REVISTA DE CIÊNCIASAGRÁRIAS
Amazonian Journal
of Agricultural and Environmental Sciences
www.ajaes.ufra.edu.br

ORIGINAL ARTICLE

Phosphate fertilizer improves plant nutrition and soybean yield in the Amazon agricultural frontier

Fertilizante fosfatado melhora a nutrição da planta e o rendimento da soja na fronteira agrícola amazônica

João Cardoso de Souza Junior[1]
Aline Cristina Richart[2]
Leila Sobral Sampaio[3]
Ana Regina da Rocha Araujo[4]
Possidônio Guimarães Rodrigues[5]*
Mário Lopes da Silva Júnior[6]

[1] Soil and Water Science Department, Indian River Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Fort Pierce, Florida, USA, 34945
[2] University of São Paulo, "Luiz de Queiroz" College of Agriculture, Piracicaba, São Paulo, BRA, 13418-900
[5] Federal Institute of Pará. Education, Research and Extension Department, Castanhal, Pará, BRA, 68000-400
[3,4,6] Federal Rural University of Amazon, Belém, Pará, BRA, 66077-830

*** Corresponding Author:**
E-mail: possidonio.rodrigues@ifpa.edu.br

KEYWORDS
Biological nitrogen fixation
Glycine max
Grain yield
Oxisol
Soil phosphorus

PALAVRAS-CHAVE
Fixação biológica do nitrogênio
Glycine max
Rendimento de grão
Latossolo
Fósforo do solo

ASSOCIATE EDITOR
Elaine Maria Silva Guedes

Received: 03/09/2021
Accepted: 26/10/2021

ABSTRACT: The utilization of phosphate fertilizers for soybean growing on amazon soils is a challenge. Some soils are very clayed, which means they can easily fix phosphorus (P) from fertilizers. However, soybeans are very responsible to P since this nutrient has a direct relationship with nitrogen biological fixation and grain production. To understand the effect of P on plant nutrition and development, an experiment with soybeans was carried out in field conditions to evaluate the nutrient concentration in diagnostic leaves, P availability in soil, and grain yield of soybeans cultivated in a very clayey Oxisol. The objective was to evaluate the effect of phosphate fertilizer on the availability of P in the soil, as well as the concentration of N, P, and S in the diagnostic leaves, suggesting a proper rate of P_2O_5 for the first soybean crop in an area of abandoned pasture in the eastern Amazon. The phosphate fertilization increased the availability of soil P and the concentrations of P, N, and S in the diagnostic leaves. The concentrations of P and S in the leaves were highly correlated with N concentration. The rates of P increased the grain yield, dry mass of one thousand grains, number of pods per plant, and plant height, attributes that were highly correlated with the concentration of P, S, and N in the leaves. We recommend the rate of P_2O_5 at 120 kg ha^{-1} for the first soybean cultivation in an abandoned pasture located in eastern Amazon.

RESUMO: *A utilização de fertilizantes fosfatados para o cultivo da soja em solos amazônicos é um desafio. Alguns solos são muito argilosos, o que significa que podem facilmente fixar o fósforo (P) dos fertilizantes. No entanto, a soja é muito sensível ao P, uma vez que este nutriente tem relação direta com a fixação biológica de nitrogênio e a produção de grãos. Para compreender o efeito do P na nutrição e desenvolvimento das plantas, foi realizado um experimento com soja em condições de campo no intuito de avaliar a concentração de nutrientes nas folhas diagnósticas, a disponibilidade de P no solo e a produtividade de grãos da soja cultivada em um Latossolo Amarelo muito argiloso. O objetivo foi avaliar o efeito da adubação fosfatada sobre a disponibilidade de P no solo, bem como a concentração de N, P e S nas folhas diagnósticas, sugerindo uma dose adequada de* P_2O_5 *para o primeiro cultivo de soja em uma área de pasto abandonado na Amazônia oriental. A adubação fosfatada aumentou a disponibilidade de P no solo e as concentrações de P, N e S nas folhas diagnósticas. As concentrações de P e S nas folhas foram altamente correlacionadas com a concentração de N. As doses de P aumentaram a produtividade de grãos, a massa seca de mil grãos, o número de vagens por planta e a altura da planta, atributos altamente correlacionados com a concentração de P, S e N nas folhas. Recomenda-se a dose 120 kg ha*$^{-1}$ *de* P_2O_5 *para o primeiro cultivo de soja realizado em área de pasto abandonado na Amazônia oriental.*

1 Introduction

The global production of soybean (*Glycine max* L. Merr.) in 2019 was 334 million tons and Brazil was the first largest producer with 114 million tons (Fao, 2019). Soybean production has been increased in recent years and the success of its cultivation is in part attributed to an expansion of croplands, especially in north Brazil. From the year 2000 to 2019, the soybean croplands have been increased more than 1000%, from 0.4 million ha to 4.6 million ha (Song *et al.*, 2021). However, the grain production in that area is controversial due to its association with deforestation. Thus, the use of degraded areas such as abandoned pastures for soybean production has become important (Nepstad *et al.*, 2014).

