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Replacement fertilization and nutrient balance in built-up fertility soils: responsible nutritional management in grain production

Abstract − The objective of this work was to check and validate the replacement fertilization to offset crop-removed nutrients associated with nutrient balance, for greater use efficiency of fertilizers in high built-up fertility soil of the Brazilian Cerrado. The treatments were compared during three cycles of first/second crop, in systems with or without ruzigrass (*Urochloa ruziziensis*) as cover crop, as follows: control, no fertilization; replacement fertilization based on the removal of N, P, and K in grains; replacement plus 30%; replacement minus 30%; system fertilization; farm standard; and farm plus 30%. An experimental design was carried out in randomized blocks, to evaluate the following variables: grain yield, profitability, nutrient balance, use efficiency of fertilizers, and soil fertility. Fertilization has no influence on soybean (*Glycine max*) crops, but affects grain yield of second-crop maize (*Zea mays*). Intercropping with ruzigrass reduces sorghum (*Sorghum bicolor*) yield and does not affect maize in the second crop, but improves subsequent soybean yield. Replacement fertilization, associated with nutrient balance, maintains yield and profitability levels, with more efficient use of fertilizers, while preserving soil fertility, and avoiding nutrient deficits or surpluses in the crop system. Therefore, it constitutes a responsible nutritional management strategy for built-up fertility soils in Brazil, contributing to high production performance with environmental safety.

Index terms: Brazilian savannah, cropping systems, no tillage, nutrient use efficiency, precision agriculture.

Adubação de restituição e balanço de nutrientes em solo de fertilidade construída: manejo nutricional responsável na produção de grãos

Resumo − O objetivo deste trabalho foi aferir e validar a adubação de restituição associada ao balanço de nutrientes para maior eficiência de uso de fertilizantes na produção de grãos, em solo de Cerrado com fertilidade construída. Durante três ciclos de safra/segunda safra, em sistemas com ou sem braquiária (*Urochloa ruziziensis*) em consórcio, compararam-se os seguintes tratamentos: controle sem adubação; adubação de restituição de N, P e K exportados; restituição mais 30%; restituição menos 30%; adubação de sistema; padrão da fazenda; e padrão da fazenda mais 30%. Um delineamento experimental de blocos ao acaso foi utilizado, para avaliar as seguintes variáveis: produtividade, rentabilidade, balanço e eficiência de uso de nutrientes e fertilidade do solo. A adubação não influencia a soja (*Glycine max*), mas

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afeta a produtividade do milho (*Zea mays*) segunda safra. O consórcio com braquiária prejudica o sorgo (*Sorghum bicolor*) e não compromete o milho segunda safra, mas aumenta a produtividade da soja subsequente. A adubação de restituição vinculada ao balanço de nutrientes mantém os níveis de produtividade e rentabilidade, com uso mais eficiente de fertilizantes, enquanto preserva a fertilidade do solo e previne deficits ou excessos de nutrientes. Portanto, constitui estratégia de manejo nutricional responsável em solos de fertilidade construída no Brasil, o que contribui para um alto desempenho produtivo com segurança ambiental.

Termos para indexação: Cerrado, sistemas de cultivo, plantio direto, eficiência de uso de nutrientes, agricultura de precisão.

Introduction

Annual crops have high demands for nitrogen (N), phosphorus (P), and potassium (K), leading to the consumption of large amounts of fertilizers to supply production systems in Brazil, especially for crops such as soybean, maize, cotton, bean, wheat, and sorghum (Cunha et al., 2023). Crop diversification contributes to the efficiency in the use and cycling of nutrients applied in fertilization, with the potential to reduce the need for fertilizers (Withers et al., 2018).

The succession system of soybean/second-crop maize in the Cerrado biome has evolved with the introduction of forage grasses intercropped with maize, notably *Urochloa ruziziensis* (syn. *Brachiaria ruziziensis*) functioning as a cover crop in the off-season. Beyond to increasing straw in the system to protect the soil, *U. ruziziensis* favors the increase of organic matter, nutrient cycling, and biological quality, in addition to improving the physical conditions of the soil through the action of roots, which results in gains in soybean yield (Mendes et al., 2019; Ferreira et al., 2021; Balbinot Junior et al., 2023).

Soils in areas of consolidated cultivation in the Cerrado have accumulated considerable nutrient stocks, overcoming the condition of low natural fertility, thanks to the use of acidity correction practices, no-tillage seeding, and successive fertilizer applications (Resende et al., 2019; Rodrigues et al., 2021). From this point on, the soil ceases to act as a sink, and its nutrient reserves are sufficient to sustain high crop yields for some time, even without any fertilization, especially in clayey environments with good organic matter content (Resende et al., 2019). However, the magnitude of these reserves varies according to the soil type, fertilization history, crop combination, and the nutrient considered, oscillating according to the input/output balance in the system over time. In view of these variations, the diagnosis for fertilization decisions needs to be site-specific.

The main approach to soil fertility management in Brazil is based on the interpretation of soil analysis, critical nutrient levels in the soil, and fertilization recommendations according to crop requirements and yield ranges, with well-defined criteria for the Cerrado region (Sousa & Lobato, 2004). However, despite the remarkable technological advances and the increase of the production potential of agricultural environments in the Cerrado, fertilization management is still performed without proper refinement on most farms. There is still a tendency to use fertilizers always in the same formulations or fixed amounts of N, P, and K, recurrently. Besides, in general, producers do not bother to calculate the nutrient balance, unaware of the value of this piece of information (Resende et al., 2019).

Situations of imbalance between the quantities of nutrients applied via fertilization and those removed in the harvested crop products are common. On the one hand, when this balance is deficient over time, yield becomes limited, as soil nutrient reserves are depleted (Moterle et al., 2019; Simão et al., 2020; Balbinot Junior et al., 2023). On the other hand, a balance with surpluses can lead to the conversion of nutrients into unavailable forms or their loss from the system, with possible negative impacts on environmental quality (Withers et al., 2018; Ferreira et al., 2021; Wu et al., 2021). Both deficits and surpluses in fertilization reduce profitability and efficiency in the use of fertilizers, and can also imply a higher carbon footprint of the harvested product (Paustian et al., 2016; Chojnacka et al., 2019; Sainju & Allen, 2023), a factor of increasing relevance in issues involving agricultural sustainability and market access. Therefore, it is imperative to implement ways that are more precise to determine nutrient requirements and fertilizer applications, in order to optimize production efficiency and mitigate the environmental impacts of agriculture (Xing & Wang, 2024).

