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The effects of gypsum on the chemical properties of oxisol in the Amazon savannah

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ABSTRACT

The majority of soils in the Amazon savannah have low natural fertility, with issues of high acidity and high Al^{3+} saturation that restricts root growth. Lime is an alternative for soil correction, but its effects are limited to the soil surface. In contrast, gypsum acts in the subsurface, reducing the activity of Al^{3+}. This study aimed to assess the impact of different surface gypsum rates on the distribution of the root system, soybean nutrition, and the chemical improvement of Xanthic Haplustox in the Amazon savannah. A study evaluated the effects of different gypsum rates (0, 1.5, 3, 6, and 12 t ha^{-1}) on the BRS 8381 soybean cultivar in a no-till system. Leaf analyses were performed to determine nutrient contents and vegetative production analyses were conducted. Trenches were also opened to analyze the root system visually. The application of gypsum increased the foliar contents of nitrogen, sulfur, and zinc while decreasing magnesium in soybeans. Although it did not affect grain yield, it improved the chemical environment, particularly during periods of water deficit, by enhancing the distribution of the soybean root system in Xanthic Haplustox in the Amazon savannah.

Keywords: *Glycine max* (L.) Merrill; Root analysis; Tropical soils.

Gesso agrícola na melhoria química de Latossolo Amarelo Distrófico na savana amazônica

RESUMO

Solos da savana amazônica, em sua maioria, apresentam baixa fertilidade natural, onde ocorre problemas de elevada acidez e saturação por Al^{3+}, restringindo o crescimento de raízes. O calcário é utilizado como alternativa, mas possui ação limitada à superfície do solo, diferente do gesso agrícola que atua em subsuperfície, reduzindo a atividade do Al^{3+}. O objetivo do estudo foi avaliar o efeito das doses superficiais de gesso agrícola na distribuição do sistema radicular, nutrição da soja e na melhoria química e físico-química de Latossolo Amarelo Distrófico típico na savana amazônica. O experimento foi instalado em 2018, a cultivar de soja BRS 8381 foi submetida a cinco doses de gesso agrícola, sendo elas 0; 1,5; 3; 6 e 12 t ha^{-1} em sistema de plantio direto. Foram realizadas análises foliares para determinar teores de nutrientes, análises vegetativas e abertura de trincheiras para análise visual do sistema radicular. A aplicação de gesso agrícola aumentou os teores foliares de N, S e Zn e reduziu Mg na soja, não afetou a produção de grãos, mas proporcionou um melhor ambiente químico e físico-químico principalmente para períodos de déficit hídrico, com a melhoria distribuição do sistema radicular da soja em Latossolo Amarelo Distrófico na savana amazônica.

Palavras-chave: Análise radicular; *Glycine max* (L.) Merrill; Solos tropicais.

1. Introduction

The expansion of soybean (*Glycine max* (L.) Merrill) into grassland and savannah areas in the Amazon region is a fact. The savannah area in the state of Roraima, located in northern Brazil, covers approximately four million hectares. Most of this area has soils with low natural fertility (Melo et al., 2010; Batista et al., 2018; Menezes et al., 2019), which is associated with extremely low levels of phosphorus (P), high acidity, high aluminum saturation, low CEC, organic matter content, and base saturation (Vale Júnior et al., 2011). These factors restrict root development at depth, especially for modern cultivars that are more sensitive to aluminum toxicity (Besen et al., 2021; Feitosa et al., 2016).

Currently, there have been investments in management systems, cultivars, and management of fertilization and soil correction in the region (Augusti et al., 2023; Hermógenes et al., 2022; Rocha et al., 2024; Silva et al., 2023; Uchoa et al., 2018). The increasing demand for understanding the role of soil-root interactions in crop yield and their environmental impacts has become more significant. Interactions between roots and their environment can affect root development. Digital image analysis is a more reliable tool than traditional methods for evaluating these interactions because it eliminates subjective evaluations (Carducci et al., 2014; Jorge and Silva, 2010).

Practices such as adopting the no-tillage farming system (NT) have been highlighted to maintain soil quality and integrate the native Amazonian savannah environment into the productive sector. In this system, soil acidity is corrected by applying lime on the soil surface without incorporation (Bossolani et al., 2022). The establishment of NT led to an aggravating factor, namely the low solubility of limestone in water. This factor limits the action of limestone to the first few centimeters of the soil surface, and its neutralizing action depends on the contact surface and soil humidity (Borgmann et al., 2021; Bossolani et al., 2022; Minato et al., 2023; Moraes et al., 2023; Tiecher et al., 2018). However, this aggravating factor has been overcome through the use of gypsum.