Tropical soils are generally in high stages of weathering with high acidity and low availability of nutrients (Novais *et al.*, 2007). Phosphorus (P) deserves special attention in those soils because this nutrient can be fixed on clay surface or into structures of Fe and Al oxides, affecting P availability to plants (Schoninger *et al.*, 2013). Therefore, tropical soils have low availability of native P, which means crops such as soybeans need to be fertilized with P to ensure proper grain yield (Riskin *et al.*, 2013).

The availability of P and its uptake by soybean depends on soil type, soil texture, and P fertilization. In the Eastern Brazilian Amazon, the main soil verified is Oxisol, occurring major in clayey or very clayey textures (Idesp, 2014). In this context, the knowledge about the effect of phosphate fertilizer on nutritional status and plant development can help farmers to understand how to better manage nutrients for soybeans (Novais & Smyth, 1999; Riskin *et al.*, 2013). Thus, it is important to understand how P applied affects P availability, nutritional status, and soybean development (Veloso *et al.*, 2009).

According to Novais *et al.* (2007), simple superphosphate is a potential source of P because it contains 18 and 11 % of P_2O_5 and sulfur (S), respectively. This fertilizer is important because there is a direct correlation between the concentration of P and S in diagnostic leaves for improving grain yield of soybean due to their importance on root development, protein synthesis, and biological N fixation (Raij, 1991; Fageria *et al.*, 2011; Chiasson *et al.*, 2014).

The objective was to evaluate the effect of phosphate fertilizer on the availability of P in the soil, as well as the concentration of N, P, and S in the diagnostic leaves, suggesting a proper rate of P_2O_5 when the first cultivation of soybean is carrying out in an abandoned area.

2 Material and methods

The experiment was carried out in Dom Eliseu town, state of Pará (eastern Amazon), Brazil, from February 2nd to May 17th, 2014 (Figure 1). The area was an abandoned pasture for more than 10 years. The soil was classified as very clayey Oxisol (Soil Survey Staff, 1999). Among the soil chemical analysis, the low availability of extractable P (Table 1) is highlighted.

The weather is classified as Aw4 type according to Köppen (Idesp, 2014), which means there is a defined dry period with an average annual temperature at 25 ºC, and average annual precipitation at 2000 mm. The accumulation of rainfall in the area during 105 days of the experiment was 1207 mm (Figure 2).

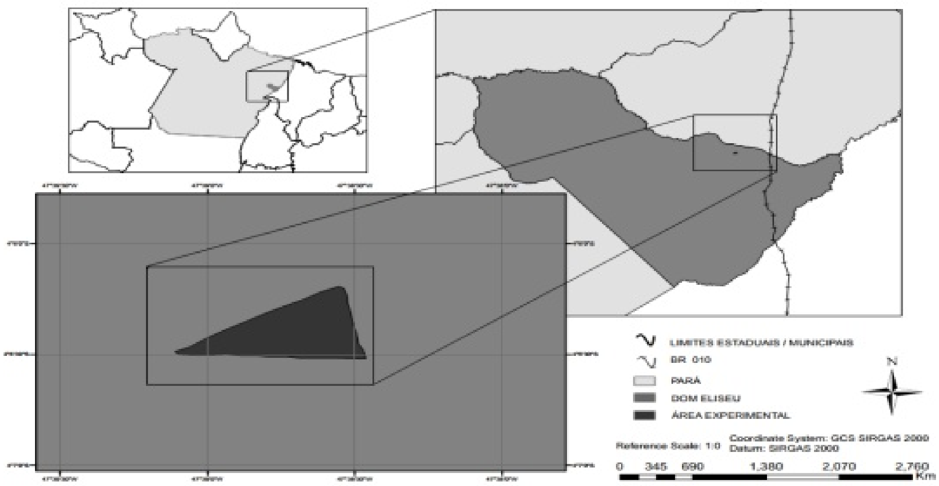

Figure 1. Location map of the experimental area in Dom Eliseu-PA. Source/elaboration: The authors, 2021.

Figura 1. Mapa de localização da área experimental em Dom Eliseu-PA. Fonte/elaboração: Os autores, 2021.

Table 1. Chemical and physical characterization of a very clayey Oxisol, before the treatments application.

Tabela 1. Caracterização química e física de um Latossolo muito argiloso, antes da aplicação dos tratamentos.

Depth	pH		P	S	K	Ca	Mg	Al	CEC	V	m	O.M	Sand	Silt	Clay
– m –	H_2O	$CaCl_2$	– mg dm^{-3} –			— cmol$_c$ dm^{-3} —				– % –		— g kg^{-1} —			
0,0 – 0,2	6,5	6,0	3,5	8,1	90	7,7	0,7	0,00	10,7	81,2	0,0	35	199	106	695

*pH: Hydrogen potential; CEC: Cation exchange capacity; V%: Base saturation; m%: Aluminum saturation; OM: Organic matter.

*pH: Potencial hidrogeniônico; CEC: Capacidade de troca catiônica; V%: Saturação por bases; m%: Saturação por Alumínio; OM: Matéria orgânica.

