Nutrient concentration in soybean harvest residues in western Pará

Concentração de nutrientes nos resíduos da colheita de soja no oeste do Pará

Concentración de nutrientes en los residuos de cosecha de soja en el oeste de Pará

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ABSTRACT

The expansion of soybean cultivation in Eastern Amazonia poses challenges to the sustainability of soil management systems, particularly regarding nutrient cycling in highly weathered environments. This study aimed to quantify and compare macronutrient concentrations in soybean crop residues under no-tillage (NT) and conventional tillage (CT) systems in the Santarém Plateau, western Pará State, Brazil, and to assess their potential contribution to soil fertility. Crop residues were collected immediately after harvest using a 0.25 m^2 quadrat, in a completely randomized design with two treatments and ten replicates per system. After drying and grinding, samples were subjected to sulfuric acid digestion and analyzed by photometry to determine nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations. The results showed no statistically significant differences ($p > 0.05$) between management systems for the evaluated nutrients. The descending order of nutrient accumulation in the residues was K > N > Ca > Mg > P, highlighting potassium as the predominant nutrient in the crop residues, with values exceeding 40 kg ha^{-1}. Phosphorus exhibited extremely low concentrations, attributed to high export by grains and strong adsorption in dystrophic Yellow Oxisols. It is concluded that, in the short term, soil management systems do not substantially alter the nutritional composition of soybean crop residues. However, maintaining crop residues on the soil surface represents an important mechanism for nutrient cycling, particularly for potassium, while low phosphorus levels reinforce the dependence on mineral fertilization in Amazonian agricultural systems.

Keywords: Nutrient Cycling. Crop Residues. No-Tillage. Eastern Amazonia.

RESUMO

A expansão da cultura da soja na Amazônia Oriental impõe desafios relacionados à sustentabilidade dos sistemas de manejo do solo, especialmente quanto à ciclagem de nutrientes em ambientes altamente intemperizados. Este estudo teve como objetivo quantificar e comparar a concentração de macronutrientes nos resíduos culturais da soja cultivada sob sistemas de plantio direto (PD) e plantio convencional (PC) no planalto santareno, oeste do estado do Pará, avaliando seu potencial de contribuição para a fertilidade do solo. A palhada foi coletada imediatamente após a colheita, utilizando gabarito de 0,25 m², em delineamento inteiramente casualizado, com dois tratamentos e dez repetições por sistema. Após secagem e moagem, as amostras foram submetidas à digestão sulfúrica e analisadas por fotometria para determinação das concentrações de nitrogênio (N), fósforo (P), potássio (K), cálcio (Ca) e magnésio (Mg). Os resultados indicaram ausência de diferenças estatisticamente significativas ($p > 0,05$) entre os sistemas de manejo para os nutrientes avaliados. A ordem decrescente de concentração nos resíduos foi K > N > Ca > Mg > P, evidenciando o potássio como o nutriente predominante na palhada, com valores superiores a 40 kg ha^{-1}. O fósforo apresentou concentrações extremamente baixas, atribuídas à elevada exportação pelos grãos e à forte adsorção em Latossolos Amarelos distróficos. Conclui-se que, no curto prazo, o sistema de manejo não altera substancialmente a composição nutricional dos resíduos culturais da soja. Entretanto, a manutenção da palhada sobre o solo representa importante mecanismo de ciclagem de nutrientes, especialmente de K, enquanto os baixos teores de P reforçam a dependência de fertilização mineral em sistemas agrícolas amazônicos.

Palavras-chave: Ciclagem de Nutrientes. Resíduos Culturais. Plantio Direto. Amazônia Oriental.

RESUMEN

La expansión del cultivo de soja en la Amazonía Oriental impone desafíos relacionados con la sostenibilidad de los sistemas de manejo del suelo, especialmente en lo que respecta al ciclo de nutrientes en ambientes altamente intemperizados. Este estudio tuvo como objetivo cuantificar y comparar la concentración de macronutrientes en los residuos culturales de la soja cultivada bajo sistemas de siembra directa (SD) y siembra convencional (SC) en el altiplano santareño, oeste del estado de Pará, evaluando su potencial de contribución a la fertilidad del suelo. La paja fue recolectada inmediatamente después de la cosecha, utilizando una plantilla de 0,25 m², en un diseño completamente aleatorizado, con dos tratamientos y diez repeticiones por sistema. Después del secado y molienda, las muestras fueron sometidas a digestión sulfúrica y analizadas mediante fotometría para determinar las concentraciones de nitrógeno (N), fósforo (P), potasio (K), calcio (Ca) y magnesio (Mg). Los resultados indicaron ausencia de diferencias estadísticamente significativas ($p > 0,05$) entre los sistemas de manejo para los nutrientes evaluados. El orden decreciente de concentración en los residuos fue K > N > Ca > Mg > P, evidenciando el potasio como el nutriente predominante en la paja, con valores superiores a 40 kg ha^{-1}. El fósforo presentó concentraciones extremadamente bajas, atribuidas a la elevada exportación por los granos y a la fuerte adsorción en Oxisoles Amarillos distróficos. Se concluye que, a corto plazo, el sistema de manejo no altera sustancialmente la composición nutricional de los residuos culturales de la soja. Sin embargo, el mantenimiento de la paja sobre el suelo representa un importante mecanismo de ciclaje de nutrientes, especialmente de K, mientras que los bajos contenidos de P refuerzan la dependencia de la fertilización mineral en los sistemas agrícolas amazónicos.

