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Fertilization strategy drives phosphorus retention and potassium vulnerability in a tropical integrated crop–livestock system

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Abstract

Integrated crop–livestock systems (ICLS) can enhance nutrient cycling and reduce dependence on external inputs, particularly in tropical Oxisols where phosphorus (P) fixation and potassium (K) mobility limit nutrient use efficiency. This study quantified annual fluxes, stocks, and balances of P and K in a soybean–pasture system under contrasting fertilization strategies, including fertilizer placement (pasture vs. soybean) and nitrogen (N) application in the pasture phase. Annual P cycling ranged from 70 to 87 kg ha^{-1}, with system fertilization increasing residual P in pasture by 18% compared to conventional fertilization. Nitrogen application enhanced soybean P uptake by 21%, although crop P balances remained positive across all treatments. Potassium cycling ranged from 178 to 198 kg ha^{-1} and showed greater variability, with strong interactions between fertilization strategy and N supply. Potassium balances ranged from −48.9 to +18.4 kg ha^{-1}, with the largest deficit observed under system fertilization combined with N. These results indicate that fertilizer placement in pasture improves P retention and redistribution, whereas K dynamics are more sensitive to N inputs and grazing-mediated nutrient return. In tropical ICLS, short-term nutrient balances are strongly influenced by the interaction between fertilization strategy and N management, with contrasting implications for P stability and K vulnerability.

Keywords: Integrated crop–livestock systems; Oxisol; Nutrient cycling; Fertilization strategy; Tropical systems.

1. Introduction

The increasing global dependence on agricultural inputs, particularly in regions with intensive

production such as South America, Asia, and Europe, has heightened the vulnerability of agricultural systems to price fluctuations and supply chain disruptions (Sandström et al., 2024). This challenge is especially critical in tropical environments, where high phosphorus (P) fixation, elevated potassium (K) mobility, and marked rainfall seasonality limit the synchronization between nutrient availability and crop demand (Borghi et al., 2014; De Oliveira et al., 2023). In this context, improving nutrient use efficiency while reducing reliance on external inputs has become a central objective for sustainable agricultural intensification.

Integrated crop–livestock systems (ICLS) have emerged as a promising strategy to enhance nutrient cycling and system resilience. In these systems, fertilization strategies can be designed at the system level, redistributing nutrients temporally and spatially between pasture and crop phases. This approach promotes greater residual use of nutrients and may reduce losses associated with fixation and leaching (Davi et al., 2022; Assmann et al., 2017). In addition, the animal component accelerates nutrient cycling through grazing and excreta return, contributing to soil organic matter accumulation, improved aggregation, and enhanced fertility (Alves et al., 2019). It is estimated that more than 70% of ingested nutrients are returned to the soil during grazing, reinforcing nutrient recycling processes in highly weathered tropical soils (Denardin et al., 2020; Alves et al., 2022).

Despite these advances, most studies on P and K cycling in ICLS have been conducted in subtropical regions of Southern Brazil (Assmann et al., 2017; Alves et al., 2019; Farias et al., 2025), where soils exhibit lower acidity and reduced contents of Fe and Al oxides. These conditions differ substantially from tropical Oxisols of the Cerrado, which are characterized by high weathering, strong geochemical reactivity, and pronounced hydrological seasonality. Such differences directly influence nutrient retention, mobility, and redistribution, limiting the extrapolation of results across regions.

Moreover, previous studies have rarely integrated all system compartments simultaneously (soil,

63 pasture, animal, and crop), nor have they evaluated contrasting strategies for P and K fertilization
64 placement combined with nitrogen (N) supply during the pasture phase. As a result, the mechanisms
65 governing nutrient redistribution and short-term balances under tropical ICLS remain insufficiently
66 understood.

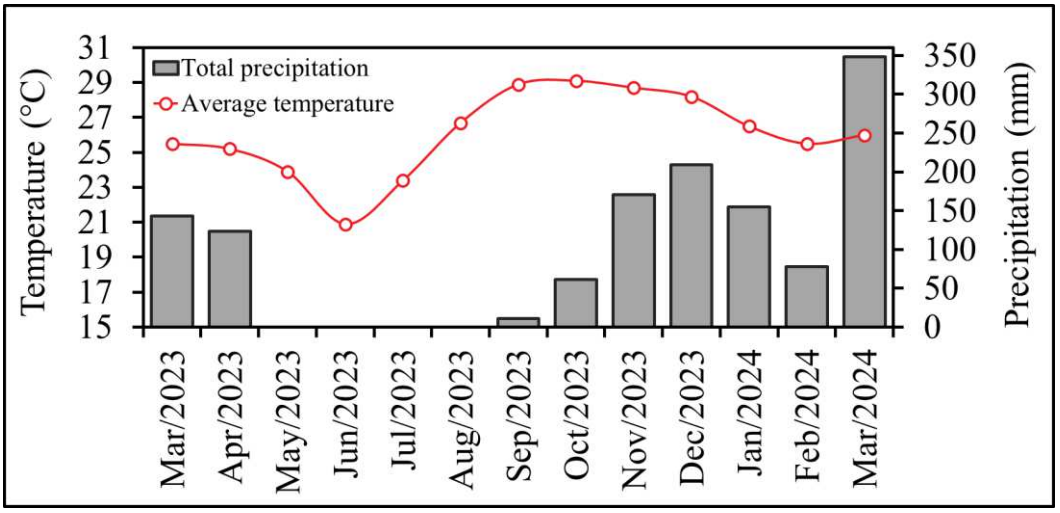
67 Therefore, there is still a lack of integrative assessments quantifying P and K fluxes across soil–
68 plant–animal compartments under contrasting fertilization strategies in tropical Oxisols. This gap limits
69 the understanding of how fertilization positioning and nitrogen inputs interact to influence nutrient
70 cycling efficiency in highly weathered environments.

71 Based on this context, we hypothesize that (i) the application of P and K during the pasture phase
72 enhances residual nutrient use and redistribution within the system, and (ii) nitrogen fertilization
73 intensifies nutrient cycling by stimulating plant growth and microbial activity. Thus, the objective of
74 this study was to quantify the flows, stocks, and annual balances of phosphorus and potassium across
75 soil, pasture, animal, and soybean compartments in an integrated soybean–pasture system under
76 contrasting fertilization strategies in a tropical Oxisol of the Brazilian Cerrado.

77 **2. Material and Methods**

78 *2.1. Location and characterization of the experimental area*

79 The study was conducted at Fazenda Guarita, located in Rondonópolis, Mato Grosso, Brazil
80 (16°33'54" S, 54°41'08" W; 401 m altitude), in an area of 22.8 ha. The region's climate is tropical type
81 Aw according to the Köppen classification, characterized by a rainy season in summer and a well-
82 defined dry period in winter (Alvares et al., 2014), with an average annual temperature of 26°C and
83 precipitation concentrated between October and March (Figure 1).