The modality of replacement fertilization involves a classic concept, appropriate to the management of high-fertility soils, in which the aim is to size the quantities of nutrients, to provide only what is necessary to replace the removal by harvesting and eventual losses of the system. Once soil sufficiency levels have been established, recommendations should be based on replacing the quantities exported by crops (Withers et al., 2018; Resende et al., 2019), instead of being linked to the indications of tables in the fertilization manuals. Although this modality is the most rational for built-up fertility fields, it is still little adopted in practice. In line with responsible nutritional management, replacement fertilization associated to nutrient balance would make it possible to compensate for deficits and/or surpluses in each crop season, providing balances closer to neutrality. This simple and practical approach would lead to greater efficiency of use and possible saving of fertilizers, while preserving soil fertility and the yield potential of crops, contributing to greater agricultural and environmental sustainability.

Therefore, the objective of this study was to assess the effectiveness and validate the replacement fertilization associated with the balance of N, P, and K, as a strategy for higher efficiency in the use of fertilizers in grain production in Cerrado soil with built-up fertility.

Materials and Methods

The study was carried out at Fazenda Decisão, in the municipality of Unaí, in the state of Minas Gerais, Brazil (16.412S, 47.301W, at 992 m altitude), in a field cultivated for about 25 years with annual crops under no-tillage. The soil of the experimental area is classified as a very clayey Latossolo Vermelho-Amarelo, according to Brazilian Soil System Classification (Santos et al., 2018), corresponding to a Typic Haplustox, with a high-level of built-up fertility, according to the initial soil analysis of the area (Table 1). The distribution of rainfall during the experimental period is shown (Figure 1).

The study consisted of the comparison of NPK fertilization options, during three cycles of soybean/second-crop maize (or sorghum), in two adjacent experiments involving systems with (+R) or without (-R) ruzigrass (*Urochloa ruziziensis*), intercropped in the second season and remaining as a cover crop in the off-season.

The experimental design was applied in randomized blocks with four replicates. The plots, adjusted to the dimensions of the machinery available on the farm, were 30 m wide by 150 m long, with 0.5 m spacing between rows.

The NPK fertilization treatments were the following: control without fertilization (CONT); replacement fertilization to offset nutrient exports in grains from the previous crop (RPLC); replacement fertilization plus 30% to cover any losses of the system (RPLC+30); replacement fertilization minus 30%, to assess the possibility of reducing fertilization (RPLC-30); replacement fertilization with all P and K for the crop system applied to soybean (SYST); farm standard fertilization (FARM); and farm fertilization plus 30%, to assess possible additional yield gains (FARM+30).

In the three cycles, the soybean cultivar 'M6210 IPRO' was sown as the first crop, at densities from 250,000 to 260,000 seed ha^{-1}, on October 26, 2018, November 07, 2019, and November 04, 2020. The second crops included the sorghum cultivar 'Enforcer', at 180,000 seed ha^{-1}, sown on February 21, 2019, and the maize cultivars 'MG408 PowerCore' (50,000 seed

Table 1. Soil chemical characterization before setting up the experiment.

Soil attribute	Depth	
	0−10 cm[1]	10−20cm[1]
pH_{water}	6.6	6.1
$P_{Mehlich-1}$ (mg dm^{-3})	38	23
$K_{Mehlich-1}$ (mg dm^{-3})	183	157
Ca ($cmol_c$ dm^{-3})	5.2	3.3
Mg ($cmol_c$ dm^{-3})	1.8	1.1
CEC ($cmol_c$ dm^{-3})	9.7	8.3
Base saturation (%)	77	57
B (mg dm^{-3})	0.5	0.4
Cu (mg dm^{-3})	0.9	0.9
Fe (mg dm^{-3})	25	31
Mn (mg dm^{-3})	35	26
Zn (mg dm^{-3})	9	9
Organic matter – SOM (g kg^{-1})	41	34
S (mg dm^{-3}) [2]	5	22
Clay (g kg^{-1}) [3]	470, 650, and 690	

[1]Analytical methods described in Teixeira et al. (2017). [2]Sulfur (S) content at 0−20 cm and 20−40 cm soil depths, respectively. [3]Clay content at 0−20, 20−40 and 40−60 cm soil depths, respectively.

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ha^{-1}, sown on March 05, 2020), and 'AS1820 VT Pro3' (60,000 seed ha^{-1}, sown on March 10, 2021).

For the RPLC treatment, the applied amounts of P and K were defined considering their removal rates (kg Mg^{-1}) in grains of each previous soybean (4.2, 17.8), sorghum (2.7, 3.5), or maize (2.1, 3.1) crops, and their respective yields. The amount of N for sorghum or maize was defined considering the expected yield (6,000 and 7,500 kg ha^{-1}, respectively), and the removal rate for these crops (13.3 and 13.1 kg Mg^{-1}), respectively.

The first soybean cultivation in the experiments (2018/2019) was carried out on the straw of millet (*Pennisetum glaucum*) intercropped with *Crotalaria ochroleuca*, and the RPLC treatment was sized according to the yield of the previous soybean harvest in 2017/2018. After that, the calculations were based on the nutrient export determined by the previous crop, in the following sequence: soybean/sorghum/soybean/maize/soybean/maize. In the SYST treatment, the total replacement of P and K for the first/second crop was applied entirely to soybean. In turn, topdressing N for