Palabras clave: Ciclaje de Nutrientes. Residuos Culturales. Siembra Directa. Amazonía Oriental.

1 INTRODUCTION

The expansion of grain production in the Amazon has intensified over the last three decades, driven by growing global demand for agricultural commodities, the availability of areas with low slopes, and strategic logistical investments. The Santarém Plateau, in western Pará, has become one of the primary examples of this advancement, particularly since 1997, when state policies favored the establishment of corporate soybean production systems. Since then, the municipalities of Santarém, Belterra, and Mojuí dos Campos have consolidated as important agricultural hubs, concentrating the largest cultivated areas and the highest production volumes in the region. In 2013, these three municipalities alone produced approximately 88,000 tons of soybeans, 59,000 tons of corn, and 19,000 tons of rice, demonstrating the socioeconomic relevance of the regional agribusiness (IBGE, 2020; Eloy et *al*., 2023; Barbosa; Moreira, 2017; Chelala; Chelala, 2022).

Despite the economic benefits, agricultural intensification in humid tropical ecosystems raises environmental concerns, particularly regarding impacts on soil, considered a strategic resource for maintaining long-term productivity. In Amazonian environments, the combination of high temperatures, intense microbial activity, and abundant precipitation regimes promotes the accelerated decomposition of organic matter and increased vulnerability to erosion processes. Thus, the adoption of inadequate management systems can compromise both soil fertility and structural stability, influencing the sustainability of productive systems (Paustian et *al*., 2016; Lal, 2015; Pavinato et *al*., 2020; Midleton, 2020).

Conventional tillage (CT), still widely used in many agricultural expansion areas, is characterized by intensive soil disturbance through plowing and harrowing, practices that expose the surface to direct solar radiation and rainfall, while also accelerating organic matter decomposition. This set of processes contributes to reduced aggregation, permeability, and water retention capacity, increasing susceptibility to compaction and nutrient loss, especially in highly weathered tropical soils, such as the predominant Oxisols (Latossolos) of the Santarém Plateau (Nascimento et *al*., 2020).

In response to these challenges, conservation practices have been widely studied and recommended for tropical agricultural systems. No-till farming (NT) stands out among these practices by operating under three fundamental principles: minimum soil disturbance, permanent soil cover, and crop rotation. When applied appropriately, these strategies can increase the resilience of tropical soils under intensive use, promoting physical, chemical, and biological improvements that translate into greater productive stability over the years (Pittelkow et *al*., 2015; Bünemann et *al*., 2018).

The crop residue mulch, formed by the cultural residues deposited on the soil surface, is a central element for the effective functioning of NT. In the past, it was believed that its primary function was merely to reduce evaporation, keeping the soil moister. However, recent studies demonstrate that the straw layer also regulates fundamental soil organic matter dynamics, contributes to greater microbial activity, improves water infiltration, increases aggregate stability, and actively participates in nutrient release and cycling (Blanco-Canqui, 2021; Castioni et *al*., 2019). In systems with high biomass production, such as soybean cultivation in humid tropical environments, the chemical composition of these residues becomes a key piece for understanding the agroecosystem's nutritional balance (Bordonal et *al*., 2018).

In the Amazonian context, characterizing the nutritional quality of soybean crop residues acquires additional relevance. Conditions of high rainfall and high temperatures can intensify both nutrient mineralization and leaching, altering soil fertility dynamics and influencing the potential for biogeochemical cycling. However, despite the significant expansion of soybean cultivation in the eastern Amazon, there are still few systematic investigations on the nutrient composition of crop residues produced in the region, which limits the development of specific agronomic recommendations adapted to local conditions (Bordonal et *al*., 2018).

Given these gaps, the central hypothesis of this study is that the soybean crop residues produced on the Santarém Plateau present nutrient concentrations compatible with a high capacity for biogeochemical cycling, influenced by regional edaphoclimatic conditions and the adopted management system. Based on this hypothesis, it is assumed that the nutritional quality of the straw can significantly contribute to maintaining soil fertility, especially in conservation systems such as no-till farming.