Sources: INMET and the experimental area's weather station of the experimental area.

Figure 1. Climatic conditions and description of the management practices carried out in the area from February 2023 to March 2024.

The soil was classified as a dystrophic Red Latosol with a clayey texture (39% clay), equivalent to an Oxisol in the North American classification system (USDA, 1999). The mineralogical analysis indicated Fe_2O_3: 172 g kg^{-1}; Fed: 64 g kg^{-1}; Feo: 0.9 g kg^{-1}; Ct: 932 g kg^{-1}; Gt: 68 g kg^{-1}; Hm: 86 g kg^{-1} and the ratio Ct/(Ct+Gb): 0.9 g kg^{-1}, demonstrating high weathering and predominance of Fe and Al oxides, typical characteristics of Cerrado Oxisols.

The area, originally under native vegetation, had a history of soybean-corn succession under conventional tillage before the adoption of the integrated system. Since 2019, it has been part of an Integrated Crop Livestock Systems (ICLS) under continuous no-till. The evaluations in this study correspond to the 2023–2024 agricultural cycle, thus representing a temporal snapshot within an already consolidated system, in which residual effects accumulated since 2019 are part of the natural dynamics of ICLS.

The chemical characterization of the soil was carried out in February 2023, in the 0–0.20 m layer, according to Tedesco et al. (1995), and is presented in Table 1. According to the criteria of Sousa

and Lobato (2004), the following were observed: adequate pH; adequate Ca and Mg; low Al; high CEC; high K and P, high V%, and low m%.

Table 1. Chemical analysis of the soil in the 0.00–0.20 m layer at the beginning of the 2023 agricultural cycle.

pH	P	K	Ca	Mg	H+Al	M.O	SB	CTC	v	m
$CaCl_2$	--- mg dm^3 ---		---- $cmol_c$ dm^{-3} ----			g kg^{-1}	$cmol_c$ dm^{-3}		------- % -------	
6,0	54, 5	104,1	3,8	2,0	2,0	31,7	6,1	8,1	75,1	0,0

pH: Hydrogen potential; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; H+Al: Hydrogen + Aluminum; M.O: Organic matter; SB: Sum of bases; CTC: Cation exchange capacity; v: Base saturation; and m: Aluminum saturation.

2.2. Chronology of management and sampling

The managements followed a previously defined experimental schedule, considering the phenological stages of the crops and regional technical recommendations (Figure 2). The experiment included two productive cycles: pasture (2023) and soybean (2023/2024), totaling one agricultural year.



SOURCE: Author (2025).

Figure 2. Chronology of management practices and collections conducted from February 2023 to March 2024.

2.3. Experimental design and treatments

The experiment was conducted in a randomized block design, in a 2×2 factorial scheme, with three replications, totaling 12 experimental units (Figure 3; Figure 4).

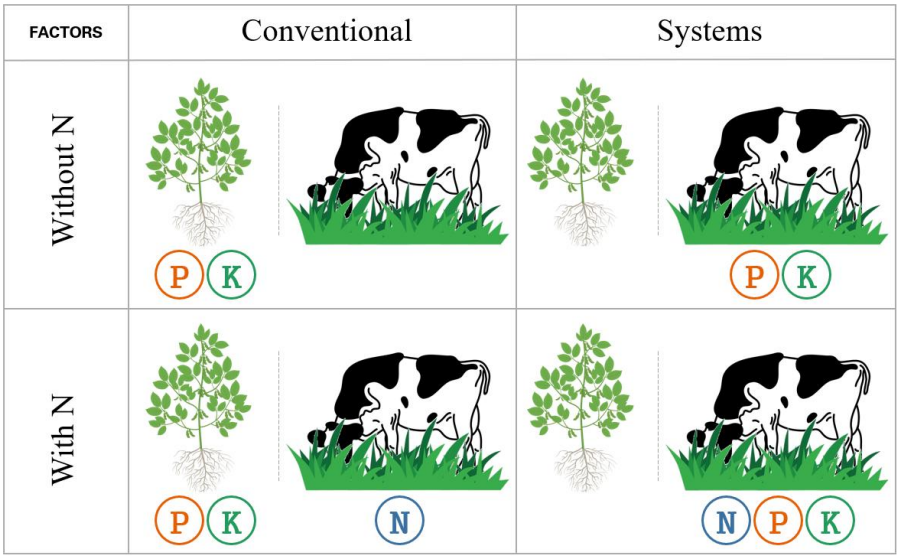
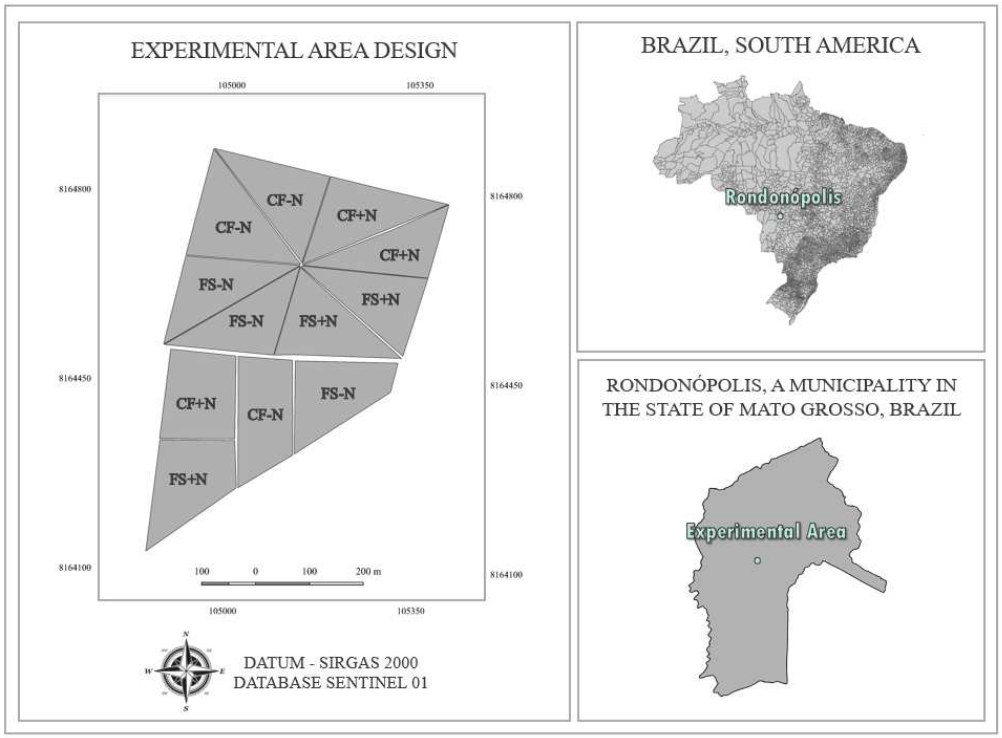


Figure 3. Simplified conceptual map of the 2x2 factorial scheme (1st factor: arranged horizontally; 2nd factor: arranged vertically).



