the average value and error is the standard error of the mean (n = 4). Different letters between bars represents statistical differences (P < 0.05) between averages.

Bheight, Chlorophyll and Yield and a high negative correlation with Tsurface, Rsoil and Tsoil.

A global and objective understanding of the results was facilitated by the graphical PCA analysis (Fig. 12), since it allowed the identification of 3 treatment groups: 1 (SWSC), 2 (MGC and GSC), and 3 (GPSC). *Brachiaria ruziziensis* growing freely or managed with mowing during the off-season (Group 2) contributes to greater production of ground cover biomass, resulting in greater moisture retention. In addition, when the animals are inserted into the system for grazing (Group 3), the *Brachiaria* residues showed a greater accumulation of nutrients (N, P, K, Ca, Mg and S), an increase in TOC and OM in the soil and consequently enzyme activity (β. glucosides, Phosphatase and Arylsulfatase), positively influencing the soybean chlorophyll index and growth parameters (Bsoybean and Bheight) and soybean yield compared to soybean cultivation without soil cover (Group 1).

4. Discussion

The findings demonstrate that treatment of *Brachiaria ruziziensis* in free growth produced the highest soil cover, due to the prolonged growth period from March to October 2021 (Fig. 2), allowing for the accumulation of dry matter. Forage species from Brachiaria genus have high adaptability to tropical regions, exhibiting strong growth performance (Momesso et al., 2022). Their deep and aggressive root system enhances nutrient recycling, leading to greater dry matter accumulation (Muniz et al., 2021; Silva et al., 2024), which in turn promotes higher production of soil cover residues (Lima et al., 2023; Prado et al., 2025).

Although less soil cover is observed after animal grazing, this method has shown positive results for soil and grain production. Muniz et al. (2021) observed that the presence of animals in the off-season in integrated systems increases nutrient recycling. Soares et al. (2023) found an increase in the labile fractions of organic matter in sandy soil, as well

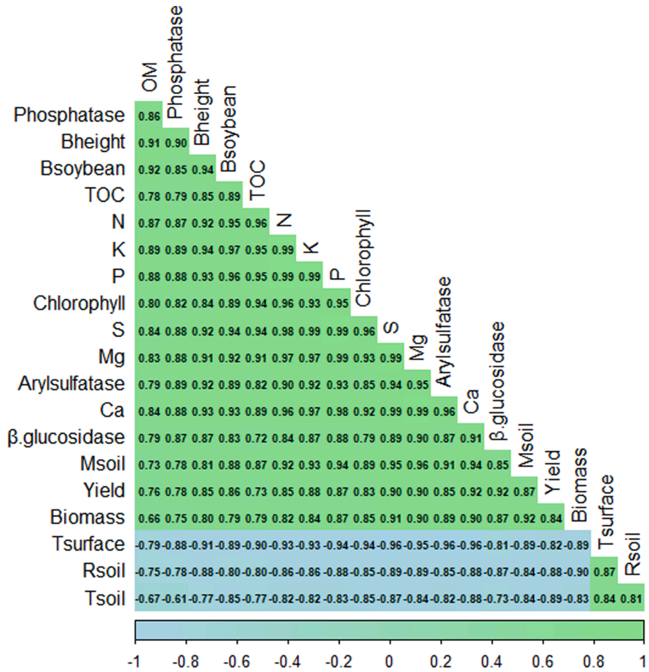

Fig. 11. Heatmap showing the correlation coefficient (r) between the parameters. Positive correlations are represented by green backgrounds, while negative correlations are shown with blue backgrounds. Parameters: TOC: total organic carbon content; OM: organic matter; Bsoybean: soybean aerial biomass; N: nitrogen concentration; K: potassium concentration; Bheight: soybean plant height; P: phosphorus concentration; Chlorophyll: soybean chlorophyll index; S: sulfur concentration; Mg: magnesium concentration; Ca: calcium concentration; Msoil: soil moisture; Biomass: soil cover biomass; Tsurface: soil surface temperature; Rsoil: soil respiration; Tsoil: soil temperature (5 cm depth); β.glucosidase: β-glucosidase content; Phosphatase: acid phosphatase content; Arylsulfatase: arylsulfatase content; Yield: grain yield soybean.