Thus, the objective of this study was to quantify and characterize the nutrient concentration present in soybean crop residues from the Santarém Plateau, aiming to understand their potential as a natural source of nutrient recycling and their relevance for the sustainability of Amazonian production systems.

It is expected that the obtained results will: identify the potential of crop residues as contributors to the nutritional balance in local agricultural systems; provide technical support for the proper management of straw in NT and CT systems; guide management strategies that reduce dependence on mineral fertilizers; and, support the development of sustainable intensification practices adapted to Amazonian conditions, contributing to soil conservation and long-term productive stability.

By integrating regional knowledge with current evidence on nutrient cycling and conservation management, the study seeks to fill a relevant gap for expanding agricultural systems in the Amazon, strengthening the scientific foundation necessary to guide public policies and agronomic practices aligned with sustainability.

2 MATERIALS AND METHODS

The study was conducted on two agricultural properties located in the municipality of Mojuí dos Campos, in western Pará State, situated on the Santarém Plateau, a region marked by the recent expansion of grain cultivation in humid tropical forest environments. The study areas represent two contrasting soybean cultivation management systems: a No-Till System (NTS) and a Conventional Tillage System (CTS).

The first area, managed under NTS, is located at coordinates 2°40’09.75” S and 54°39’21.17” W, while the area under CTS is at 2°44’19.38” S and 54°37’00.60” W. Both have a consolidated history of agricultural use with successive annual crops, but differ in soil preparation, crop residue management, and tillage intensity, aspects that directly influence biogeochemical cycling processes.

2.1 ENVIRONMENTAL CHARACTERIZATION OF THE AREA

The region has a Köppen Ami climate type, characterized by high temperature and humidity, with rainfall concentrated between December and June. The mean annual temperature is 25.6°C, ranging from 22.5°C (mean minimum) to 31°C (mean maximum). Relative air humidity exceeds 80% for most of the year, while mean annual precipitation is approximately 2000 mm. These conditions favor intense microbial activity and accelerated decomposition of plant residues, influencing nutrient dynamics (Oliveira Junior; Correa, 2001; Pará, 2011).

The predominant soils in both areas are Dystrophic Yellow Oxisols (Latossolos Amarelos Distróficos), with clayey to very clayey texture and clay contents ranging between 490 and 930 g kg^{-1}. These highly weathered soils, rich in kaolinite and Fe and Al oxides, exhibit high structural stability but low natural fertility and high phosphorus (P) adsorption capacity, typical characteristics of humid tropical regions (Oliveira Junior; Correa, 2001).

2.2 COLLECTION OF CROP RESIDUES

The soybean straw was collected one day after harvest in both areas, ensuring that the present crop residues reflected the actual conditions of the adopted management. A 0.25 m^2 (0.50 m × 0.50 m) metal frame was used, placed directly on the soil. In each area, 10 systematic random samplings were performed, distributed to avoid field edges and areas with anomalous interference, following protocols recommended for biomass and crop residue studies (Kumar, 2020; Castioni et *al*., 2019).

All plant material contained within the frame was manually removed, placed in pre-labeled Kraft paper bags, and transported to the laboratory. The choice of paper bags was adopted to minimize risks of moisture condensation during transport and processing.

2.3 SAMPLE PROCESSING

The samples were dried in a forced-air circulation oven at 65°C until constant mass was achieved, a procedure widely used to standardize dry biomass determination and reduce variations due to moisture (Cherubin et *al*., 2018). After drying, the material was manually sieved to remove adhering soil particles.

Subsequently, the straw's dry mass was determined using an analytical balance with a precision of 0.01 g, subtracting the weight of the packaging. This step allowed obtaining the mass of crop residues per area, expressed in g m^{-2}.

For chemical analysis, the dried material was ground in a Wiley-type mill equipped with a 20-mesh sieve, resulting in homogeneous samples suitable for chemical digestion. Digestion was performed using a sulfuric acid mixture (H_2SO_4/H_2O_2) in a digestion block at 300°C, until complete clarification of the samples. Sulfuric acid digestion is a widely used method for determining macronutrients in plant tissues (Embrapa, 2017).

The resulting extracts were diluted in distilled water and used to determine the concentrations of nitrogen ($N\text{-}NH_4^+$ + $N\text{-}NO_3^-$), phosphorus ($P\text{-}PO_4^{3-}$), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). Analyses were conducted using a HI 83200 Multiparameter Photometer (Hanna Instruments), with specific reagents provided by the manufacturer for each element. The photometer was previously calibrated according to certified standards, and readings were performed in triplicate for each extract, ensuring analytical reproducibility.

2.4 EXPERIMENTAL DESIGN

The study was conducted using a completely randomized design (CRD), consisting of two treatments corresponding to the management systems (NTS and CTS) and 10 independent replications per treatment, totaling 20 sampling units. Each replication consisted of a representative straw sample collected from a 0.25 m^2 quadrant.