SOURCE: Author (2025).

Figure 4. Location and sketch of the fertilization systems experiment in SIPA, highlighting the arrangement of the experimental plots.

The factorial design included two experimental factors:

Factor 1: Positioning of phosphorus and potassium fertilization: Application during the crop phase (soybean) or during the pasture phase.

Factor 2: Nitrogen fertilization in the pasture: with or without N application.

The applied doses were: 80 kg ha^{-1} of P_2O_5 and K_2O, as recommended for a soybean yield of 4.8 Mg ha^{-1}, and 100 kg ha^{-1} of N (NH_4NO_3) when provided by the treatment. Fertilizations were broadcasted, regardless of the adopted strategy.

The pasture was composed of *Urochloa brizantha* cv. Piatã (VC 74%), sown at 2 cm depth (8.8 kg ha^{-1}; 45 cm spacing). Grazing was continuous, following the rotatinuous concept (Carvalho, 2013), with non-castrated Nelore breed males (234 ± 55 kg), and stocking rate adjustment using the Put and Take method (Moot & Lucas, 1952).

Soybean (*Glycine max*, cv. ULTRA 75I77 IPRO-BRASMAX) was sown in October under no-till system, with 255,000 seeds ha^{-1}, 5 cm depth, 45 cm row spacing, and inoculation with *Bradyrhizobium japonicum* (300 mL 50 kg^{-1} seed) and *Azospirillum* (150 mL 50 kg^{-1} seed).

2.4. Soil and biomass sampling

Soil sampling was conducted in February 2023 and March 2024, after soybean harvests. Each plot was sampled with eight subsamples in the 0-0.20 m layer, forming a composite sample, which represents a single observation per plot.

It is important to note that this approach assumes homogeneity of the 0–20 cm layer and does

not include measurements at greater depths, which represents a methodological limitation, especially for potassium, whose mobility in the profile is greater in highly weathered tropical soils.

The samples were air-dried, sieved (2 mm), and analyzed according to Tedesco et al. (1995). The stocks of P and K were estimated based on the levels (mg dm^{-3}) and soil density (kg dm^{-3}), according to Gasques et al. (2025).

The accumulation of aboveground biomass of the pasture was determined at the beginning and end of the grazing period using exclusion cages (1.2 m^2), following the double pairing method (Klingman et al., 1943). The forage accumulation rate (Tj, kg DM ha^{-1} day^{-1}) was estimated according to Campbell (1966):

$$Tj = \frac{Ci - Fg_{(i-1)}}{n}$$

where G_i is the forage mass inside the cage in assessment i, $Fg_{(i-1)}$ is the mass outside the cage in the previous assessment, and n the number of days in period j.

2.5. Determination of nutrient flows and balances

The nutrient flows were quantified through a combination of direct measurements and estimates based on coefficients. The absorption of P and K by soybeans was calculated from the aboveground biomass and grain yield, multiplied by the nutrient concentrations in the tissues, determined by laboratory analyses. The residual levels of P and K from the pasture were estimated based on the residual dry matter mass and the respective nutrient concentrations.

The export of nutrients by the animal component was estimated based on protein production, using established coefficients in the literature (Williams et al., 2007), while the return of nutrients via excreta was calculated as the difference between total intake and export.

The annual balances were estimated to indicate short-term trends in P and K dynamics and are not interpreted as long-term system balances. Nutrient cycling via excreta (CE) was calculated according to Ferreira et al. (2011):

$$\mathrm{CE} = \mathrm{NI} - \mathrm{NE}$$

where NI represents the total intake of P and K, and NE the total exported via carcass.

The balances were determined considering two compartments: crop balance (BL) and apparent soil balance (0–0.20 m) (BS):

$$\mathrm{BL} = \mathrm{EA} - \mathrm{ES}$$

where EA is the input via fertilization, ES is the export via grains and meat.

$$\mathrm{BS} = \mathrm{SI} - \mathrm{SF}$$

where SI and SF are the initial and final levels of P and K in the soil.

The stocks were calculated according to Gasques et al. (2025). All equations, variables, units, sources, and premises used to calculate the P and K balance are presented in the Supplementary Material (Table S1).

2.6. Statistical analysis

The residues were evaluated for normality using the Shapiro-Wilk test ($p > 0.05$). The variables were analyzed by a mixed linear model, considering the phosphorus and potassium fertilization strategy (conventional or system-based) and nitrogen fertilization during the pasture phase (with or without N), as well as their interaction, as fixed effects, and the experimental block as a random effect. The statistical model adopted was:

$$Yijk = \mu + F1i + F2j + (F1 \times F2)ij + Bk + \varepsilon ijk$$

where Y_{ijk} represents the response variable, μ is the overall mean, $F1_i$ corresponds to the levels of Factor1, $F2_j$ to the levels of Factor2, $(F1 \times F2)ij$ the interaction between the factors, B_k represents the random effect of Block, and ε_{ijk} the experimental error.

The models were fitted using the lmer() function from the lme4 package in R software (R Core Team, 2024), adopting a significance level of 5%. When the interaction between factors was significant ($p \leq 0.05$), the results were presented as adjusted model means (*emmeans*) for each treatment combination, with multiple comparisons using the Tukey test ($\alpha = 0.05$) and graphical representation of interactions with 95% confidence intervals.

In the absence of significant interaction, the main effects were interpreted independently, with adjusted means and their respective standard errors presented. Models with singular structure were retained as they did not compromise the inference of fixed effects, considering the balanced structure of the experimental design.

All results presented in tables and figures correspond to the adjusted means of the mixed linear model, ensuring consistency between statistical analysis, data presentation, and biological interpretation. The significance of fixed effects, the normality of residuals, and model diagnostics are presented in the Supplementary Material (Table S2).

3. Results

Pasture productivity varied among fertilization strategies and nitrogen fertilization levels (Table 2). Canopy height was not influenced by treatments ($p > 0.05$), remaining between 31.1 and 32.7 cm. The forage accumulation rate responded significantly to nitrogen fertilization. Treatments with N showed average values of 118.9 kg DM ha^{-1} day^{-1} (AS+N) and 109.1 kg DM ha^{-1} day^{-1} (AC+N),

corresponding to increments of approximately 20% and 10%, respectively, compared to treatments without N. The highest value was observed in AS+N, surpassing AC+N by about 9%.

The total forage accumulation over the grazing period ranged from 6130 to 7568 kg DM ha^{-1}, with an absolute amplitude of 1438 kg DM ha^{-1} among treatments. The highest accumulation was recorded in AS+N, representing an increase of approximately 23% compared to the lowest value observed in treatments without nitrogen fertilization ($p \leq 0.05$). The available forage mass did not show significant differences between treatments, indicating that the effects of fertilization were expressed in the accumulation dynamics and not in the instantaneous biomass stock (Table 2).