as a short-term increase in grain yield. Leal et al. (2024) observed that livestock farming combined with crops increased land use efficiency by 15 %, without harming commercial crop yields. Marques et al. (2024) in a recent study observed that forage biomass in crop-livestock integration systems enriches the soil through the return of fertilizer equivalents, contributing to greater sustainability of agricultural systems.

The higher N concentration observed in the soil cover residues under the Grass prost-grazing cover treatment during the off-season (Fig. 6a) can be attributed to the return of nutrients through the excretion of manure and urine. Animal excreta directly influences nutrient concentrations (Dias et al., 2020) and soil microbial communities, benefiting the decomposition of organic matter and the availability of N (Soares et al., 2022).

Animals in grazing systems act as catalysts for nutrient recycling by consuming forage, followed by the temporary immobilization of nutrients during digestion, and returning the nutrients to the soil through the excretion of manure and urine (Leal et al., 2024). Therefore, grazing systems modify nutrient cycling dynamics compared to systems where forages are grown exclusively for soil cover residue production (Carpinelli et al., 2020). Consequently, the input of nutrients through animal excreta improves nutrient cycling, reduces the need for fertilizer application, and enhances soil quality (Soares et al., 2022).

The results showed that grazing can also increase the initial concentrations of P, K, and S (Figs. 6b, 6c, and 6f) in the soil cover biomass. Grazing animals can be considered regulators of labile P due to the recycling of animal manure and urine, increasing the efficiency and availability of P in the soil (Assmann et al., 2017). Additionally, grazing stimulates the emission of new tillers and roots in forages (Muniz et al., 2022), with the latter contributing to the absorption of K in deeper soil layers (Huot et al., 2020). By consuming the pasture, animals contribute to increased K cycling as they return this nutrient to the soil through the excretion of feces and urine (Almeida et al., 2021). Furthermore, animal excreta contribute to the input of OM into the soil, as previously mentioned, which enhances S availability (Sharma et al., 2024). Therefore, the findings demonstrate the importance of selecting appropriate management practices for *Brachiaria ruziziensis* during the off-season, and how the presence of animals contributes to improving soil health by increasing total organic carbon (Soares et al., 2022; Leal et al., 2024) and enhancing nutrient cycling (Dias et al., 2020; Silva et al., 2024; Soares e al., 2024).

In this study, it was observed that soil respiration was higher in the soybean plots without soil cover (Fig. 7a). This finding contradicts previous studies where soil respiration showed no significant difference between conventional cultivation methods and integrated systems (Silva et al., 2024c). The efflux of CO_2 from soil to the atmosphere is a complex process influenced by various interacting edaphoclimatic factors, including soil temperature, moisture, organic matter, structure, and aeration. In this study, it was found a strong positive correlation between soil respiration and soil temperature (Fig. 11). Therefore, it was hypothesize that the higher soil temperatures observed in the plots without soil cover were the primary drivers of increased soil respiration. This result suggests that, under certain soil types and conditions, traditional cultivation methods may have a reduced capacity to retain carbon in the soil, leading to higher CO_2 emissions to the atmosphere.

In the plots with soil cover, regardless of management, it was possible to observe that the soil surface temperature and the temperature at a depth of 5 cm were on average 8°C lower ($p < 0.05$) than in the plots without soil cover (Fig. 7). This was reflected in soil humidity, where it was possible to observe lower humidity in the plots where soybeans were grown without soil cover compared to the other treatments (Fig. 7d). Demattê and Demattê, (2024) point out that the presence of live or dead cover on sandy soil helps to reduce water evaporation, as well as reducing temperature peaks due to the reflection of solar radiation by the straw.