2.5 STATISTICAL ANALYSIS

The evaluated variables included: straw dry mass ($g\ m^{-2}$) and concentrations of N, P, K, Ca, and Mg ($g\ kg^{-1}$). Initially, all data were assessed for normality of residuals using the Shapiro-Wilk test and for homogeneity of variances using Levene's test, at a 5% significance level.

Once parametric assumptions were met, treatment means were compared by one-way analysis of variance (ANOVA). When significant differences were identified, the Tukey test ($p \leq 0.05$) was applied for multiple comparisons between means. For variables that did not meet the assumptions, log or square root transformations were applied; if non-normality persisted, the non-parametric Mann-Whitney test was used.

All statistical analyses were performed using R software (version 4.3.2), utilizing the *stats* and *agricolae* packages. Graphs and visual inspections of residuals were produced with *ggplot2*, following current recommendations for reproducible and visually robust analyses (Mangiafico, 2025).

3 RESULTS AND DISCUSSION

Statistical analysis indicated no significant differences ($p > 0.05$) between the management systems—Conventional Tillage (CTS) and No-Till (NTS)—for the concentrations of mineral nitrogen ($NH_4^+ + NO_3^-$), available phosphorus (PO_4^{3-}), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) present in the soybean crop residues (Table 1). These results indicate that, under the evaluated edaphoclimatic conditions, the type of soil preparation was not a determining factor in altering the residual nutrient content of the straw at the end of the crop cycle.

Table 1. Average stocks of macronutrients accumulated in soybean crop residues under Conventional Tillage (CTS) and No-Till (NTS) on the Santarém Plateau, Eastern Amazon.

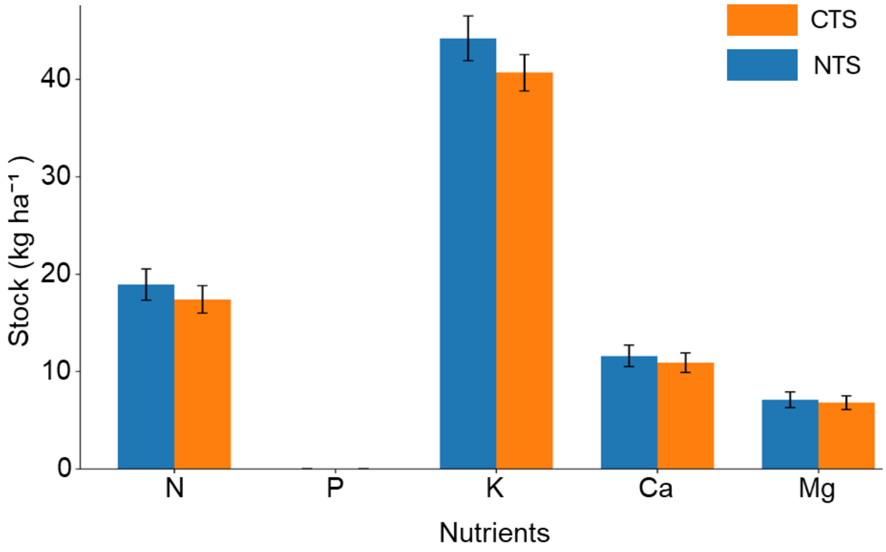
Management System	**N (kg ha⁻¹)**	**P (kg ha⁻¹)**	**K (kg ha⁻¹)**	**Ca (kg ha⁻¹)**	**Mg (kg ha⁻¹)**
CTS	18.9 ± 1.6	0.033 ± 0.004	44.18 ± 2.30	11.6 ± 1.1	7.1 ± 0.8
NTS	17.4 ± 1.4	0.028 ± 0.003	40.67 ± 1.87	10.9 ± 1.0	6.8 ± 0.7
p-value	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05

Note: Values expressed as mean ± standard error. There was no significant difference between management systems (t-test, $p > 0.05$). Fonte: os autores. 2025

The absence of differences between the management systems suggests that nutrient uptake, redistribution, and export by soybeans occurred similarly in CTS and NTS, possibly due to comparable levels of soil chemical fertility and equivalent yields. In humid tropical environments like the Eastern Amazon, high temperatures and high relative humidity intensify microbial activity and accelerate organic matter decomposition processes, reducing the persistence of contrasts between management practices, especially in short-term evaluations (Brown et *al*., 2018; Pierri et *al*., 2019; Rigon et *al*., 2022). Furthermore, long-term studies indicate that the effects of no-till on nutrient dynamics in crop residues tend to manifest more clearly over time, as changes in soil structure, organic carbon content, and microbial biomass accumulate (Bordonal et *al*., 2018; Santos et *al*., 2021). Thus, the results obtained in this study are consistent with the literature in indicating that, during initial or intermediate phases of system adoption, differences between CTS and NTS may be subtle or statistically undetectable.