Table 2. Effect of fertilization strategy and nitrogen fertilization on structural and productive characteristics of Urochloa brizantha cv. Piatã pasture in SIPA compartments over an annual cycle.

Variables	Factors								CV (%)
	Fertilization strategy				Nitrogen fertilization				
	AC	SE	AS	SE	Without	SE	With	SE	
Canopy height (cm)	31,6	1,2	32,1	1,1	32,7	1,3	31,1	1,0	13,7
Accumulation rate (kg DM ha^{-1} day^{-1})	102,7	5,3	110,1	5,1	98,8	4,9	114,0	5,0	5,2
Forage accumulation (kg DM ha^{-1})	6537	670	7008	715	6289	642	7256	733	10,2
Forage mass (kg DM ha^{-1})	3328	137	3181	130	3184	132	3325	135	4,1

AC: Conventional fertilization; AS: System fertilization; SE; standard error. Means estimated by a mixed linear model adjusted via lmer() (lme4 package), considering block as a random effect. SOURCE: Author (2025).

The animal performance indicators showed variation among the evaluated strategies (Table 3). The average daily gain (ADG) ranged between 0.701 and 0.800 kg animal^{-1} day^{-1}, being higher in the AS+N treatment. Animal productivity varied between 147.9 and 186.5 kg ha^{-1}, corresponding to an absolute difference of 38.6 kg ha^{-1} between treatments. The AS+N treatment surpassed AC–N by 26%, reflecting the combined effect of higher individual gain and higher stocking rate. The stocking rate

ranged from 2.6 to 3.1 AU ha^{-1}, with 15% increases in treatments fertilized with N, indicating greater pasture carrying capacity under these management practices.

Table 3. Effect of fertilization strategy and nitrogen fertilization on animal performance indicators in the SIPA compartments over an annual cycle.

Variables		Factors							
		Fertilization strategy			Nitrogen fertilization				CV (%)
	AC	SE	AS	SE	Without N	SE	With	SE	
Average daily gain (kg animal^{-1} day^{-1})	0,739	0,050	0,751	0,048	0,713	0,052	0,777	0,049	13,7
Animal productivity (kg ha^{-1})	155,9	12,6	168,3	13,1	149,0	12,2	175,2	13,5	8,1
Stocking rate (AU ha^{-1})	2,75	0,13	2,95	0,14	2,70	0,12	2,99	0,15	4,9

AC: Conventional fertilization; AS: System fertilization; AU = animal unit; SE: standard error. Estimated means by adjusted linear mixed model via lmer() (lme4 package), considering block as a random effect. SOURCE: Author (2025).

Soybean productivity ranged between 3,031.6 and 3,266.8 kg ha^{-1} throughout the evaluated cycle. Considering the main effects, system fertilization resulted in an average productivity approximately 6% higher than conventional fertilization. In contrast, nitrogen fertilization applied during the pasture phase did not influence soybean productivity, and no interaction was observed between the evaluated factors.

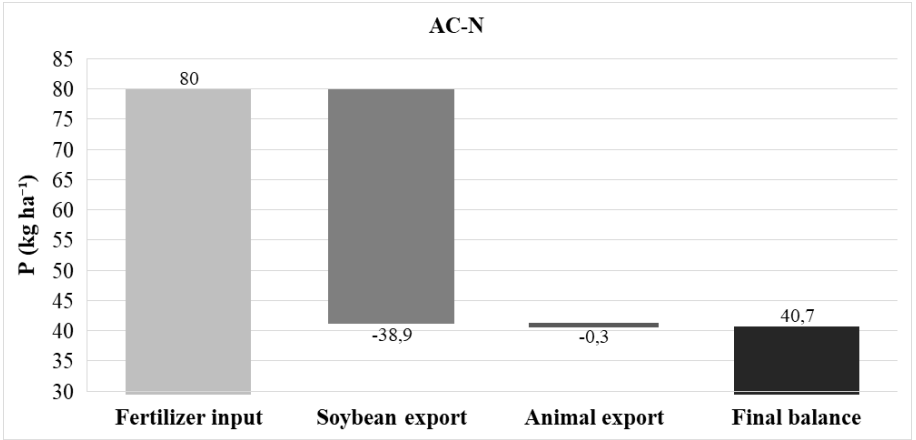
The annual phosphorus cycling in the soil-plant-animal compartments ranged between 70 and 87 kg ha^{-1}, with a relative amplitude of approximately 24% among treatments (Table 4). The phosphorus accumulated in soybean biomass was higher in treatments with nitrogen fertilization, showing an average increase of about 23% compared to treatments without N. The remaining phosphorus in the pasture after grazing showed values approximately 2 kg ha^{-1} higher under system fertilization (AS) compared to conventional fertilization (AC). The compartments associated with animal cycling (export and return via excreta) did not show significant differences among the evaluated factors.

Table 4. Annual phosphorus cycling in SIPA compartments during one year (between pasture and soybean) under fertilization strategies.

Phosphorus (P)	Factors								CV
	Fertilization strategy				Nitrogen fertilization				
	AC	SE	AS	SE	Without	SE	With	SE	
	--- kg ha^{-1} ---								%
Soybean biomass	51	7	54	7	47	7	58	7	14
Pasture residual	9	1	11	1	10	1	9	1	9
Animal export	0.3	0.03	0.3	0.03	0.3	0.03	0.3	0.03	9
Animal excreta	13	2	16	2	15	2	14	2	17
Total cycled	75	5	82	5	74	5	83	5	7

AC: Conventional fertilization; AS: System fertilization; SE: Standard error. Means estimated by a mixed linear model adjusted via lmer() (lme4 package), considering block as a random effect. SOURCE: Author (2025).

The annual phosphorus balance indicated positive balances in the crop across all treatments, ranging from +37.8 to +40.7 kg ha⁻¹. In the apparent soil balance (0–0.20 m), the balances varied between –9.1 and +4.2 kg ha⁻¹, with a deficit observed only under conventional fertilization without N (Figure 5).