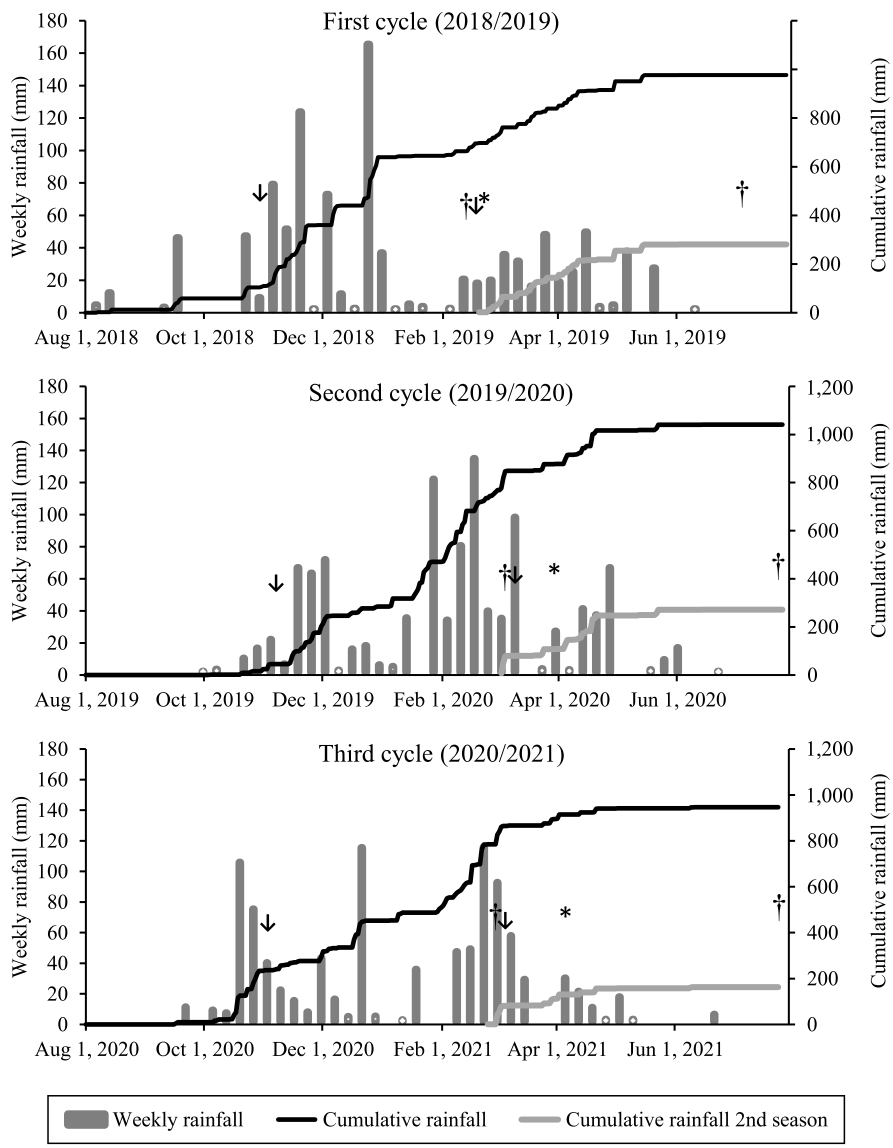

Figure 1. Weekly distribution and accumulated rainfall in the three crop cycles of the experimental period. Markers: ↓ sowing; † harvest; * nitrogen topdressing.

sorghum or maize was conventionally applied in their early vegetative phase.

The sources of N, P, and K varied according to the fertilizers acquired by the farmer. All P was always applied in the sowing furrow, while K was broadcast in pre-sowing of soybean or initial post-sowing of sorghum and maize. Despite the fertilizations at sowing added some N (5 to 36 kg ha^{-1}, depending on the year/treatment) along with P, the broadcast topdressing represented the largest proportion of the N supply for sorghum and maize. According to the treatments, the doses of basal and topdressing fertilizations automatically varied in the plots, by means of a satellite-guided system and variable-rate application devices, available in the pneumatic seeder and in a centrifugal fertilizer spreader. The quantities of nutrients related to the treatments in each crop, as well as the total applied in the study period, are presented (Table 2).

Ruzigrass was broadcast sown with 8 kg ha^{-1} seed (80% of cultural value) in the intercropped experiment, immediately before sowing sorghum or maize. After harvesting, ruzigrass was kept as cover crop and desiccated before the following soybean crop. Weed

Table 2. Quantities of N, P_2O_5, and K_2O (kg ha^{-1}) applied according to fertilization treatment and crop, in systems with (+R) or without (-R) ruzigrass (*Urochloa ruziziensis*) as cover crop, and total applied in the 2018–2021 period.

Nutrient (kg ha^{-1})	Treatment/system/crop[(1)]													
	CONT		RPLC		RPLC+30		RPLC-30		SYST		FARM		FARM+30	
	+R	-R	+R	-R	+R	-R	+R	-R	+R	-R	+R	-R	+R	-R
Soybean 2018/2019														
N	0	0	12	12	15	15	8	8	12	12	20	20	26	26
P_2O_5	0	0	56	56	72	72	39	39	56	56	94	94	122	122
K_2O	0	0	107	107	139	139	75	75	107	107	54	54	70	70
Sorghum 2019														
N	0	0	83	83	108	108	58	58	83	83	49	49	64	64
P_2O_5	0	0	41	41	53	53	29	29	41	41	78	78	101	101
K_2O	0	0	98	98	127	127	68	68	98	98	60	60	78	78
Soybean 2019/2020														
N	0	0	11	13	15	17	8	9	21	22	18	18	23	23
P_2O_5	0	0	54	63	70	81	38	44	98	106	83	83	108	108
K_2O	0	0	31	37	40	48	22	26	127	133	90	90	117	117
Maize 2020														
N	0	0	102	102	132	132	71	71	77	77	118	118	153	153
P_2O_5	0	0	44	44	57	57	31	31	0	0	50	50	65	65
K_2O	0	0	96	96	125	125	67	67	0	0	90	90	117	117
Soybean 2020/2021														
N	0	0	8	7	10	9	5	5	17	17	14	14	19	19
P_2O_5	0	0	38	36	50	47	27	25	85	83	72	72	94	94
K_2O	0	0	32	23	42	30	22	16	135	126	90	90	117	117
Maize 2021														
N	0	0	102	102	133	133	72	72	92	92	114	114	148	148
P_2O_5	0	0	47	47	61	61	25	25	0	0	114	114	149	149
K_2O	0	0	103	103	134	134	72	72	0	0	90	90	117	117
Total 2018–2021														
N	0	0	318	319	413	415	222	223	302	303	333	333	433	433
P_2O_5	0	0	279	286	362	371	188	192	279	286	491	491	639	639
K_2O	0	0	466	463	606	602	326	324	466	463	474	474	616	616

[(1)]Fertilization treatments: CONT, control without NPK; RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%. Crop systems: +R, with ruzigrass; -R, without ruzigrass. N-P_2O_5-K_2O formula as starter fertilization: 11-52-00 or 14-25-00 or 08-40-00. Topdressing K: potassium chloride (60% K_2O). Topdressing N: ammonium nitrate (27% N) or NBPT-urea (45% N). Soybean crops received *Bradyrhizobium* inoculant at sowing.

control and phytosanitary treatments were carried out using machinery, inputs, and procedures of the farm, observing the technical guidelines related to the crops.

Field evaluations were always carried out in the most central portion of the plots, avoiding the transition zones. Soil sampling, as well as yield evaluations, were performed at georeferenced points, previously defined in each plot and located using portable GPS. An area of 4.5 m^2 was harvested for soybean and sorghum (3 rows with 3 m length), and 6 m^2 for maize (4 rows with 3 m length), correcting grain moisture content to 13%.