The relative distribution of macronutrients in the crop residues revealed the predominance of potassium, followed by nitrogen, calcium, magnesium, and phosphorus (Figure 1), establishing the hierarchy K > N > Ca > Mg > P in both management systems. Potassium stood out as the predominant nutrient in the crop residues, with average values of 44.18 ± 2.30 kg ha^{-1} in CTS and 40.67 ± 1.87 kg ha^{-1} in NTS. This pattern is widely described for soybean crops and reflects the physiological role of potassium in plant metabolism, associated with osmotic regulation, enzymatic activation, and control of stomatal opening, resulting in high uptake and accumulation of this nutrient in vegetative tissues (Gaspar et *al*., 2017; Tamagno et *al*., 2017). The high K content in the straw, compared to other macronutrients, is also related to its lower incorporation into stable organic structures and its high mobility in the phloem, meaning a significant portion of potassium remains in the crop residues after grain harvest. This differs from nitrogen and phosphorus, which are intensively remobilized to reproductive organs (Ciampitti; Salvagiotti, 2018; Rosolem et *al*., 2021).

Figure 1. Bar chart showing the average stocks (kg ha⁻¹) of N, P, K, Ca, and Mg in the crop residues, with error bars (± SE), for CTS and NTS.



Fonte: os autores. 2025

From a biogeochemical perspective, this behavior gives the straw a strategic role in the surface cycling of potassium, especially in tropical soils with high leaching susceptibility. Maintaining residues on the soil surface, particularly under no-till, acts as a temporary compartment for this nutrient, delaying its vertical transport and favoring its reuse by subsequent crops (Rosolem et *al*., 2010; Rosolem et *al*., 2021).

When analyzing the concentrations of macronutrients in the dry matter of the crop residues (Table 2), a similar pattern was observed between CTS and NTS. Nitrogen content ranged between 10.11 and 10.33 g kg⁻¹, potassium between 15.60 and 15.70 g kg⁻¹, calcium between 6.0 and 7.0 g kg⁻¹, and magnesium between 3.75 and 4.0 g kg⁻¹. These values remained close to reference ranges for soybeans in tropical systems, where the internal redistribution of nutrients throughout the cycle exerts strong control over the final chemical composition of the straw (Sfredo, 2008; Silva et *al*., 2015; Santos et *al*., 2021). In contrast, phosphorus consistently showed low values (0.011–0.012 g kg⁻¹), reinforcing its low retention in the residues.

Table 2. Average concentration of macronutrients in the dry matter of soybean crop residues under Conventional Tillage (CTS) and No-Till (NTS).

Management System	**N (g ha⁻¹)**	**P (g ha⁻¹)**	**K (g ha⁻¹)**	**Ca (g ha⁻¹)**	**Mg (g ha⁻¹)**
CTS	10.33 ± 0.42	0.012 ± 0.002	15.70 ± 0.61	7.0 ± 0.5	4.0 ± 0.3
NTS	10.11 ± 0.38	0.011 ± 0.001	15.60 ± 0.58	6.0 ± 0.4	3.75 ± 0.3
p-value	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05

Note: Values expressed as mean ± standard error. Concentrations determined on a dry matter basis. Fonte: os autores. 2025

The observed values of nitrogen and potassium in the crop residues were higher than those reported in classic studies conducted in subtropical regions, such as those by Werner et *al*. (2020), which recorded approximately 14 kg ha⁻¹ of N and 16.5 kg ha⁻¹ of K. This increase can be attributed to the genetic advancement of modern cultivars, characterized by greater aboveground biomass production, higher nutrient absorption efficiency, and better adaptation to high-productivity tropical environments (Bordonal et *al*., 2018; Silva et *al*., 2015). Comparisons with regional studies further indicate that the observed values exceed those reported by Sousa Neto & Taketomi (2012) for the Santarém Plateau itself, suggesting that recent agricultural intensification, associated with soil fertility correction and the use of more productive cultivars, has resulted in greater accumulation of biomass and nutrients in the vegetative fraction. Recent evidence from the Eastern Amazon corroborates this pattern, indicating a progressive increase in nutrient content in soybean and corn straw over the last decade, especially under conservation practices (Moreira, 2021; Rodrigues et *al*., 2025).

In contrast, phosphorus content in the crop residues was extremely low (0.033 and 0.028 kg ha⁻¹ for CTS and NTS, respectively), values substantially lower than those reported in previous studies (Leite, 2015) and well below reference values for soybean aboveground biomass, which indicate average concentrations close to 2.4 g kg^{-1} (Costa et *al*., 2025). This behavior confirms the low recycling efficiency of phosphorus via soybean straw and can be largely explained by the high export of this nutrient by the grains, often exceeding 60% and potentially reaching up to 87% in high-yield systems (Ciampitti; Salvagiotti, 2018).