In recent years, studies that integrate the assessment of the soil's chemical and biological properties have been used as decision-support tools for land managers aiming for high and sustainable agronomic yields in no-till systems (Serafim et al., 2023; Chaves et al., 2024). The chemical property values for pH ($CaCl_2$), P, K and Ca, for the different *Brachiaria ruziziensis* management systems in the off-season, indicate good soil quality and are the result of the presence of plant residues (Serafim et al., 2023). Plant residues are a labile source of nutrients, and their decomposition favors the immobilization of nutrients (Soares et al., 2024). Although the evaluations of the different off-season managements in this study were carried out in just one-year, better soil chemical characteristics were observed in the systems with soil cover. In addition, the presence of animals in the off-season has shown the potential to contribute positively to the soil's chemical characteristics, due to the increase in organic carbon reserves through the deposition of excreta (feces and urine) on the soil (Soares et al., 2023).

The different *B. ruzizienis* managements have been shown to contribute to increasing SOC stocks, and grazing management has shown the greatest potential for increasing organic matter and NT in the soil (Table 3). These findings are in line with Tan et al. (2024) who found that in environments with managed grazing there is an increase in organic carbon storage and consequently a greater input of organic matter (OM) into the soil. Marks et al. (2024) point out that this increase is due to the deposition of plant residues from grazing and fecal material after animal digestion. This may have contributed to the increase in soil organic matter, even with the short duration of the integrated crop-livestock system.

In a recent study, Chakraborty et al. (2024) observed that the addition of animal excreta (feces and urine) to the soil surface through grazing induces an increase in soil organic carbon stocks and total nitrogen. Moreover, the physical disturbance caused by grazing and animal trampling can improve soil structure, enhancing soil aeration and