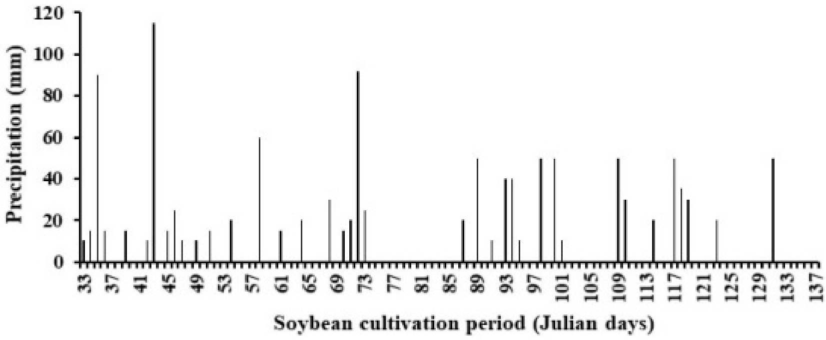

Figure 2. Distribution of rainfall precipitation (mm) on the field during the experimental with soybean from February to May 2014 in Julian days (JD) in Dom Eliseu, State of Pará, eastern Amazon, Brazil.

Figura 2. Distribuição da precipitação pluviométrica (mm) no campo durante o experimento com soja entre fevereiro e maio de 2014 em dias julianos (JD) em Dom Eliseu, Estado do Pará, Amazônia oriental, Brasil.

A randomized complete block design with four replications was used. The treatments were six rates of P_2O_5 (48, 66, 84, 120, 156, and 192 kg ha^{-1}). The first-rate of P_2O_5 at 48 kg ha^{-1} was supplied exclusively by applying mono ammonium phosphate at 100 kg ha^{-1}. The other rates of P_2O_5 were supplied as a fixed rate of mono ammonium phosphate at 100 kg plus applications of simple superphosphate at 100, 200, 400, 600, and 800 kg ha^{-1}, according to the rates of P_2O_5. For the availability of P found in the soil, the recommendation of P_2O_5 would be around 100 kg ha^{-1}, which is recommended for clayey soils in the Brazilian Amazon, state of Pará, and guided the rates of P_2O_5 applied in the experiment (Brasil *et al.*, 2020).

The phosphate fertilizers were mixed according to the treatments and applied in each experimental plot along the seeding furrows. Soil analyses performed before cultivation (Table 1) showed that no liming and K correction was needed, as the V % and K availability were proper for soybean cultivation (Brasil *et al.*, 2020). The area was treated with glyphosate for weeding before sowing. Soybean strain MSOY 9144 RR was treated with the fungicide Maxim (fludioxonil + metalaxyl-M), insecticide, and nematicide Avicta 500 FS (abamectin), and inoculant *Bradirizobium Japonicum*. Afterward, the soybeans were sown manually with a spacing of 0.5 m.

Each plot measured 25 m^2 with a useful area of 6 m^2 in the middle of the plots for collecting plant and soil samples. The control of weeds, pests, and diseases was done by using mechanized spraying. Weeds were controlled by using Zapp QI (Glyphosate Potassium), and insects and mites were controlled by using Match CE (Lufenuron), Engeo Pleno (Tiametoxan and Lambda-cyhalothrin), and Polo 500 SC (Diafentiurom). For the control of fungi, Elatus (Azoxystrobin and Benzovindiflupir) and Flexi Score (Propiconazole and difenoconazole) was applied. The density of sowing was equivalent to 240,000 plants per ha^{-1}.

The soil sampling was performed at the R2 stage (JD 81) according to Novais *et al*. (2007). The soil samples were disaggregated, homogenized, and air-dried for 72 h. The concentration of P was determined by using the ion exchange resin method since Mehlich-3 extractant can overestimate the P availability in very clayey soils (Raij *et al*., 1986). The concentrations of P, S, and N were performed according to Malavolta (2006), collecting 20 the 3rd and 4th newly expanded leaves at the R2 stage (JD 81). The plant samples were dried at 65 °C for 72 h in an oven with forced air circulation. The concentration of total nitrogen (N) in the diagnostic leaves was determined according to the Kjeldahl method. The concentrations of P and S in the plant samples were determined from nitric-perchloric digestion, quantifying the P concentration by spectrophotometry and S by turbidimetry (Sarruge & Haag, 1974).

Soybean plants were harvested at the R9 stage (JD 137). The average of plant height (H), number of pods per plant (NPP), and number of grains per pod (NGP) for each treatment's plot were evaluated. To estimate the grain yield (GY) and mass of one thousand grains (MTG), the humidity was corrected to 13 % (Brasil, 2009).

The analysis of variance (ANOVA) at 5% was carried out. When the ANOVA was significant, polynomial regression and correlation analyses were performed. The equation adjustment was adopted based on the significance of the polynomial models. When the adjustment was quadratic, the optimum rate was calculated by the nullity of the derivative. However, when the adjustment was linear, the evaluation was carried out at the extreme points. The ANOVA was carried out by using "R" software (R Core Team, 2017).