Additionally, the predominant soils in the study area, classified as highly weathered Oxisols, have a high phosphate adsorption capacity due to the abundance of iron and aluminum oxides, which reduces P availability in the soil solution and limits its reincorporation into plant biomass and its return via crop residues (Novais et *al*., 2007; Withers et *al*., 2018). This combination of factors makes phosphorus the most critical element in terms of biogeochemical cycling in Amazonian agricultural systems.

In this context, management strategies that favor the biological cycling of phosphorus become essential. These include the use of cover crops with a greater capacity for P mobilization, the adoption of phosphorous sources with higher agronomic efficiency, and practices that stimulate microbial activity and the formation of organic complexes in the soil (Pavinato et *al*., 2020; Withers et *al*., 2018). Thus, while soybean straw contributes significantly to the cycling of potassium and, to a lesser extent, nitrogen, phosphorus remains the most critical nutrient for maintaining soil fertility in long-term Amazonian agricultural systems.

3.1 EXTENDED ECOLOGICAL AND BIOGEOCHEMICAL DISCUSSION

The high concentration of K in the crop residues assumes a strategic role in no-till systems. In humid tropical environments, K exhibits high mobility in the soil and is easily leached, especially in soils with high macroporosity and elevated water saturation during the rainy season. Maintaining straw on the soil surface acts as a temporary compartment for this nutrient, delaying its vertical transport and favoring its surface cycling, which contributes to greater root absorption efficiency by subsequent crops (Rosolem et *al*., 2010).

For nitrogen, the relatively low values observed in the residues may be associated with the rapid straw decomposition in the Ami climate, which intensifies mineralization and reduces the retention of organic N in plant biomass (Bordonal et *al*., 2018). Furthermore, during the final phase of the cycle, soybeans intensively remobilize N from leaves to grains, significantly decreasing its concentration in the remaining straw (Zambon et *al*., 2023).

Calcium and magnesium exhibited concentrations compatible with those observed in highly weathered tropical systems. The low mobility of Ca in the phloem explains its greater persistence in plant tissues, even after nutrient translocation to grains (Taiz et *al*., 2022). Although no-till systems tend to favor the gradual accumulation of Ca and Mg over time, the absence of statistical differences in this study may be related to the short temporal scale evaluated.

In summary, the results highlight that soybean straw plays a relevant role in nutrient cycling in Amazonian agroecosystems, especially for potassium, while phosphorus remains the primary element limiting the long-term sustainability of these systems, demanding specific management strategies to increase the use efficiency of this nutrient.

4 CONCLUSIONS

Under the edaphoclimatic conditions of the Santarém Plateau in the Eastern Amazon, the conventional tillage and no-till systems did not differ in terms of the stocks and concentrations of macronutrients in the soybean crop residues. This indicates that, in the short term, the type of soil preparation was not a determining factor in modifying the chemical composition of the straw. This behavior reflects the similarity in nutrient uptake, redistribution, and export by the crop, associated with comparable levels of soil fertility and productivity between the evaluated systems.

Irrespective of the management system, potassium was the predominant macronutrient in the crop residues, establishing itself as the primary element recycled via soybean straw. This result confirms the strategic role of straw in the surface cycling of K in tropical agricultural systems, especially in soils with high leaching susceptibility, such as the highly weathered Oxisols of the Amazon region.

In contrast, phosphorus exhibited low stocks and residual concentrations, highlighting its low recycling efficiency via soybean crop residues. This pattern results from the high export of the nutrient by the grains and the strong phosphate adsorption in tropical soils, reinforcing the role of phosphorus as the primary element limiting the sustainability of agricultural systems in the Eastern Amazon.

Taken together, the results indicate that the nutrient dynamics in soybean crop residues are strongly controlled by edaphoclimatic factors and the crop's physiology, while the effects of soil management tend to manifest more gradually and cumulatively over time.

5 PRACTICAL IMPLICATIONS

The results of this study indicate that, in soybean production systems in the Eastern Amazon, the adoption of no-till, while essential for soil conservation, does not by itself guarantee immediate increases in the nutrient stocks of the straw when compared to conventional tillage. Therefore, management strategies should prioritize fertilizer use efficiency and productivity maintenance, rather than isolated changes in soil preparation.

The high contribution of soybean straw to potassium cycling underscores the importance of maintaining crop residues on the soil surface, especially in areas susceptible to leaching. Excessive removal or incorporation of the straw can compromise K availability for subsequent crops, increasing dependence on potassium fertilization.

Conversely, the low persistence of phosphorus in the crop residues reinforces the need for specific strategies to manage this nutrient in Amazonian soils. Among the recommended practices are the use of cover crops with a greater capacity for P mobilization, the selection of phosphorous sources with higher agronomic efficiency, and the adoption of practices that stimulate soil biological activity, such as diversifying crop rotations and increasing organic residue inputs.