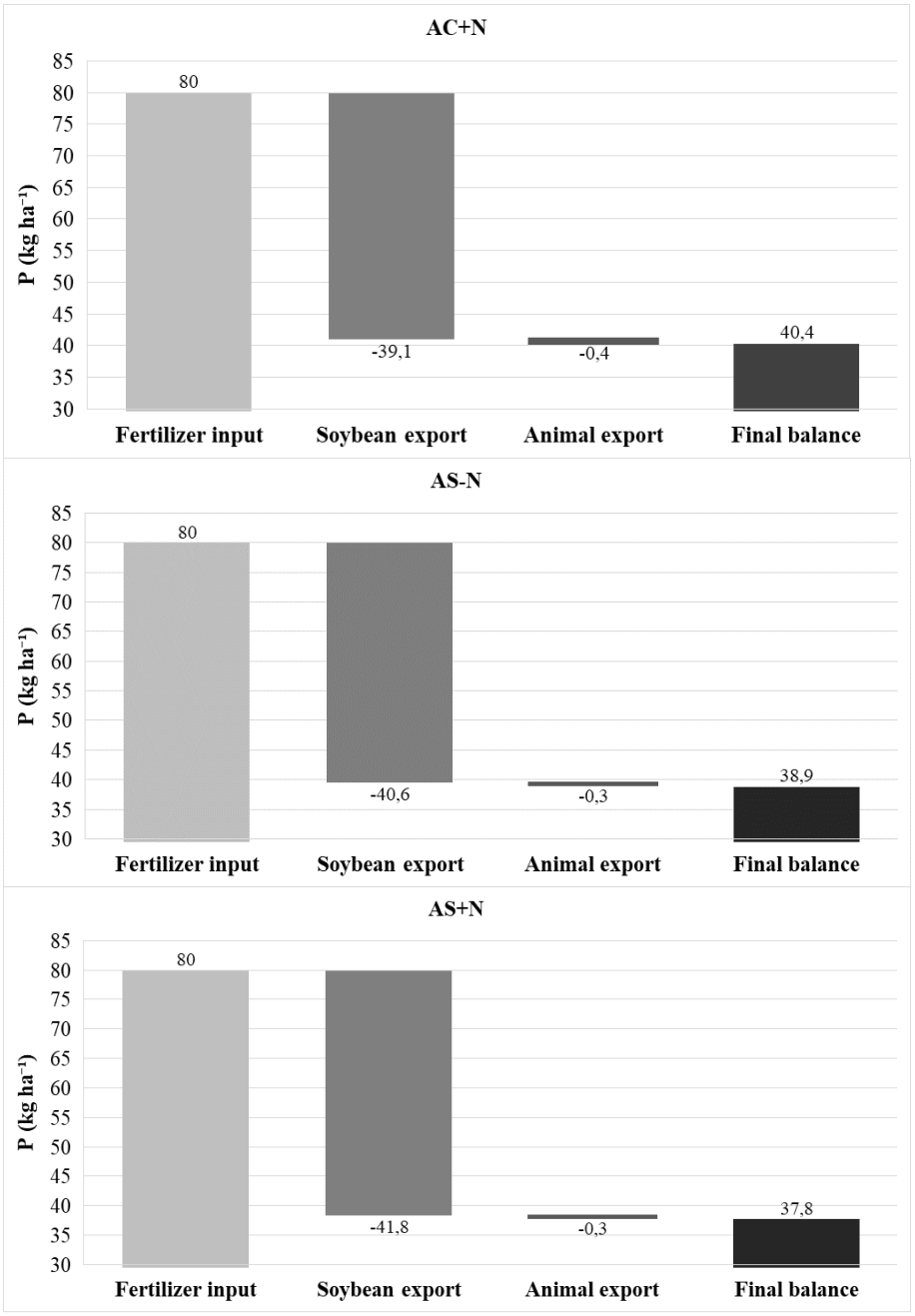


Figure 5. Annual phosphorus (P) balance in the crop and soil in an integrated agricultural production system under different fertilization strategies. The panels represent: (a) conventional fertilization without nitrogen (AC–N), (b) conventional fertilization with nitrogen (AC+N), (c) system fertilization without nitrogen (AS–N), and (d) system fertilization with nitrogen (AS+N). The bars indicate the inputs of P via fertilization, the outputs associated with soybean grain export and animal production, as well as the annual nutrient balance in the system.

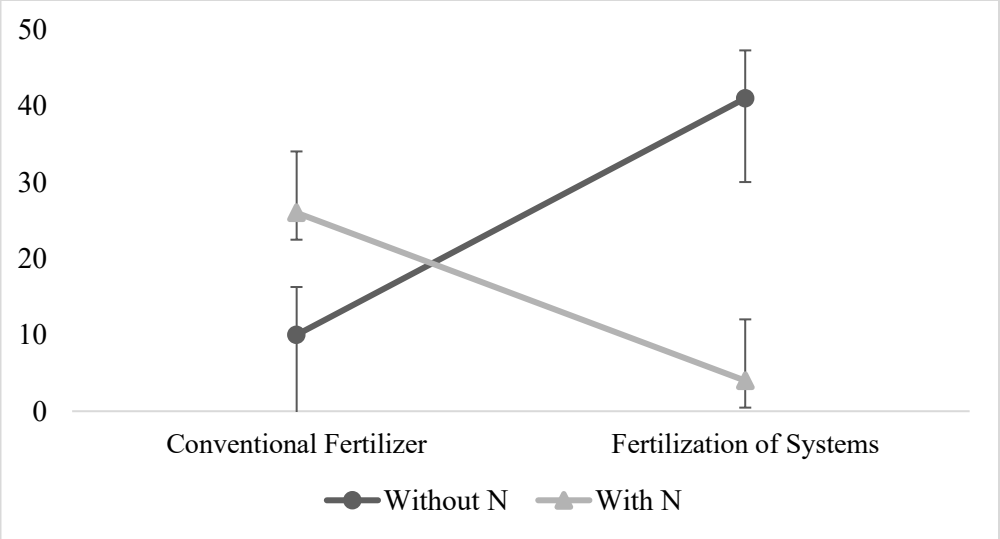
Potassium cycling showed greater variability among treatments compared to phosphorus (Table 5). The total annual K cycled ranged from 178 to 198 kg ha^{-1}, with no significant statistical differences between fertilization strategies. K accumulation in soybean biomass varied between 139 and 160 kg ha^{-1}, while residual K from pasture ranged between 14 and 19 kg ha^{-1}, with no consistent pattern among the evaluated factors. K export via carcass remained below 1 kg ha^{-1} in all treatments.