3 Results and Discussion

The availability of P in the soil increased with the applications of fertilizers, reaching up to 47 mg dm^{-3}, higher than the plant needs (Figure 3). This increasing was due to the high solubility of the fertilizers, showing that the P can be potentially available to the plants even in soils with a high amount of clay. The availability of P in the clayey soil increased linearly (Figure 3), which suggests the soil may have a capacity of receiving a high amount of that nutrient. However, due to the structural properties of that soil, a high amount of clay can also attach or fix large amounts of P (Bedin *et al.*, 2003), which means a proper amount of P fertilizers must be applied to plants aiming decrease the losses through the soil fixation.

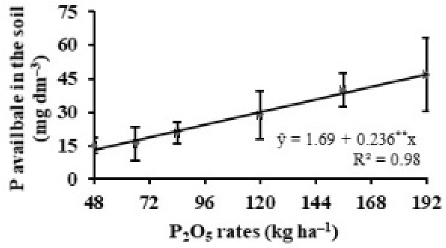

Figure 3. Availability of P in a very clayey Oxisol cultivated with soybean as a function of phosphate fertilization in the eastern Amazon. Error bars show standard deviation. Coefficient of variation (%) = 13.8.

Figura 3. Disponibilidade de P em Latossolo muito argiloso cultivado com soja em função da adubação fosfatada na Amazônia oriental. Barras de erros mostram o desvio padrão. Coeficiente de variação (%) = 13,8.

According to the recommendation proposed by Brasil *et al.* (2020) regarding soils from the state of Pará, the phosphate fertilizers applied to the soil increased the availability of P from a low availability (3.5 mg kg^{-1}) to a very high availability (47 mg kg^{-1}). The same authors consider that the proper availability of P for soybean cultivation in clayey soils is above 11 mg kg^{-1}. The value reached with the highest P_2O_5 rate in the present study was higher than the availability found in the soil from Cerrado in São Paulo (Raij *et al*., 1997). For soils found in São Paulo, the availability of P up to 16 mg dm^{-3} indicates that the fertilization of at least 80 kg ha^{-1} of P_2O_5 is required to obtain productivity around 3 t ha^{-1} (Embrapa, 2013). Bedin *et al*., (2003) verified that the supply of P by using triple superphosphate increased the availability of P to 117 mg dm^{-3} in a clayey Oxisol.

The concentration of P in the diagnostic leaves showed a quadratic model as a function of the phosphate fertilization, reaching up to 3.2 g kg^{-1} with P_2O_5 at 166 kg ha^{-1} (Figure 4a). This result suggests that the P uptake was sufficiency for soybeans production since the range varies from 2.3 to 3.4 g kg^{-1} in the leaves with petiole (Embrapa, 2013). This result shows that the phosphate fertilizer was correctly applied in the soil and proper utilized by the plants. Phosphorus in plants acts as a structural element, participating in the constitution of nucleic acids and phospholipids. In addition to it, phosphorus is indispensable for energy metabolism, acting on energy transfer reactions and regulation of metabolic pathways (Marschner, 1995).

For the concentration of S in the leaves, values between 2.0 and 3.0 g kg^{-1} are considered sufficient for proper soybean growth (Embrapa, 2013). In the present study, the concentration of S in the diagnostic leaves reached up to 2.0 g kg^{-1} with the application of P_2O_5 at 146 kg ha^{-1} (Figure 4b). This indicated that the soybean plants were properly supplied with S that came from the simple superphosphate applied to the plants. The journal of soybean production in central Brazil suggests an application of S at 60 kg ha^{-1} for clayey soils when the availability of this nutrient is low, aiming to reach a satisfactory yield of 3 t ha^{-1} (Embrapa, 2013), agreeing with our results.

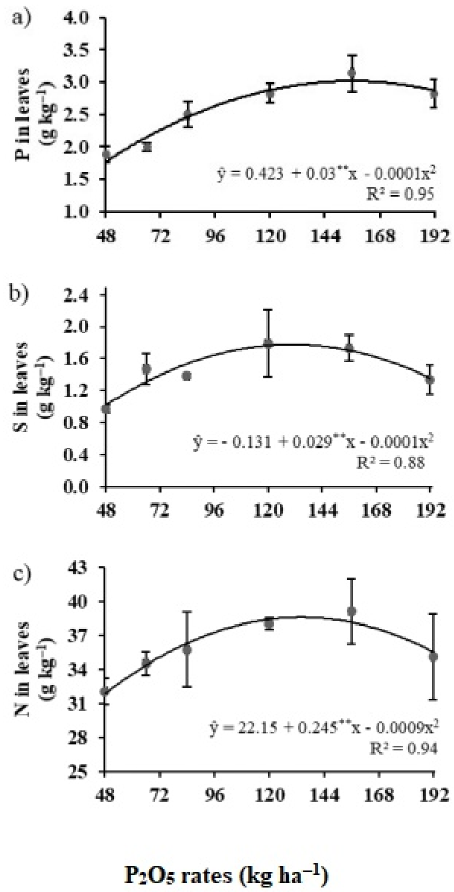

Figure 4. Concentrations of P (a), S (b), and N (c) in the diagnostic leaves of soybeans as a function of phosphate fertilization in a very clayey Oxisol in the eastern Amazon. Error bars show standard deviation. Coefficient of variation (%) = 7.4 (a), 14.9 (b), and 6.9 (c).