Finally, the results suggest that the gains associated with recent agricultural intensification in the region, expressed by the greater accumulation of biomass and nutrients in the straw, must be sustained by long-term conservation practices. The integration of appropriate fertility management, soil conservation, and rotation system planning is fundamental to ensuring the productive and environmental sustainability of soybeans in the Eastern Amazon.

REFERENCES

BARBOSA, J. A.; MOREIRA, E. C. P. Impactos socioambientais da expansão do agronegócio da soja na microrregião de Santarém (Pará–Brasil). **Revista Jurídica Uni7**, Fortaleza, v. 14, n. 1, p. 73–87, jan./jun. 2017. Disponível em: https://periodicos.uni7.edu.br/index.php/revistajuridica/article/view/258. Acesso em: 15 dez. 2025.

BLANCO-CANQUI, H. Cover crops and carbon sequestration: lessons from U.S. studies. **Soil Science Society of America Journal**, v. 85, n. 2, p. 501–519, 2021. DOI: https://doi.org/10.1002/saj2.20378.

BORDONAL, R. O. et al. Sustainability of sugarcane production in Brazil: a review. **Agronomy for Sustainable Development**, v. 38, art. 13, 2018. DOI: https://doi.org/10.1007/s13593-018-0490-x.

BROWN, V. et al. Efeitos no solo e nas culturas após vinte anos de cultivo convencional e semeadura direta. **Revista Brasileira de Ciências Agrárias**, v. 13, n. 1, e5501, 2018. DOI: https://doi.org/10.5039/agraria.v13i1a5501.

BÜNEMANN, E. K. et al. Soil quality – a critical review. **Soil Biology and Biochemistry**, v. 120, p. 105–125, 2018. DOI: https://doi.org/10.1016/j.soilbio.2018.01.030

CASTIONI, G. A. F. et al. Straw removal affects soil physical quality and sugarcane yield in Brazil. *BioEnergy Research*, v. 12, p. 789–800, 2019. DOI: https://doi.org/10.1007/s12155-019-10000-1.

CHELALA, C.; CHELALA, C. Os obstáculos para a produção de grãos na Amazônia: o caso do estado do Amapá. *Revista de Economia e Sociologia Rural*, Piracicaba, v. 60, n. 2, e249653, 2022. DOI: https://doi.org/10.1590/1806-9479.2021.249653.

CHERUBIN, M. R. et al. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. *Scientia Agricola*, Piracicaba, v. 75, n. 3, p. 255–272, 2018.

CIAMPITTI, I. A.; SALVAGIOTTI, F. New insights into soybean biological nitrogen fixation: a review. *Agronomy Journal*, v. 110, n. 4, p. 1185–1196, 2018. DOI: https://doi.org/10.2134/agronj2017.06.0348.

COSTA, J. D.; RAMOS, J.; BENITES, V. D. M.; KANNO, J. A. V. Avaliação da eficiência agronômica de fosfatos naturais brasileiros em ensaios em vaso. 2025. Disponível em: http://www.alice.cnptia.embrapa.br/alice/handle/doc/1177314. Acesso em: 15 dez. 2025.

ELOY, L.; SENRA, E. B.; SILVA, A. L. da; CAMPOS, C. A. A aceleração recente da produção de soja na Amazônia: uma história do desmonte ambiental “em prática" no estado de Roraima. *Nuevo Mundo Mundos Nuevos*, 2023. DOI: https://doi.org/10.4000/nuevomundo.93688.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA SOJA). *Tecnologias de produção de soja: região central do Brasil 2014*. Londrina: Embrapa Soja, 2013. 266 p.

GASPAR, A. P. et al. Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels. *Crop Science*, v. 57, p. 2193–2204, 2017. DOI: https://doi.org/10.2135/cropsci2016.05.0378.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). *Produção agrícola municipal 2019*. Rio de Janeiro: IBGE, 2020. Disponível em: https://www.ibge.gov.br. Acesso em: 15 dez. 2025.

KUMAR, S. et al. *Manual on soil and plant analysis*. Westville: Westville Publishing House, 2020.

LAL, R. Restoring soil quality to mitigate soil degradation. *Sustainability*, v. 7, n. 5, p. 5875–5895, 2015. DOI: https://doi.org/10.3390/su7055875.

LEITE, J. N. F.; CRUZ, M. C. P.; FERREIRA, M. E. Formas orgânicas e inorgânicas de fósforo no solo em função de plantas de cobertura e de adubação nitrogenada. 2015. Dissertação (Mestrado em Agronomia) – Universidade Estadual Paulista, Jaboticabal, 2015.

MANGIAFICO, S. S. *Summary and analysis of extension program evaluation in R*. Version 1.23.2. New Brunswick: Rutgers University, 2025.