Yield data were subjected to joint analysis of variance, in order to check the existence of interaction between fertilization treatments and systems with or without ruzigrass. Before performing the analysis of variance, the model assumptions were tested using the R software, version 4.4.0 (R Core Team, 2024). Residual normality was assessed using the Shapiro-Wilk's test, the independence of errors was evaluated using the Durbin-Watson's statistics, and the homoscedasticity was checked with the Breusch-Pagan's test. For all tests, a significance level at 5% probability was adopted. Since none of the tests indicated violations of the assumptions, no data transformations were required. When the F test was significant (α=0.05), the means were compared by the Scott-Knott's test, using the SISVAR program (Ferreira, 2019). The net revenue derived from the treatments was estimated by the difference between the gross revenue from the sale of the grains and the costs related to fertilizers and ruzigrass seed, based on the respective quotations obtained by the farm.

The partial nutrient balance (kg ha^{-1}) was calculated by the difference between the quantities applied in the fertilizations and those exported in grain harvest. For the N balance, we considered the scenario in which the amount exported by soybean would be equivalent to the input via biological fixation (Ciampitti & Salvagiotti, 2018). The agronomic efficiency of P and K fertilization was assessed by the relationships between grain yield and the applied amount of these nutrients (kg kg^{-1}). An estimate of the apparent recovery of P and K from fertilization was expressed by the proportion (%) of these nutrients exported at harvest relatively to inputs via fertilizers (Cunha et al., 2023).

At the end of the experimental period (November 2021), soil sampling was carried out in the central area of the plots, at 0–10, 10–20, and 20–40 cm soil depths. Samples composed of nine collection points were analyzed for fertility, as described by Teixeira et al. (2017). The relationships between the soil P and K availability, and the cumulative balance of these nutrients after the six harvests was established. For P, this relationship was determined considering the P Mehlich-1 contents at the 0–10 cm soil depth, which concentrate most of the stock available to plants in clayey soils. The average contents at the 0–20 cm soil depth were considered for K, which has greater mobility in the profile.

Results and Discussion

Soybean showed no difference for various fertilization options (Table 3). Even in the control treatment, in the fifth crop without NPK fertilization, there was not a reduction in the yield. This result confirms that P and K reserves present in the soil were sufficient to meet the soybean demand for some cultivation cycles.

In consolidated crop fields, in clayey soils with a high content of organic matter, the initial P and K contents – available (Table 1) above the respective critical levels of 10 and 80 mg dm^{-3} (Sousa & Lobato, 2004) – were already indicative of the low potential for response to fertilization.

Investments in building up soil fertility, with liming and corrective fertilization with P, K, and micronutrients, is recognized as an essential step toward making agriculture viable in the Cerrado region. In this context, the common perception of grain producers is that a higher fertilizer load in maintenance fertilization acts as a risk reduction factor, and many are afraid of reducing the quantities applied to seek a better adjustment, even in the case of fields cultivated for decades.

The system with ruzigrass as cover crop in the off-season promoted higher yields of subsequent soybean, with mean increments of 335 and 214 kg ha^{-1}, in the 2019/2020 and 2020/2021 harvests, respectively (Table 3).

Some studies have reported variable increments in soybean yield, after the intercropping of maize with ruzigrass, from 258 to 818 kg ha^{-1} (Correia et al., 2013), and from 573 to 611 kg ha^{-1} (Balbinot Junior et al., 2023). As to soybean after maize intercropped with *U. brizantha*, Fortes et al. (2016) recorded 286 kg ha^{-1} yield gain compared to the sole-crop maize system.

This positive impact on soybean crop has been attributed to the effects of the input of *Urochloa* straw and roots, promoting soil protection, improvement of physical, chemical, and biological conditions, water retention, in addition to nutrient cycling (Mendes et al., 2019; Balbinot Junior et al., 2017, 2023; Ferreira et al., 2021).

In the present study, on average, intercropped ruzigrass contributed with 2,515 kg ha^{-1}, 617 kg ha^{-1}, and 873 kg ha^{-1} of shoot dry mass, for sorghum harvest (2019), and maize harvest (2020 and 2021), respectively. Therefore, a higher percentage of soil cover by straw was found in the system with ruzigrass (+R) at the time of soybean sowing subsequent to intercropping.

Sorghum yield was impaired in the +R system, due to the strong competition of ruzigrass that led to an average reduction of 20% in grain yield, in comparison with sole-crop system (Table 3). The negative impact of intercropping on sorghum can be attributed to the more vigorous growth of ruzigrass in high soil fertility and, mainly, to the short stature (135 to 150 cm tall at flowering) and lower shading capacity of the grain sorghum cultivar. As *Urochloa* plants receive more light, their growth is stimulated, which intensifies their capacity for interspecific competition. Despite that, the average sorghum yield in the intercropping reached 7.131 kg ha^{-1}, which is above the state average of 3.492 kg ha^{-1} in 2019.

Maize was not affected in the intercropping system with ruzigrass, due to its greater shading capacity, faster canopy closure, and taller plant stature (Table 3). However, there were clear differences due to NPK fertilization treatments. Yield in maize crops in 2020 and 2021 was reduced in the replacement minus 30% treatment (RPLC -30), and markedly in the control (CONT) treatment, with effects on the cumulative yield of the three first/second-crop cycles.

Nitrogen insufficiency was expected to be the main restricting factor in the CONT and RPLC -30, considering the high demand by maize and the limited supply capacity of tropical soils. Nitrogen extraction by modern maize cultivars is of 26.5 kg Mg^{-1} of grains produced (Silva et al., 2018), which would correspond to a demand of 180 kg ha^{-1} for yield of 6.8 Mg ha^{1}, that was the average result of the second crop of 2021 in the present study.

Table 3. Analysis of variance and means for grain yield of six crops and cumulative yield, as affected by systems with or without ruzigrass as cover crop and different options of NPK fertilization[(1)].