Figura 4. Concentração de P (a), S (b) e N (c) nas folhas diagnósticas de soja em função da adubação fosfatada em um Latossolo muito argiloso na Amazônia oriental. Barras de erros mostram o desvio padrão. Coeficiente de variação (%) = 7,4 (a), 14,9 (b) e 6,9 (c).

Rheinheimer *et al.* (2005) reported that the application of S up to 20 kg ha^{-1} shows no response for soybean cultivated an Ultisol. However, the S rate studied by Rheinheimer *et al.* (2005) was approximately 1/3 of the optimal rate verified in the present study, suggesting that the application of the phosphate fertilizers have major effects when high rates of S are applied. The highest concentration of N at 38.7 g kg^{-1} found in the diagnostic leaves (Figure 4c), as a function of P_2O_5 at 133 kg ha^{-1}, is considered proper for soybean since the optimum range of N in the leaves varies from 36.8 to 46.9 g kg^{-1} (Embrapa, 2013). The application of phosphate fertilizers increased the concentrations of N in the diagnostic leaves (Figure 4c). Previous research showed that phosphate fertilization can influence the nodulation of soybean roots, leading to increase N fixation and consequently soybean yield (Salvagiotti *et al.*, 2013). It happens because P plays a key role in energy transferring and the N fixation process requires a large amount of chemical energy, which is supplied in the form of ATP formed from inorganic phosphorus from soil (Salvagiotti *et al.*, 2013).

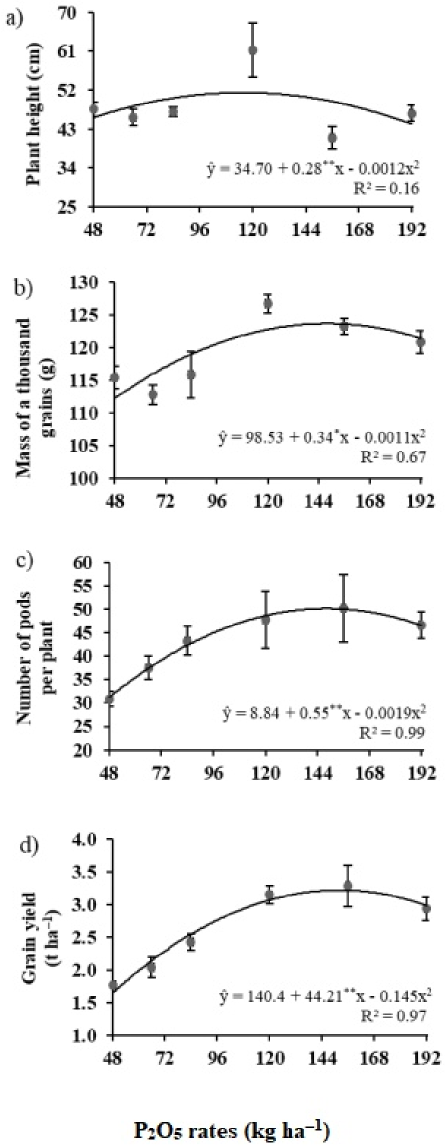

Figure 6. Plant height (a), mass of one thousand grains (b), number of pods per plant (c), and grain yield (d) of soybean as a function of phosphate fertilization in a very clayey Oxisol in the eastern Amazon. Error bars show standard deviation. Coefficient of variation (%) = 6.4 (a), 6.9 (b), 10.2 (c), and 6.9 (d).

Figura 6. Altura da planta (a), massa de mil grãos (b), número de podas por planta (c), e rendimento de grãos (d) da soja e função da adubação fosfatada em Latossolo muito argiloso na Amazônia oriental. Barras de erro mostram o desvio padrão. Coeficiente de variação (%) = 6,4 (a), 6,9 (b), 10,2 (c) e 6,9 (d).

The increase in the N concentration in the diagnostic leaves caused by phosphate fertilizers is attributed directly to the supply of P and S from fertilizers since N was not applied to the crop. This can be confirmed by the highly positive correlation found between both N with P concentration in diagnostic leaves (Figure 5a) and N with S concentration in the diagnostic leaves (Figure 5b). The application of P and S in a proper amount by using phosphate fertilizers favored the biological nitrogen fixation since P and S are essential for this process (Salvagiotti *et al.*, 2013; Chiasson *et al.*, 2014). Nitrogen fixation is highly dependent on chemical energy in the form of ATP and enzymatic complexes that transfer electrons (Chiasson *et al.*, 2014).

The phosphate fertilization influenced H, NPP, and MTG. However, the NGP was not significant for the treatments. The optimal values of H (52 cm), MTG (124 g), and NGP (49) were reached with the P_2O_5 rates at 120, 154, and 146 kg ha^{-1}, respectively (Figure 6). The comparisons between the production attributes and the concentrations of P, S, and N in the diagnostic leaves suggest that the proper concentration of these elements are responsible for improving the H, MTG, NGP, and GY.