Table 5. Annual potassium cycling in the compartments of the SIPA system during one year (between pasture and soybean) under fertilization strategies

Potassium (K)	**Factors**								**CV**
	Fertilization strategy				**Nitrogen fertilization**				
	AC	**SE**	**AS**	**SE**	**Without**	**SE**	**With**	**SE**	
	--- kg ha^{-1} ---								%
Soybean biomass	154	7	150	7	147	7	157	7	7
Pasture residual	17	5	16	5	15	5	18	5	29
Animal export	0.5	0.05	0.6	5	0.5	0.05	0.6	0.05	9
Animal excreta	18	10	23	10	26	10	15	10	57
Total cycled	191	23	189	23	191	23	189	23	12

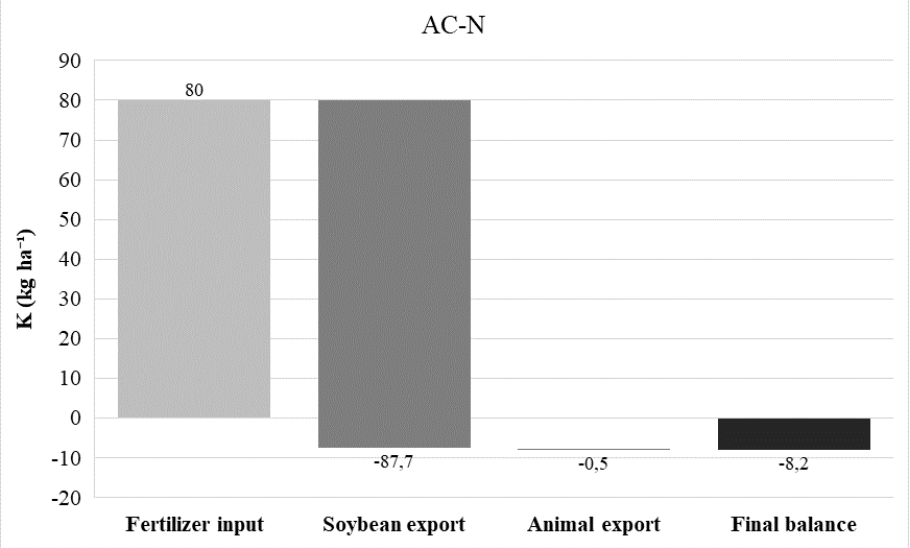
AC: Conventional fertilization; AS: System fertilization; SE: Standard error. Estimated means by a linear mixed model adjusted via lmer() (lme4 package), considering block as a random effect. SOURCE: Author (2025).

However, a significant interaction was observed between the fertilization strategy and nitrogen fertilization in the return of K via excreta ($p \leq 0.05$). The highest return was recorded in AS–N (41 kg ha^{-1}), while AS+N showed a substantially lower return (4 kg ha^{-1}), representing a reduction of over 90% between these combinations (Figure 6). This interaction highlighted high variability in animal return flows, reflecting on the final potassium balances in the system (Figure 7).



SOURCE: Author (2025).

Figure 6. Adjusted means (± 95% CI) of potassium returned to the soil via animal excreta as a function of the interaction between phosphorus and potassium fertilization strategies and nitrogen fertilization in the pasture phase of an integrated soybean-pasture system.



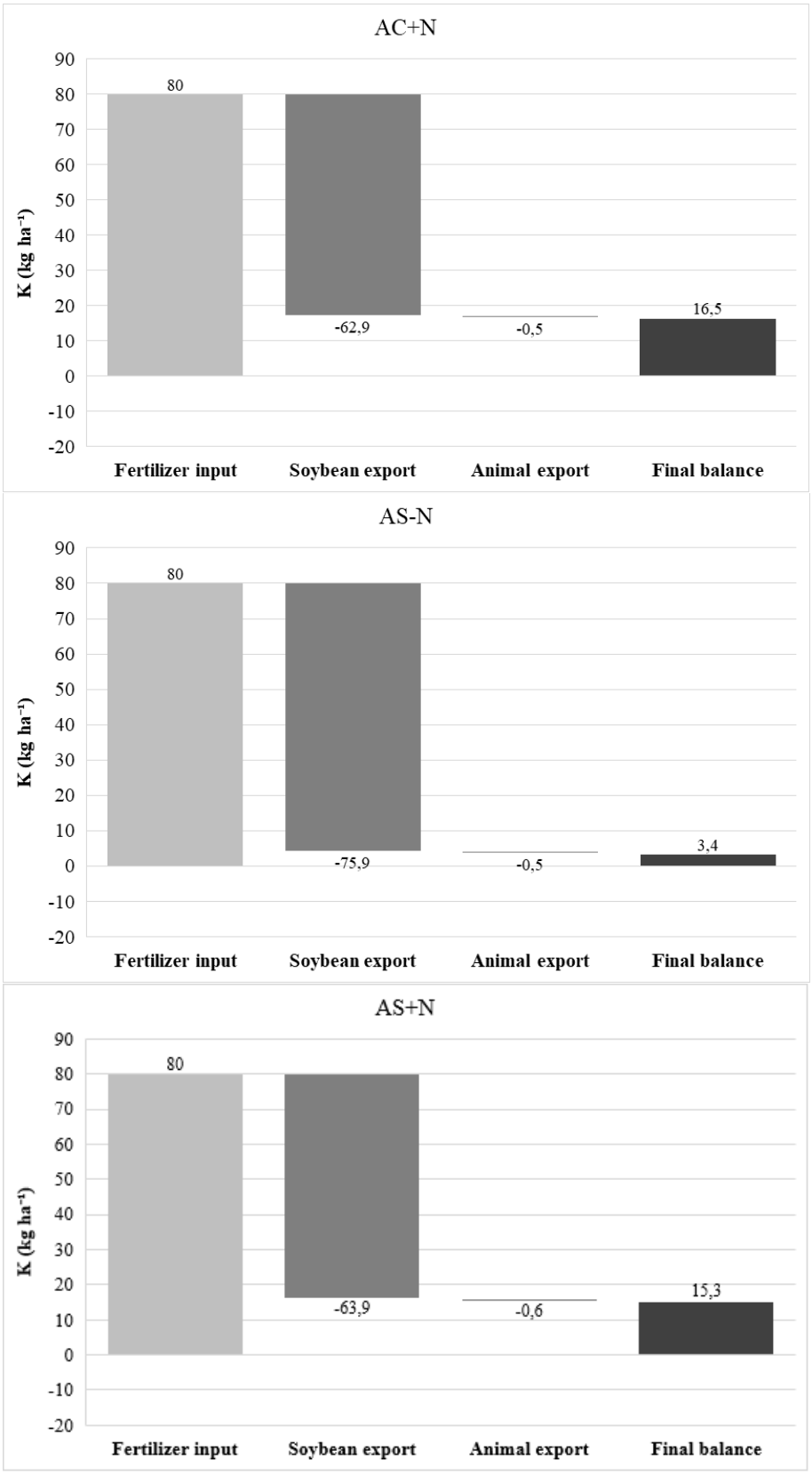


Figure 7. Annual potassium (K) balance in the crop and soil under four fertilization strategies in an integrated crop-

livestock system. Each panel presents a specific treatment: a) conventional fertilization without nitrogen (AC–N), b) conventional fertilization with nitrogen (AC+N), c) system fertilization without nitrogen (AS–N), and d) system fertilization with nitrogen (AS+N). The bars illustrate the inputs via fertilizer, exports by soybean and the animal component, as well as the annual final balance of the nutrient in the system.