Source of variation	Soybean 2018/2019	Sorghum 2019	Soybean 2019/2020	Maize 2020	Soybean 2020/2021	Maize 2021	Cumulative yield
				p-value			
System-S	0.664	<0.001	<0.001	0.104	0.001	0.428	<0.001
Block (S)	0.973	0.828	<0.001	0.002	0.146	0.022	0.024
Fertilization-F	0.289	0.656	0.616-	<0.001	0.313	<0.001	<0.001
S x F	0.955	0.008	0.293	0.605	0.075	0.330	0.307
Coefficient of variation (%)	8.03	7.12	4.39	5.95	4.67	8.60	3.25
System[(2)]				Yield (kg ha^{-1})			
+ Ruzigrass	4,646	7,131B	4,669A	7,459	4,884A	6,717	35,505B
- Ruzigrass	4,602	8,946A	4,334B	7,659	4,670B	6,842	37,054A
NPK Fertilization[(3)]				Yield (kg ha^{-1})			
CONT	4,427	7,734	4,577	5,075d	4,864	4,061c	30,738c
RLPC	4,473	8,022	4,411	7,901b	4,885	7,483a	37,176a
RLPC+30	4,803	8,306	4,552	8,624a	4,775	7,579a	38,639a
RLPC-30	4,560	8,021	4,456	7,189c	4,838	6,558b	35,623b
SYST	4,609	8,033	4,524	7,342c	4,672	6,908b	36,088b
FARM	4,794	8,118	4,458	8,298a	4,682	7,503a	37,847a
FARM+30	4,702	8,041	4,533	8,482a	4,723	7,362a	37,844a

[(1)]Means in each column followed by different letters, uppercase for systems and lowercase for fertilization, indicate significant differences by the Scott-Knott's test, at 5% probability. [(2)]Crop systems: +R, with ruzigrass; -R, without ruzigrass as cover crop. [(3)]Treatments: CONT, control without NPK; RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%.

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Estimates of N credits (Simão et al., 2020) can be made by considering the contribution of plant residue from the previous soybean crop (17 kg N Mg^{-1} of soybean grains produced), and from the mineralization of soil organic matter (12 kg of N for each 1% of organic matter at 0–10 cm soil depths of the profile). This contribution would correspond to about 128 kg N ha^{-1} for maize, in the second crop of 2021. Even so, there would be a deficit to be provided by fertilization. Specifically, the second crop of 2021 was the sixth successive crop without N, P, and K inputs in basal or topdressing fertilization, in the CONT treatment, which produced 46% less than the best-performing treatment at the time (RPLC+30) (Table 3).

The quantities of N, P, and K supplied in the first/second-crop succession were the same for RPLC and SYST, with the difference that, in the second option, the application of sources containing all P and K was made on the soybean crop. As soybean crops did not take advantage of SYST, the lower cumulative yield in this treatment (Table 3) can be attributed to the fact that the second-crop maize loses yield, when it no longer receives basal fertilization with P and some N (Duarte et al., 2017).

There was no significant difference for grain yield between RPLC and FARM fertilization in five of the six crops (Table 3). Considering the cumulative yield, the treatments RPLC, FARM, RPLC+30, and FARM+30 were equal, forming the group with the best performance. This leveling confirms the effectiveness of the management approach based on the replacement of nutrients exported at harvest. Thus, RPLC constitutes a more rational criterion for sizing maintenance fertilizations in clayey soils with built-up fertility.

Based on the cumulative result of the six crops, in the means of the systems with and without ruzigrass, the net revenue (US$ ha^{-1}) derived from the different fertilization options showed the following descending order: RPLC+30 (US$ 7,607), RPLC (US$ 7,568), FARM (US$ 7,510), RPLC-30 (US$ 7,392), SYST (US$ 7,305), FARM+30 (US$ 7,261), and CONT (US$ 6,760). Thus, the nutritional management of the farm (FARM) was less profitable than that which aimed to replace the export of N, P, and K (RPLC). Mainly the option of increasing farm fertilization by 30%, maintaining the same N/P/K ratio (FARM+30), did not result in yield gains that would generate a more significant revenue margin. In this aspect, the substantial excess of P supplied in FARM+30, in comparison with the other treatments, should also be taken into account (Table 2).

The comparison between the production systems, in the average of the fertilization options, indicated a higher financial return with the absence (US$ 7,380) than with the presence (US$ 7,307) of intercropped ruzigrass. In this case, the lower cumulative revenue was attributed to the reduction of sorghum yield by 20% when intercropped with ruzigrass.

The RPLC fertilization led to higher phosphorus use efficiency than the FARM standard (Table 4). These treatments showed very different yield ratios per kilogram of P_2O_5 applied, proportionally reflecting on the apparent recovery of phosphate fertilizer. These results were mainly due to the lower consumption of phosphate fertilizer in the RPLC treatment (Table 2).

Table 4. Agronomic efficiency (kg kg^{-1}) and apparent recovery of fertilizer (%), as affected by different options of NPK fertilization and crop systems with (+R) or without (-R) ruzigrass. Average of six successive harvests.

NPK fertilization(1)	P				K			
	Agronomic efficiency(2)		Apparent recovery(3)		Agronomic efficiency(2)		Apparent recovery(3)	
	+R	-R	+R	-R	+R	-R	+R	-R
RPLC	133	133	92	91	83	85	88	85
RPLC+30	104	108	72	74	65	69	68	70
RPLC-30	190	191	135	133	113	115	125	120
SYST	124	133	88	92	78	84	86	85
FARM	77	80	54	55	81	87	87	87
FARM+30	60	62	41	42	63	66	66	67

(1)Treatments: RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%. (2)Agronomic efficiency: grain yield/applied P_2O_5 or K_2O (kg kg^{-1}). (3)Apparent recovery: nutrient removal from grains/ nutrient applied as fertilizer x 100 (%). Crop systems: +R, with ruzigrass; -R, without ruzigrass as cover crop.

Overall, there was no influence of production systems with or without ruzigrass on the use efficiency of fertilizers.

The soil where the experiment was set up showed high availability of P in the initial analysis (Table 1) that was above the critical level (10 mg dm^{-3}) by the Mehlich-1 extractant (Sousa & Lobato, 2004), at 0−10 cm soil depths. However, in the standard FARM management, P applications higher than the amounts removed from grains still persisted, leading to a lower apparent recovery, which was about 55% (Table 4). This fact suggests an important surplus in the P balance, highlighting a certain conservatism of the producer or apprehension of adjusting the fertilization to less. Roy et al. (2016) also reports this trend of recurrent positive balances in phosphate fertilization in Brazil, based on information from the management practiced on soybean farms, in Mato Grosso state. Therefore, RPLC management proved to have a consistent connection with the actual nutrient needs of the cultivation system, leading to lower consumption of phosphate fertilizers (Table 2), reducing production costs, promoting fertilizer savings, and increasing efficiency in nutrient use (Table 4).