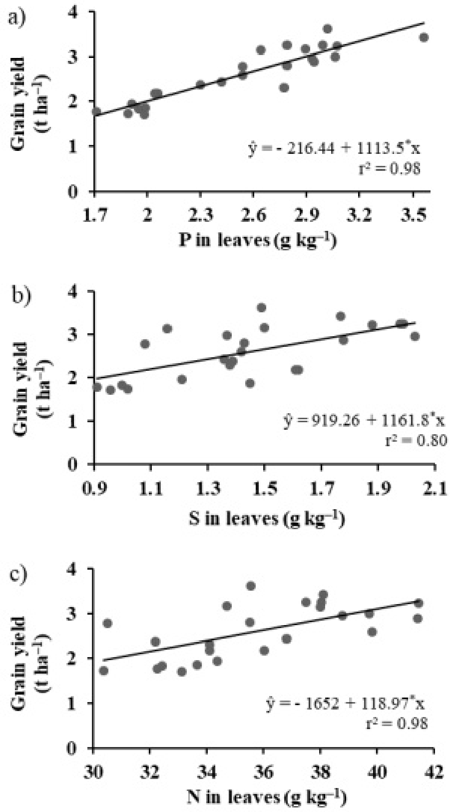

Figure 7. Pearson correlation between the concentration of nutrients in the diagnostic leaves and grain yield. The figure (a) shows P × grain yield, figure (b) shows S × grain yield, and figure (c) shows N × grain yield of soybean with phosphate fertilization in a very clayey Oxisol in the eastern Amazon.

Figura 7. Correlação de Pearson entre a concentração de nutrientes nas folhas diagnósticas e rendimento de grãos. A figura (a) mostra a relação P x rendimento de grãos, a figura (b) mostra a relação S x rendimento de grãos, e a figura (c) mostra a relação N x rendimento de grãos da soja com adubação fosfatada em Latossolo muito argiloso na Amazônia oriental.

The GY was increased as the phosphate fertilization increased, showing values of 3.22 t ha^{-1} with the P_2O_5 at 152 kg ha^{-1} (Figure 6d), improving 95 % the grain production based on the initial P_2O_5 rate at 48 kg P_2O_5 ha^{-1}. This result demonstrates that the application of phosphate fertilizers was highly beneficial for the soybean yield. The proper nutrition of P, S, and then N influenced the production with flowers, pods, and then grain filling, which are the main productive attributes of soybean productivity (Akter *et al.*, 2013). Veloso *et al.* (2009) found that the application of P_2O_5 up to 240 kg ha^{-1} in the form of simple superphosphate increased the H, MTG, and GY of soybean in a neighboring region with a predominance of very clayey Oxisol. However, the same authors recommended that the rate of P_2O_5 should not exceed 80 kg ha^{-1} due to the low responses above this rate, an effect that was not observed in the present study. Such differences may be related to the genetic material and soil nutrients background since the weather condition and type of soil, as well as the fertilizer adopted, were similar in both studies.

Neto *et al.* (2010) reported that soybean cultivated in an Oxisol in the State of Piauí, Brazil, showed the highest values of H (57 cm) and GY (2.61 t ha^{-1}) with a P_2O_5 rate at 95 kg ha^{-1}, applied in the form of triple superphosphate. The values of GY found by those authors were lower than those found in the present study, possibly due to the medium texture of the soil with a lower phosphorus buffer power than the clayey soils, as well as the weather conditions with lower rainfall precipitation. Fageria *et al.* (2011) reported that the P_2O_5 at 120 kg ha^{-1} in the form of simple superphosphate promoted a GY of 3.66 t ha^{-1} in a clayey Oxisol in the state of Tocantins, Brazil, agreeing with the present study.

The correlations between the concentration of P, S, and N in the diagnostic leaves with GY (Figure 7) confirm the importance of phosphate sources and nutrients for soybean yield. The supply of P and S are very important for grain formation and plant development due to their importance to biological nitrogen fixation, root development, photosynthesis, and enzymatic reactions, which were responsible for the satisfactory productivity of soybeans in the Amazon region (Salvagiotti *et al.*, 2013).

The rate of P_2O_5 responsible for 95 % of the maximum production was 120 kg ha^{-1}, corresponding to 3.07 t ha^{-1} of soybean grains. The availability of P in the soil that allowed 95 % of the maximum GY was 30.7 mg dm^{-3} (Figure 8). The availability of P in the soil as a function of the phosphate fertilization found in the present study was similar to that recommended in the journal for soybean production in central Brazil (Embrapa, 2013), around 40 mg dm^{-3}. Although the suggested rate of P_2O_5 for soybeans growing in clayed soils with low P availability is 90 kg ha^{-1}, our results show that would be better to increase more 30 kg ha^{-1}. The soybeans need more P to express the maximum productive potential in the eastern Amazon since the soils are very clayey with low P availability. This reinforces the need for *in situ* studies to determine the proper amount of P.