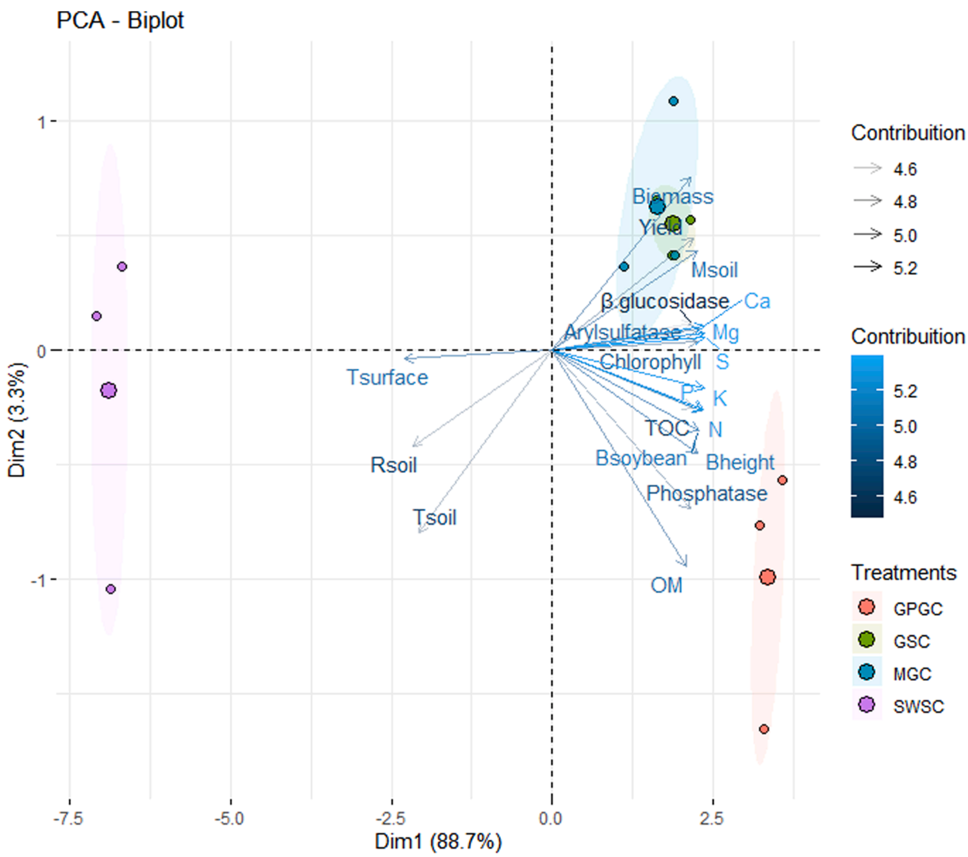

Fig. 12. Two-dimensional PCA scatter plot of scores for 20 parameters, observations, and average values for biomass production, initial nutrient concentrations in biomass, microclimate and soil respiration, chlorophyll, and soybean growth. Treatments: GPGC: grass post-grazing cover, GSC: grass soil cover, MGC: managed grass cover, SWSC: soybean without soil cover. Parameters: TOC: total organic carbon content; OM: organic matter; Bsoybean: soybean aerial biomass; N: nitrogen concentration; K: potassium concentration; Bheight: soybean plant height; P: phosphorus concentration; Chlorophyll: soybean chlorophyll index; S: sulfur concentration; Mg: magnesium concentration; Ca: calcium concentration; Msoil: soil moisture; Biomass: soil cover biomass; Tsurface: soil surface temperature; Rsoil: soil respiration; Tsoil: soil temperature (5 cm depth); β.glucosidase: β-glucosidase content; Phosphatase: acid phosphatase content; Arylsulfatase: arylsulfatase content; Yield: grain yield soybean.

water infiltration, contributing to the stabilization of organic carbon in the upper soil layers (Wilson et al., 2018). It is important to note that in the conventional cultivation system (without soil cover biomass) there is a loss of C from the soil due to a reduction in the physical protection of soil organic carbon and an increase in the decomposition of organic matter as a result of the alteration and rupture of soil aggregates (Mubvumba et al., 2022), which justifies the lower values observed in this study (Table 3).

It was observed similar enzyme content responses for the systems with soil cover, differing only for the conventional system (Fig. 8). Enzyme activity is used as an indicator of soil health, as they act as catalysts in biogeochemical cycles related to the decomposition and synthesis of organic matter, carbon sequestration, nutrient cycling and all the factors that are altered by cropping systems and changes in land use (Chaves et al., 2024). The increase of 20.42, 38.07 and 30.68 % in the content of β-glucosidase, acid phosphatase and arylsulfatase, respectively, in relation to the system without soil cover (conventional), as shown in Fig. 6, is associated with an increase in the activity of microorganisms in the soil due to the retention of residues on the soil surface (Sekaran et al., 2021; Barbosa et al., 2023). Mirzavand et al. (2022) found that the retention of residues on the soil promotes the entry of OM into the soil while reducing mineralization, consequently improving carbon stocks, nutrient content and biological activity, which corroborates the results observed in this study.

No significant differences were observed in soil enzyme content between the different *B. ruziziensis*, only in relation to soybean crops without soil cover biomass, which presented the lowest values. The results showed a multifactorial and positive correlation between soil enzymes and soil moisture, soybean chlorophyll index, organic carbon content and soil organic matter, as well as the productive characteristics and grain yield of soybeans (Figs. 11 and 12). In this way, the findings of this work, even in the short term, indicate that systems with the presence of soil cover have a positive impact on the chemical quality and biological activity of the soil (Table 3, Fig. 8). These results are in line with Silva et al. (2024c) who also observed that replacing conventional systems with no-till methods (soil cover), in the short term, alters soil quality, affecting enzymatic activity. Therefore, further research to verify the long-term effects is strongly encouraged, since the biological parameters of the soil are closely related to OM and grain yield, which are essential for the sustainability of the agricultural business (Chaves te al., 2024).