MIDDLETON, B. A. Trends of litter decomposition and soil organic matter stocks across forested swamp environments of the southeastern United States. *PLoS ONE*, v. 15, n. 1, e0226998, 2020. DOI: https://doi.org/10.1371/journal.pone.0226998.

MOREIRA, W. C. L. Sistema de manejo conservacionista do solo na agricultura familiar no sudoeste da Amazônia. 2021. Dissertação (Mestrado) – Universidade Federal do Acre, Rio Branco, 2021.

NASCIMENTO, D. M. et al. Qualidade física do solo em sistemas integrados de produção agrícola de longo prazo. *Soil and Tillage Research*, v. 183, p. 292–299, 2020. DOI: https://doi.org/10.1016/j.still.2018.08.016.

NOVAIS, R. F. et al. *Fertilidade de solos: fundamentos e aplicações*. 2. ed. Viçosa: Sociedade Brasileira de Ciência do Solo, 2007.

OLIVEIRA JÚNIOR, R. C. de; CORRÊA, J. R. V. *Caracterização dos solos do município de Belterra, estado do Pará*. Belém: Embrapa Amazônia Oriental, 2001. 39 p. (Documentos, n. 88).

PARÁ. *Zoneamento agroecológico do estado do Pará*. Belém: SAGRI, 2011.
PAUSTIAN, K. et al. Climate-smart soils. *Nature*, v. 532, p. 49–57, 2016. DOI: https://doi.org/10.1038/nature17174.

PAVINATO, P. S. et al. Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. *Scientific Reports*, v. 10, art. 15615, 2020. DOI: https://doi.org/10.1038/s41598-020-72302-1.

PIERRI, L. de et al. Soil chemical attributes and energetic potential of agricultural residual biomasses provided by 23 year soil management. *Bragantia*, 2019. DOI: https://doi.org/10.1590/1678-4499.20180255.

PITTELKOW, C. et al. Productivity limits and potentials of the principles of conservation agriculture. *Nature*, v. 517, p. 365–368, 2015. DOI: https://doi.org/10.1038/nature13809.

RIGON, J. P. G. et al. Intensive crop rotations and residue quality increase soil phosphorus lability under long-term no-till in tropical soils. *Soil and Tillage Research*, v. 215, p. 105446, 2022. DOI: https://doi.org/10.1016/j.still.2022.105446.

RODRIGUES, N. E. et al. Produção de biomassa residual da soja sob plantio direto e convencional no bioma Amazônia. *Revista Observatorio de la Economia Latinoamericana*, Curitiba, v. 23, n. 10, p. 1–13, 2025. DOI: https://doi.org/10.55905/oelv23n10-001.

ROSOLEM, C. A. et al. Potassium leaching as affected by soil texture and residual fertilization in tropical soils. *Communications in Soil Science and Plant Analysis*, v. 41, n. 16, p. 1934–1943, 2010. DOI: https://doi.org/10.1080/00103624.2010.495804.

ROSOLEM, C. A.; MALLARINO, A. P.; NOGUEIRA, T. A. R. Considerations for unharvested plant potassium. In: *Potassium in agriculture and plant nutrition*. Cham: Springer, 2021. p. 147–162. DOI: https://doi.org/10.1007/978-3-030-59197-7_6.

SANTOS, J. K. F. et al. Acúmulo de matéria seca e nutrientes pelo milho sob doses de NPK mineral e organomineral. *Research, Society and Development*, v. 10, n. 5, e15126, 2021. DOI: https://doi.org/10.33448/rsd-v10i5.15126.

SFREDO, G. J. *Soja no Brasil: calagem, adubação e nutrição mineral*. Londrina: Embrapa Soja, 2008. 148 p. (Documentos, n. 305).

TAIZ, L. et al. *Plant physiology and development*. 6. ed. Sunderland: Sinauer Associates, 2022.

TAMAGNO, G. R. et al. Nutrient partitioning and stoichiometry in soybean: a synthesis-analysis. *Field Crops Research*, 2017. DOI: https://doi.org/10.1016/j.fcr.2016.09.019.

WERNER, F. et al. Nitrogen, phosphorus, and potassium released by decomposition of palisade grass to soybean in succession. *Pesquisa Agropecuária Brasileira*, v. 55, e01853, 2020. DOI: https://doi.org/10.1590/s1678-3921.pab2020.v55.01853.

WITHERS, P. J. A. et al. Transitions to sustainable management of phosphorus in Brazilian agriculture. *Scientific Reports*, v. 8, art. 2537, 2018. DOI: https://doi.org/10.1038/s41598-018-20887-z.

ZAMBON, L. M. et al. Nitrogen balance and gap of a high-yield tropical soybean crop under irrigation. *Frontiers in Plant Science*, v. 14, art. 1233772, 2023. DOI: https://doi.org/10.3389/fpls.2023.1233772.