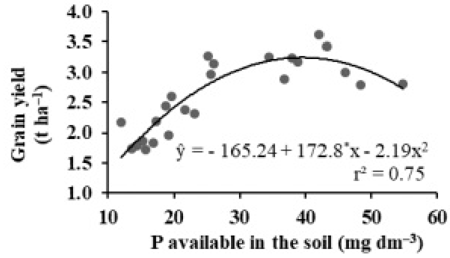

Figure 8. Critical levels of phosphorus in the soil cultivated with soybean as a function of phosphate fertilization in a very clayey Oxisol in the eastern Amazon.

Figura 8. Níveis críticos de fósforo no solo cultivado com soja em função da adubação fosfatada em Latossolo muito argiloso na Amazônia oriental.

4 Conclusion

The availability of P in the soil and the concentrations of P, S, and N in the diagnostic leaves affect the productive attributes and grain yield of soybean. In a situation of abandoned pasture with low P availability, the phosphate fertilizers must be applied for improving soybean production, specially those that contain S. We recommend the rate of P_2O_5 at 120 kg ha^{-1} when the first cultivation of soybean is carrying out. More studies should be conducted to verify the long-term effect of phosphate fertilizers to understand the importance of P in the subsequent cultivation of soybeans in the Amazon region.

Acknowledgements: This work was supported by Alagoinha Farm Research, located in Dom Eliseu countryside, state of Pará, Brazil. The author also thanks the National Council for Scientific and Technological Development and Coordination of Superior Level Staff Improvement in Brazil for the scholarship of the first and second author.

Contribution of the authors: João Cardoso de Souza Junior: conceptualization, writing-original draft, investigation, methodology, project administration, formal analysis; Aline Cristina Richart: conceptualization, formal analysis, funding acquisition, resources, visualization; Leila Sobral Sampaio: supervision, methodology, validation, visualization, writing-review & editing; Ana Regina da Rocha Araujo: validation, visualization; Possidonio Guimarães Rodrigues: validation, visualization, writing-review & editing. Mario Lopes da Silva Júnior: project administration, supervision, validation, review and editing.

Sources of funding: Private financial aid by Alagoinha Farm and Research. Proccess number 012014-437.

Conflict of interest: The authors declare no conflicts of interest.

References

AKTER, F.; ISLAM, M.N.; SHAMSUDDOHA, A.T.M.; BHUIYAN, S.S. Effect of phosphorus and Sulphur on growth and yield of soybean (*Glycine max* L.). **International Journal of Bio-resource and Stress Management**, v. 4, n. 4, p. 555-560, 2013.

BEDIN, I.; NETO, A. E. F.; RESENDE, A.V.; FAQUIN, V.; TOKURA, A. M.; SANTOS, J. Z. L. Phosphate fertilizers and soybean yield in soils with different phosphate buffer capacities. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 639-646, 2003. DOI: 10.1590/S0100-06832003000400008.

BRASIL. **Regras para análises de sementes**. Brasília: Ministério da Agricultura, Pecuária e Abastecimento (MAPA), 2009. 399 p.

BRASIL, E. C.; CRAVO, M. S.; VIÉGAS, I. J. M. **Recomendações de calagem e adubação para o estado do Pará**. Brasília: Embrapa, 2020. 419 p.

CHIASSON, D. M.; LOUGHLIN, P. C.; MAZURKIEWICZ, D.; MOHAMMADIDEHCHESHMEH, M.; FEDOROVA, E. E.; OKAMOTO, M.; MCLEAN, E.; GLASS, A. D. M.; SMITH, S. E.; BISSELING, T.; TYERMAN, S. D.; DAY, D. A.; KAISER, B. N. Soybean SAT1 (Symbiotic Ammonium Transporter 1) encodes a bHLH transcription factor involved in nodule growth and NH_4^+ transport. **Proceedings of the National Academy of Sciences**, v. 111, n. 13, p. 4914-4819, 2014. DOI: 10.1073/pnas.1312801111.

EMBRAPA – EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. **Tecnologias de produção de soja – Região central do Brasil 2012 e 2013**. Londrina: Embrapa Soja, 2013. 262 p.

FAGERIA, N. K.; MOREIRA, A.; CASTRO, C. Responses of soybean to phosphorus fertilization in Brazilian Oxisol. **Communications in Soil Science and Plant Analysis**, v. 42, n. 22, p. 2716-2723, 2011. DOI: 10.1080/00103624.2011.622819.

FAO – FOOD AND AGRICULTURE ORGANIZATION. FAOSTAT - **Value of Agricultural Production: 2019**. Available in: http://faostat.fao.org/. Access in August 31, 2021.

IDESP – Indicadores de desenvolvimento sócio-econômico do Estado do Pará. **Estatística do município de Dom Eliseu em 2014**. Available in: http://www.idesp.pa.gov.br/paginas/produtos/estatisticamunicipal/pdf/domeliseu.pdf. Access in: August 20, 2016.

MALAVOLTA, E. **Manual de nutrição mineral de plantas**. 1. ed. Piracicaba: Agronômica Ceres, 2006. 638 p.

MARSCHNER, H. **Mineral nutrition of higher plants**, 3. ed. San Diego: Academic Press, 2011. 651 p.