As to potassium, the RPLC and FARM treatments were equivalent, since the respective quantities of K_2O applied remained closer (Table 2), resulting in similar values for agronomic efficiency and apparent recovery of fertilizer (Table 4). Differently from what occurred for P, the K management adopted by the farm proved to be more balanced in quantities that were closer to what would be the replacement of the removal in the harvests and, therefore, with a very good use efficiency of potassium fertilizer.

As expected, the RPLC treatment resulted in N, P, and K balances closer to neutrality, with no major deficits or surpluses (Figure 2). This is a desirable condition for responsible nutritional management, aiming to combine higher efficiency in the use of fertilizers and satisfactory yields, without depleting the soil fertility (Resende et al., 2019). Adjustments to improve the nutrient use efficiency, without yield losses, are also necessary for environmental compliance, and the achievement of climate change-related agricultural policy objectives for the coming decades (Wang et al., 2017).

The RPLC and FARM fertilization options showed similar balances for N and K (Figure 2). However, the FARM management of P accumulated a much higher positive balance, expressed in P_2O_5 equivalent, characterizing an unnecessary surplus, given the conditions of high fertility previously built-up (Table 1).

Phosphate applications that generate positive balances are justified in the initial conditioning of Cerrado soils, especially those with higher clay contents, due to their high P adsorption capacity. However, with the successive additions of phosphate fertilizers over time, there is a gradual adsorption reduction, which allows a better use of fresh fertilization by plants (Roy et al., 2017). Thus, the positive balance of P is no longer critical as a way to ensure good crop yields.

After six crops, the different fertilization sizing options resulted in variations of P and K balances, which influenced the availability status of these nutrients in the soil (Figure 3). A lower P content was observed at 0−10 cm soil depth because of the CONT treatment, in which no maintenance fertilization was performed during the six cultivations. There was also a lower availability of K in this treatment, up to 20 cm soil depth. Furthermore, the presence or absence of ruzigrass in the system did not affect the P and K contents of the soil.

Grain harvests from six crops in the CONT treatment reduced the soil-P content close to the critical level (10 mg dm^{-3}), considering the 0−10 cm soil depths (Figure 3). In contrast, the RPLC+30, FARM and FARM+30 treatments maintained the highest levels of P availability at that soil depths. For every 24.35 kg ha^{-1} of negative P_2O_5 in the nutrient balance, there was a reduction of 1 mg dm^{-3} in the $P_{Mehlich-1}$ content at 0−10 cm soil depths of the profile (Figure 4). According to the literature, for the buffer capacity of soils with 60% clay content, the correspondence would be about 50 kg ha^{-1} of P_2O_5 for every 1 mg dm^{-3} of the $P_{Mehlich-1}$ content at 0−20 cm soil depths (Sousa et al., 2016).

Therefore, considering the difference of soil volume in the respective soil depths, the behavior of P dynamics in the present study confirmed the expectation based on the indicators reported in the literature. In other words, the differences of P supply between the treatments and the estimates of the P removal throughout the crops are consistent with changes of soil P availability. Thus, the balance calculation is suitable to predict the impacts on

P stocks in the soil, guiding a better sizing for future maintenance fertilization.

As to K, the CONT treatment showed availability above the critical level (80 mg dm^{-3}), considering the average of the 0−20 cm soil depths of the profile (Figure 3). Based on the response model, each 6.58 kg ha^{-1} of negative K_2O in the balance reduced the K content in the soil by 1 mg dm^{-3} (Figure 4).

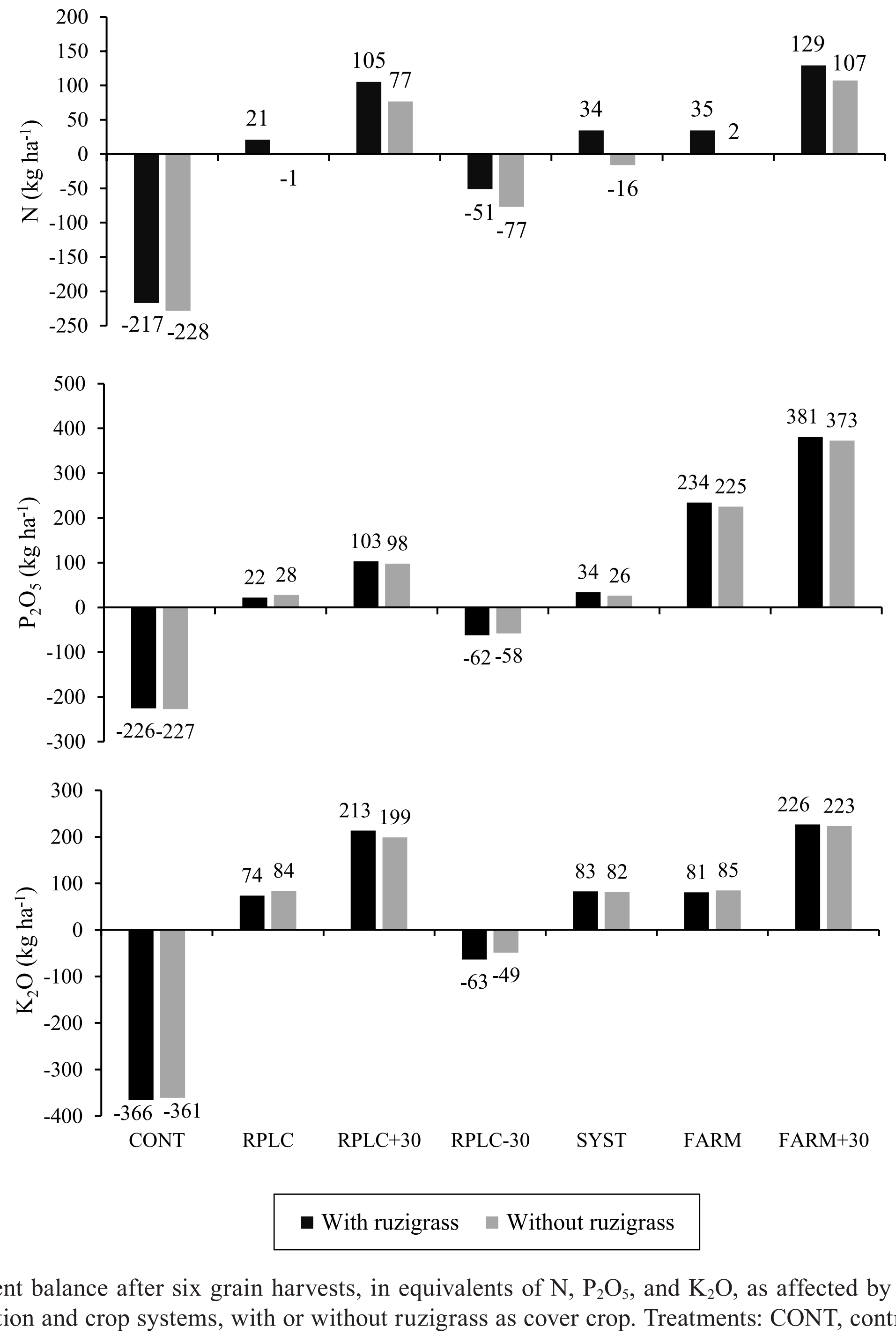

Figure 2. Nutrient balance after six grain harvests, in equivalents of N, P_2O_5, and K_2O, as affected by different options of NPK fertilization and crop systems, with or without ruzigrass as cover crop. Treatments: CONT, control without NPK; RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%.