Regarding the effects of different crop-livestock systems on soybean gas exchange, the data showed no statistical differences between treatments (Fig. 9). A smaller leaf chlorophyll index was observed in plots without soil cover (Fig. 10a) and a positive correlation between leaf chlorophyll index and soybean aboveground biomass, plant height, and N, P, K content in plant residues were observed (Fig. 11). Therefore, the higher leaf chlorophyll index was associated with an improved plant growth. The absence of synchronized results between the reduced leaf chlorophyll index and unchanged net photosynthesis rate (*A*) in the Soybean without soil cover treatment indicated that other factors may be at play in this experiment. The effects of tilling management strategies on leaf gas exchange are not homogenous during the growing season and some results may be present only during specific seasons or conditions (Bojarszczuk, 2021).

The benefits provided by the systems with the presence of *B. ruziziensis* in the off-season, especially when animals were present, in terms of soil parameters (microclimate and chemical and biological parameters), as well as chlorophyll, contributed to greater plant height and greater dry mass of the aerial part of the soybean plants (Fig. 10). In the crop-livestock integration system, animal grazing in the off-season acts as a catalyst by increasing organic carbon stocks in the soil, favoring greater nutrient cycling, as well as contributing to a greater input of organic matter (Chakraborty et al., 2024), by depositing plant residues and fecal material (feces and urine) in the soil (Cherubin et al., 2023). In addition, the residues left by grazing are used as soil cover biomass for the no-till system and these provide less variation in soil temperature and humidity (Silva et al., 2024b; Marques et al., 2024).

The highest soybean grain yields were observed when there were soil cover residues from the different *B. ruziziensis* managements, with increases of 21.39, 22.50 and 19 % for the free growth, grazing of animals cover and cut and regrowth systems, respectively, compared to the conventional cultivation method, which had the lowest grain yield. These results findings highlight the significance of cover crops for increasing grain yields (Silva et al., 2024a, 2025) and the advantages offered by integrated crop-livestock systems for improving the soil's chemical and biological properties. Furthermore, the integration of crops and livestock helps maintain or even increase crop yields (Peterson et al., 2020), introduce an alternative source of income, and intensify food production in the same area (Reis et al., 2021). Therefore, the integrated crop-livestock system, especially in sandy soils, as in this study, can contribute to the acquisition of soil resilience, even in the short term, providing improvements in the chemical and biological composition of the soil (Soares et al., 2024), which reflects positively on the yield of succession crops (Nunes et al., 2021).

5. Conclusion

The evidence shown in this analysis demonstrated that the free-growing management of *Brachiaria ruziziensis* in the off-season resulted in greater production of soil cover biomass. However, animal grazing contributed to greater nutrient availability and improvements in the soil's chemical attributes. Soil microclimatic conditions and enzyme activity were also positively influenced by the crop-livestock integration system, resulting in taller soybean plants, greater accumulation of above-ground biomass, and an average increase of 20.9 % in soybean grain yield when compared to soybeans grown without ground cover residues. The results of this study show that crop-livestock integration systems in Quartzarenic Neosol (Entisol) soil help reduce the need for mineral fertilizers, promoting sustainable agricultural production. Research to verify the long-term effects is strongly encouraged.

CRediT authorship contribution statement

Adriano Carvalho Costa: Writing – review & editing, Methodology, Investigation, Formal analysis. **João Antônio Gonçalves e Silva:** Writing – review & editing, Data curation. **João Victor Campos Pinho Costa:** Writing – review & editing, Data curation. **Eduardo da Costa Severiano:** Writing – review & editing, Formal analysis. **Carlos Alberto Martinez:** Writing – review & editing, Supervision, Methodology. **Laís Guerra Prado:** Writing – review & editing, Investigation, Data curation. **Lourival Vilela:** Writing – review & editing, Validation, Supervision, Methodology. **Fabiano Guimarães Silva:** Writing – review & editing. **Luciana Maria da Silva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Eduardo Habermann:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation. **Kátia Aparecida de Pinho Costa:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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