NEPSTAD, D.; MCGRATH, D.; STICKLER, C.; ALENCAR, A.; AZEVEDO, A.; SWETTE, B.; BEZERRA, T.; DIGIANO, M.; SHIMADA, J.; MOTTA, R. S.; ARMIJO, E.; CASTELLO, L.; BRANDO, P.; HANSEN, M. C.; MCGRATH-HORN, M.; CARVALHO, O.; HESS, L. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. **Science**, v. 344, n. 6188, p. 1118-1123, 2014. DOI: 10.1126/science.1248525

NETO, F. A.; GRAVINA, G. A.; SOUZA, N. O. S.; BEZERRA, A. A. C. Phosphorus fertilization in the soybean crop at the micro region of Alto Médio Gurguéia. **Ciência Agronômica**, v. 41, n. 2, p. 266-271, 2010. DOI: 10.1590/S1806-66902010000200014

NOVAIS, R. F.; SMYTH, T. J. **Fósforo em solo e planta em condições tropicais**. Viçosa: UFV, DPS, 1999. 399p.

NOVAIS, R. F.; SMYTH, T. J.; NUNES, F. N. Fósforo. In: NOVAIS, R. F.; ALVAREZ, V. H.; BARROS, N. F.; FONTES, R. L. F.; CANTARUTTI, R. B.; NEVES, J. C. L. (Eds) **Fertilidade do Solo**. Viçosa: Sociedade Brasileira de Ciência do Solo, 2007. p. 471-550.

R Core Team (2017). **R**: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

RAIJ, B. V.; QUAGGIO, J. A.; SILVA, N. M. Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. **Communications in Soil Science and Plant Analysis**, v. 17, n. 5, p. 547-566, 1986. DOI: 10.1080/00103628609367733

RAIJ, B. V. **Fertilidade do solo e adubação**. Piracicaba: Potafos, 1991. 343 p.

RAIJ, B. V.; CANTARELLA, H.; QUAGGIO, A. J.; FURLANI, A. M. C. **Recomendação de adubação e calagem para o Estado de São Paulo**. 2ª ed. Campinas: Instituto Agronômico de Campinas, 1997. 285 p. (Boletim técnico n. 100)

RHEINHEIMER, D. S.; ALVAREZ, J. W. R.; FILHO, B. D. O.; SILVA, L. S.; BORTOLUZZI, E. C. Crop responses for sulphur application and sulfate levels in a sandy soil under no-tillage. **Ciência Rural**, v. 35, n. 3, p. 562-569, 2005.

RISKIN, S. H.; PORDER, S.; NEILL, C.; FIGUEIRA, A. M. S.; TUBBESING, C.; MAHOWALD, N. The fate of phosphorus fertilizer in Amazon soya bean fields. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 368, n. 1619, p 1-11, 2013. DOI:

10.1098/rstb.2012.0154

SALVAGIOTTI, F.; BARRACO, M.; DIGNANI, D.; HECTOR, S.; BONO, A.; VALLONE, P.; GERSTER, G.; GALARZA, C.; MONTOYA, J.; GUDELJ, V. J. Plant stand, nodulation and seed yield in soybeans as affected by phosphate fertilizer placement, source and application method. **European Journal of Agronomy**. v. 51, n. 4, p. 25-33, 2013. DOI:10.1016/j.eja.2013.06.006

SARRUGE, J. R.; HAAG, H. P. **Análises químicas em plantas**. Piracicaba: Escola Superior de Agricultura Luiz de Queiroz, 1974. 56p.

SCHONINGER, E. L.; GATIBONI, L. C.; ERNANI, P. R. Fertilization with rock phosphate and kinetics of phosphorus uptake by soybean and cover crops of Brazilian cerrado soils. **Semina: Ciências Agrárias**, v. 34, n. 1, p. 95-106, 2013. DOI: 10.5433/1679-0359.2013v34n1p95

SOIL SURVEY STAFF. **Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys**, 2 ed. Washington D.C.: Natural Resources Conservation Service (Department of Agriculture of United States), 1999. 871p.

SONG, X.P.; HANSEN, M.C.; POTAPOV, P.; ADUSEI, B.; PICKERING, J.; ADAMI, M.; LIMA, A.; ZALLES, V.; STEHMAN, S. V.; BELLA, C. M. Di; CONDE, M. C.; COPATI, E. J.; FERNANDES, L. B.; HERNANDEZ-SERNA, A.; JANTZ, S. M.; PICKENS, A. H.; TURUBANOVA, S.; TYUKAVINA, A. Massive soybean expansion in South America since 2000 and implications for conservation. **Nature Sustainabilty**, v. 4, p. 784–792, 2021. DOI: 10.1038/s41893-021-00729-z

VELOSO, C. A. C.; EL-HUNSY, J. C.; CARVALHO, E. J. M.; SOUZA, F. R. S. **Resposta da soja à adubação com fósforo e potássio em um Latossolo Amarelo da Amazônia Oriental**. Belém: Embrapa Amazônia Oriental (Boletim técnico, 72), 2009.