For K, a greater variation amplitude was observed among treatments (Figure 7 a-d). Conventional fertilization without N resulted in a deficit in the crop balance (–8.2 kg ha^{-1}), while the other treatments showed positive balances, with values up to +16.5 kg ha^{-1}. In the apparent soil balance (0–0.20 m), only AC+N showed an increase in stocks (+18.4 kg ha^{-1}), while the other treatments recorded an apparent reduction in stocks, notably AS+N (–48.9 kg ha^{-1}).

4. Discussion

The results demonstrate that nutrient dynamics in integrated crop–livestock systems (ICLS) under tropical conditions differ markedly from those reported in subtropical environments, reinforcing the strong influence of edaphoclimatic context on nutrient cycling processes. The balances presented here should be interpreted as indicators of short-term trends and redistribution within the system, rather than as evidence of long-term sustainability, particularly given the one-year assessment and the focus on the 0–0.20 m soil layer.

Phosphorus dynamics were relatively stable across treatments, with consistently positive crop balances and limited variation in soil balance. The greater retention of P under system fertilization indicates that the pasture phase represents a strategic window for nutrient application in highly weathered Oxisols. In these soils, the high content of Fe and Al oxides promotes rapid P fixation, but also favors biological recycling pathways when nutrient inputs coincide with periods of active root growth and microbial activity. This contrasts with findings from subtropical systems, where lower soil reactivity results in more predictable P fluxes and reduced dependence on biological cycling

mechanisms.

The increase in residual P under system fertilization is likely associated with grazing-induced regrowth dynamics. Defoliation stimulates root turnover and nutrient demand, enhancing internal P cycling within the plant–soil system. In addition, greater root biomass and organic residue inputs may contribute to the stabilization of P in organic and moderately labile fractions, reinforcing the role of pasture as a key driver of P retention in tropical ICLS. These mechanisms suggest that P use efficiency in such systems is strongly linked to biological processes rather than solely to fertilizer inputs.

In contrast, potassium exhibited greater variability among treatments, reflecting its higher mobility in the soil–plant system and weaker association with stable soil fractions. The pronounced interaction between fertilization strategy and nitrogen supply, particularly in the return of K via excreta, highlights the sensitivity of this nutrient to grazing dynamics and animal behavior. The large variation in excreta-derived K indicates that, although animal cycling represents a substantial flux, its spatial heterogeneity limits its effectiveness as a consistent nutrient redistribution mechanism at the system scale.

The negative K balances observed in some treatments, especially under system fertilization combined with nitrogen, suggest a decoupling between nutrient uptake and replenishment. This pattern may result from increased plant growth and nutrient demand stimulated by nitrogen, coupled with insufficient return via excreta and potential losses through leaching or redistribution below the sampled soil layer. Such behavior is consistent with the characterization of K as a highly mobile nutrient and a preferentially exported element in grain-based systems.

The contrasting behavior of P and K highlights the existence of nutrient-specific controls within integrated systems. While P cycling appears to be regulated primarily by biological processes and soil reactivity, K dynamics are more strongly influenced by plant uptake, animal-mediated redistribution, and hydrological processes. This divergence reinforces the need for nutrient-specific management

strategies in tropical ICLS, rather than uniform fertilization approaches.

From a management perspective, the results indicate that system fertilization can enhance P retention and internal cycling, contributing to greater nutrient use efficiency. However, the same strategy may increase the risk of short-term K depletion when combined with nitrogen fertilization, particularly in systems with high export rates and limited effective nutrient return. Therefore, K management in tropical ICLS should include periodic monitoring of soil stocks and, when necessary, adjustments in fertilization strategies to compensate for potential deficits.

It is important to recognize that the apparent balances presented here do not account for nutrient redistribution below the 0–0.20 m layer or unquantified losses, which may partially explain the observed deficits, particularly for K. Additionally, the absence of controlled animal congregation points (e.g., shade or water sources) likely contributed to the spatial heterogeneity of nutrient return via excreta. These factors represent inherent limitations of studies conducted under continuous grazing conditions and should be considered when interpreting the results.

Although the study represents a single production cycle, it was conducted in a consolidated ICLS, where legacy effects from previous years likely influence current nutrient dynamics. Thus, the observed patterns reflect not only immediate treatment effects but also accumulated system processes. Long-term studies are required to determine whether the identified trends persist and to assess their implications for system sustainability.

Overall, the findings demonstrate that nutrient cycling in tropical ICLS is governed by the interaction between fertilization strategy, nitrogen inputs, and biological processes, with distinct responses for P and K. These results contribute to advancing the understanding of nutrient redistribution mechanisms in highly weathered soils and provide a basis for developing more efficient and resilient fertilization strategies in integrated agricultural systems.

5. Conclusion

Nitrogen fertilization enhanced animal performance and organic cycling in the soybean-pasture system; however, its effects on potassium balance heavily depended on the fertilization strategy adopted, potentially intensifying soil deficits when combined with system fertilization. Therefore, when the management goal is to reduce the risk of short-term K depletion, the adoption of system fertilization associated with the use of N during the pasture phase should be accompanied by frequent monitoring of soil K stocks and adjustments in nutrient replenishment.

On the other hand, the absence of nitrogen fertilization was associated with localized deficits and a reduction in K stocks in the surface layer (0–0.20 m) of the soil, highlighting the high sensitivity of this nutrient to management variations in integrated systems in the short term. In this context, strategies that prioritize cycling through residues and excreta, without additional N input, may not be sufficient to sustain the K balance under high export conditions.

For phosphorus, the annual balances remained stable among fertilization strategies, with positive balances and low variation between treatments, indicating that, within this specific production cycle, the integrated system was able to maintain P availability regardless of the fertilizer allocation method.

In the context of a soybean-pasture system conducted in Oxisol under a tropical climate, the results indicate that the combination of system fertilization and the use of N during the pasture phase favors nutrient cycling in the short term, provided it is accompanied by management strategies aimed at mitigating apparent K deficits in the surface layer. Nevertheless, as these results were obtained from a single agricultural cycle, such responses do not constitute definitive evidence of long-term sustainability, requiring multi-year assessments to capture the cumulative effects of organic cycling, recurrent K export, and the structural dynamics of the soil in highly weathered Cerrado environments.

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Declarations

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Conflicts of interest

The authors declare no conflict of interest.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All authors agree to the publication of this manuscript.

Availability of data and material

The datasets generated during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Authors' contributions

J.E.A. Davi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft.

C.C.S. Luz: Methodology, Supervision, Writing – review & editing.

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E.D. Souza: Supervision, Project administration, Funding acquisition.

L.B.O. Oliveira: Formal analysis, Validation.