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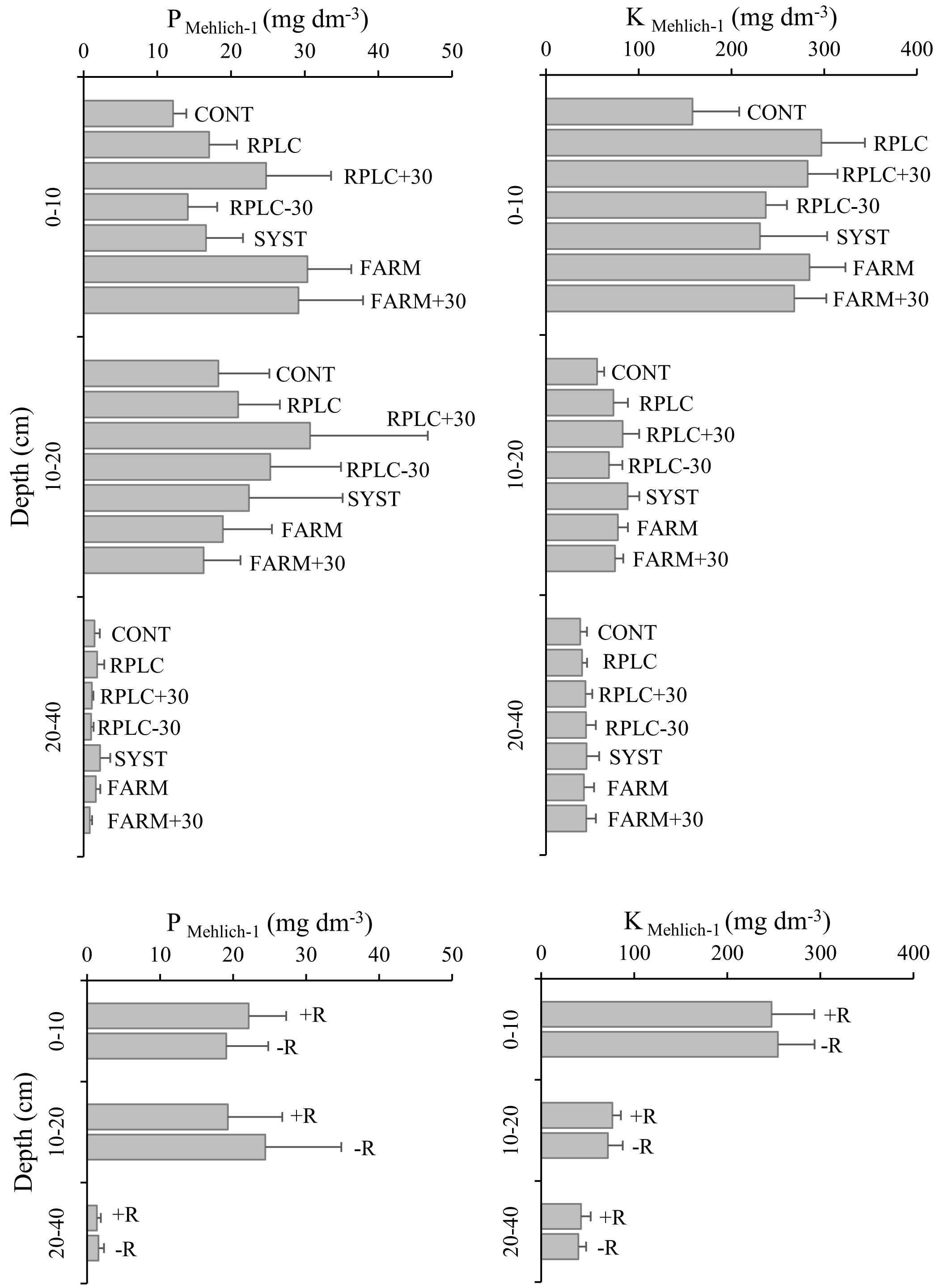

Figure 3. Soil test for P and K after six grain harvests, as affected by different options of NPK fertilization and crop systems with (+R) or without (-R) ruzigrass as cover crop. Treatments: CONT, control without NPK; RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%.

According to the literature, the corresponding ratio would be 2.4 kg ha^{-1} of K_2O for every 1 mg dm^{-3} of K in the analysis of the 0−20 cm soil depths (Sousa & Lobato, 2004). On one hand, it is necessary to consider that, unlike P, the K from fertilization is mobile in the soil, thus it is not retained only in the surface layer of the profile. On the other hand, K uptake by plants is not restricted to the 0−20 cm soil depths, and deeper roots of sorghum, maize, and *Urochloa* are capable of recycling K at greater depths (Oliveira et al., 2020; Ferreira et al., 2021). Hence, roots of these plants bring K back, replenishing the surface layer again, when crop residue is not removed from the area. These factors help to explain why K depletion at 0−20 cm soil depths was below the expectation, based on the indicators reported in the literature.

The present study endorses the replacement fertilization, associated with nutrient balance and periodic soil analysis, as the most appropriate strategy for the nutritional management of tropical clayey soils with built-up fertility. This strategy makes the supply of nutrients compatible with the quantities actually demanded by the crop system over time, avoiding extreme deficits or surpluses, with gains in

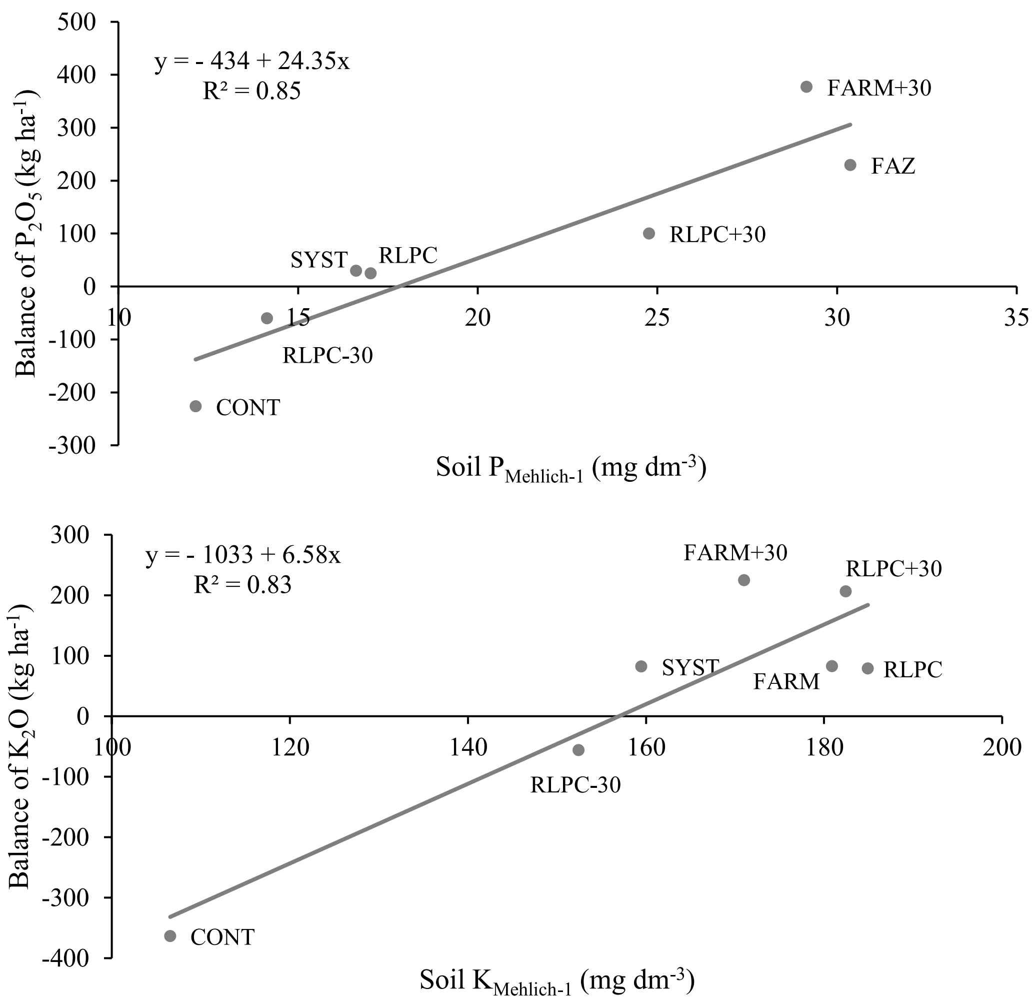

Figure 4. Relationship between nutrient balance in equivalents of P_2O_5 and K_2O, and soil test for P (0–10 cm) and K (0–20 cm) after six grain harvests, as affected by different options of NPK fertilization. Average of crop systems with or without ruzigrass as cover crop. Treatments: CONT, control without NPK; RPLC, replacement fertilization; RPLC+30, replacement plus 30%; RPLC-30, replacement minus 30%; SYST, system fertilization; FARM, farm standard; FARM+30, farm plus 30%.

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the use efficiency of fertilizers. Even more risk-averse producers can enjoy the advantages of this practical approach because, knowing the conditions that allow of fertilization reduction without negative impacts, these producers can do so sporadically, to deal with episodes of high costs of fertilizers or low marketing value of grains.

The idea of applying fertilizers only in a supplementary way, if and when nutrient inputs are needed, is also aligned with the pressing need for conscious exploitation of natural resources and greater energy efficiency, aiming at sustainability and environmental neutrality in agricultural production processes (Withers et al., 2018; Lal, 2020; Xing & Wang, 2024). Concerns about the impacts associated mainly with the use of N fertilizers have been emphasized, as their production and use result in the intensive consumption of energy and emissions of greenhouse gases (Lal, 2004; Chojnacka et al., 2019; Wu et al., 2021). However, fertilization with other nutrients also has environmental implications for pollution and energy or carbon balance (Withers et al., 2018; Wu et al., 2021; Gong et al., 2022; Daramola & Hatzell, 2023).

In this context, Lal (2004) reported that, in fertilizer production, transportation, storage, and distribution operations, the average estimates of emissions − expressed in kg of C-equivalent kg^{-1} N, P_2O_5, and K_2O − would be about 1.30, 0.20, and 0.15, respectively. Wang et al. (2017) compiled emission factor estimates of about 1.53, 1.63, and 0.65 kg of CO_2-equivalent kg^{-1} of N, P, and K fertilizers, respectively. Our study showed that, on average, RPLC fertilization resulted in a balance with surplus of 25 kg ha^{-1} of P_2O_5, after six harvests, an amount 89% lower than the surplus in standard FARM management (229.5 kg ha^{-1} of P_2O_5). Therefore, a more precise nutritional management with the RPLC approach also favors the search for environmental neutrality, by contributing to the reduction of the carbon footprint of grains produced.

As to K, our results suggest that the option for RPLC fertilization allows taking advantage of the characteristic circularity of this nutrient in the soil-plant-straw interface, enhancing the recovery of K fertilizer, stimulating the cycling and reduction of losses due to erosion and leaching. In turn, the condition for P management was emblematic, as it made clear the opportunity to provide a better-regulated supply in high-fertility soils, maintaining crop yield and soil fertility, reducing the financial costs and carbon footprint of phosphate fertilization. Thus, the adoption of RPLC fertilization, combined with nutrient balance, proves to be a good management practice, simple, low-cost, scalable, and effective to integrate gains in fertilizer use efficiency, profitability, maintenance of yield potential, and greater environmental compliance in Brazilian agriculture.

Conclusions

1. Fertilization with NPK does not influence soybean crops, but affects grain yield of second-crop maize.
2. Intercropping with ruzigrass reduces sorghum yield and does not affect maize in the second crop, but improves subsequent soybean yield.
3. Replacement fertilization associated with nutrient balance maintains yield levels, promotes fertilizer use efficiency, and increases profitability, while preserving soil fertility and avoiding nutrient deficits or surpluses in the crop system.
4. This approach constitutes a responsible nutritional management strategy for built-up fertility soils in Brazil, contributing to high-performance production with environmental safety and a lower carbon footprint of grains produced.

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Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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