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6. References

Almeida, T.F., Carneiro, R.G., Pires, M.F., Moraes, A., 2021. Forms and balance of soil potassium from a long-term integrated crop–livestock system in a subtropical Oxisol. Soil & Tillage Research 207, 104864. https://doi.org/10.1016/j.still.2020.104864

Almeida, T.O., 2024. Functional diversity as a strategy to improve soil health and forage productivity in the Cerrado of Mato Grosso, Brazil. M.Sc. Dissertation, Federal University of Paraná, Curitiba, Brazil.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Alves, F.V., Porfírio-da-Silva, V., Karvatte Junior, N., 2019. Animal welfare and ambience in ILPF. In: Bungenstab, D.J., et al. (Eds.), ILPF: Innovation with Integration of Crop–Livestock–Forestry. Embrapa, Brasília, pp. 835–860.

Alves, L.A., Deiss, L., Carvalho, P.C.F., Costa, S.E.V.G.A., Moraes, A., et al., 2019. Soil acidification

and P, K, Ca and Mg budget under grazing and crop rotation in an integrated crop–livestock system. Geoderma 351, 197–208. https://doi.org/10.1016/j.geoderma.2019.04.036

Alves, L.A., Assmann, T.S., Moraes, A., Carvalho, P.C.F., Anghinoni, I., et al., 2020. Crop rotation and grazing management effects on plant production and soil C and N stocks in long-term integrated crop–livestock systems. Soil & Tillage Research 203, 104678. https://doi.org/10.1016/j.still.2020.104678

Alves, L.A., Assmann, T.S., Moraes, A., Carvalho, P.C.F., Anghinoni, I., et al., 2022. Fertilization strategies and liming in no-till integrated crop–livestock systems: phosphorus and potassium use efficiency. Revista Brasileira de Ciência do Solo 46, e0210125. https://doi.org/10.36783/18069657rbcs20210125

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.A., Carvalho, P.C.F., Moraes, A., et al., 2017. Phosphorus and potassium cycling in long-term no-till integrated soybean–beef systems. Nutrient Cycling in Agroecosystems 107, 61–74. https://doi.org/10.1007/s10705-016-9818-6

Bindraban, P.S., Dimkpa, C.O., Pandey, R., 2020. Exploring phosphate fertilizers and fertilization strategies to improve human and environmental health. Biology and Fertility of Soils 56, 299–317. https://doi.org/10.1007/s00374-019-01430-2

Borghi, E., Bortolon, L., Avanzi, J.C., et al., 2014. Challenges of new agricultural frontiers. In: Karam, D., Magalhães, P.C. (Eds.), Efficiency in Productive Chains and Global Supply. ABMS, Brasília, pp. 263–278.

Camargo, T.A., Assmann, T.S., Moraes, A., Carvalho, P.C.F., 2024. Enhancing soil quality and grain yields through fertilization strategies in integrated crop–livestock systems. European Journal of Soil Biology 121, 103613. https://doi.org/10.1016/j.ejsobi.2024.103613

Campbell, A.G., 1966. Pasture dry matter production under grazing. Journal of Agricultural Science 67, 199–210.

Carvalho, P.C.F., Bremm, C., Bonnet, O.J.F., et al., 2013. Can grazing behavior support innovation in grassland management? Tropical Grasslands – Forrajes Tropicales 1, 137–155. https://doi.org/10.17138/tgft(1)137-155

Da Silva, S.C., Sbrissia, A.F., Pereira, L.E.T., 2015. Ecophysiology of C4 forage grasses. Agriculture 5, 598–625. https://doi.org/10.3390/agriculture5030598

Davi, J.E.A., Assmann, T.S., Moraes, A., Carvalho, P.C.F., Anghinoni, I., et al., 2022. Diversified systems in sandy soils of the Cerrado: nutrient dynamics and soybean yield. Journal of Plant Nutrition 46, 1650–1667. https://doi.org/10.1080/01904167.2022.2093744

Denardin, L.G.O., Moraes, A., Carvalho, P.C.F., et al., 2020. Soybean yield does not rely on mineral fertilizer in integrated crop–livestock systems. Agronomy 10, 1371. https://doi.org/10.3390/agronomy10091371

Ernani, P.R., De Almeida, J.A., Santos, F.C., 2007. Potassium. In: Novais, R.F., Alvarez, V.H., Barros,

N.F., Fontes, R.L.F., Cantarutti, R.B., Neves, J.C.L. (Eds.), Soil Fertility. Brazilian Soil Science Society, Viçosa, pp. 552–594.

Ferreira, E.V.O., Costa, S.E.V.G.A., Santos, F.C., et al., 2009. Soil potassium under no-till integrated crop–livestock systems with different grazing intensities. Revista Brasileira de Ciência do Solo 33, 1675–1684.

Ferreira, E.V.O., et al., 2011. Potassium cycling and soybean yield in integrated crop–livestock systems. Revista Brasileira de Ciência do Solo 35, 161–169. https://doi.org/10.1590/S0100-06832011000100017

Freitas, C.M., Assmann, T.S., Moraes, A., Carvalho, P.C.F., Anghinoni, I., et al., 2023. System fertilization in the pasture phase enhances integrated crop–livestock systems. Journal of Agricultural Science 161, 755–762. https://doi.org/10.1017/S0021859623000606

Gasques, L.R., et al., 2025. Poultry litter improves Oxisol fertility in the Cerrado. Acta Scientiarum. Agronomy.

Hasanuzzaman, M., Bhuyan, M.H.M.B., Zulfiqar, F., Raza, A., Mohsin, S.M., Mahmud, J.A., et al., 2018. Potassium as a regulator of stress tolerance. Agronomy 8, 31. https://doi.org/10.3390/agronomy8030031

Klingman, D.L., Miles, S.R., Lantow, J.L., 1943. The cage method for pasture consumption. Agronomy Journal 35, 739–746.

Lemaire, G., Hodgson, J., Chabbi, A., 2023. Domestic herbivores and sustainable agriculture. Agronomy 13, 982. https://doi.org/10.3390/agronomy13040982

Mai, W., Xue, X., Feng, G., et al., 2018. Simultaneously maximizing root/mycorrhizal growth and phosphorus uptake by cotton plants by optimizing water and phosphorus management. BMC Plant Biology 18, 334. https://doi.org/10.1186/s12870-018-1550-8

Moot, G.O., Lucas, H.L., 1952. Grazing trial design. Proceedings of the International Grassland Congress 6, 1380–1395.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Sousa, D.M.G., Lobato, E., 2004. Cerrado: Soil Correction and Fertilization. Embrapa, Brasília.

Tedesco, M.J., Gianello, C., Bissani, C.A., Bohnen, H., Volkweiss, S.J., 1995. Analysis of Soils, Plants and Other Materials. Federal University of Rio Grande do Sul, Porto Alegre.

USDA–NRCS, 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, 2nd ed. USDA, Washington, DC.

Xun, W., Yan, R., Ren, Y., et al., 2018. Grazing-induced microbiome alterations drive soil organic carbon turnover. Microbiome 6, 170. https://doi.org/10.1186/s40168-018-0544-y

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