Although gypsum is not an active acidity corrector, it can be used to reduce Al^{3+} activity in the subsurface soil layers. This is due to its ability to redistribute Ca^{2+}, Mg^{2+}, and K^{+} while reducing Al^{3+} saturation (m%) in the deeper soil layers, improving the mobility of cations in the soil profile. Additionally, gypsum has a water solubility about 170 times greater than limestone (Brignoli et al., 2023; Minato et al., 2023). Gypsum promotes deeper root growth in subsurface soil layers, increasing plants' tolerance to water deficits (Araújo et al., 2018; Nora et al., 2017; Souza et al., 2023) and reducing the physiological effects of water stress during the soybean production cycle.

Until the 1990s, the criteria for gypsum recommendations in grassland and Cerrado areas of central Brazil soils was to only suggest gypsum in situations where m% (Al saturation) was greater than or equal to 20% (Ribeiro et al., 1999; Sousa and Lobato, 2004). However, recent studies with more sensitive cultivars have shown responses even in conditions with low m% values (Nora et al., 2017; Serafim et al., 2023) and without water deficit. Pias et al. (2020) found that the probability of increasing cereal grain yields by applying gypsum to soils with more than 5% saturation was between 77% and 97% when water deficiency occurred. A positive response to gypsum for soybeans was observed in water-deficient soils with Al saturation of more than 10%, where the average yield increase was 12%.

This research hypothesizes that there are benefits in the chemical properties of the profile of Amazon savannah soils managed with gypsum, which allows the implementation of sustainable production systems, such as the NT system with soybeans, regardless of the water conditions in the Amazon savannah of Roraima. Studies on the surface application of limestone and gypsum to soils in the Amazon savannah are limited in scope and scarce. This study aimed to evaluate the effect of surface gypsum rates on the root system, soybean nutrition, and chemical improvement of a Xanthic Haplustox in the Amazon savannah.

2. Material and Methods

The study was conducted in Boa Vista, Roraima, Brazil, from May to September 2018 (2º52'20.83" N, 60º42'44.99" W, altitude 90 m) (Figure 1). The study area is located in the central portion of the Amazon savannah, characterized by predominantly flat to gently undulating relief with vegetation parkland savannah and grassy-woody savannah (Hermógenes et al., 2022).

The region has an Aw-type climate classification according to the Köppen system. It experiences a rainy season from April to September and a dry season from October to March. The average annual rainfall is 1,657 mm (Couto-Santos et al., 2014). The monthly minimum and maximum temperature averages and rainfall during the experiment are shown in Figure 2. The data was obtained from the automatic weather station located in Boa Vista, RR A135, part of INMET's network of stations (INMET, 2024).

The soybean crop water balance was calculated using the Agricultural Decision Support System (SISDAGRO, 2024), developed by the INMET and shown in Figure 3.

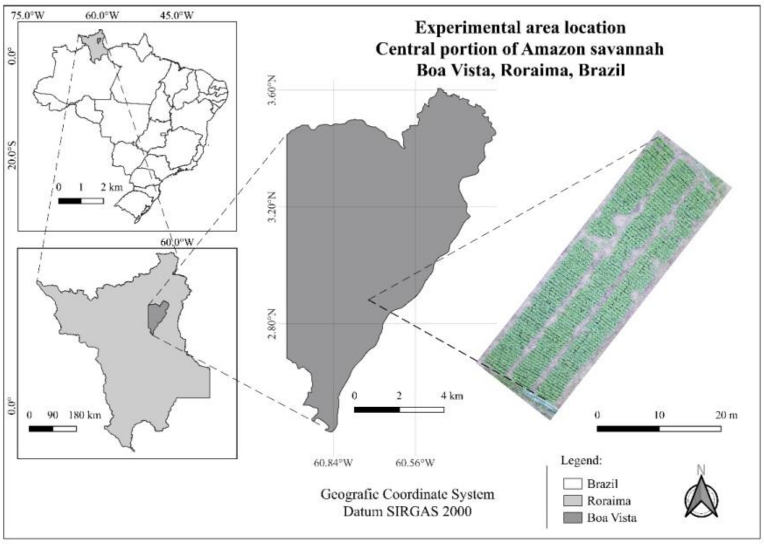

Figure 1. Location of the experimental area, Boa Vista, Roraima, Brazil.

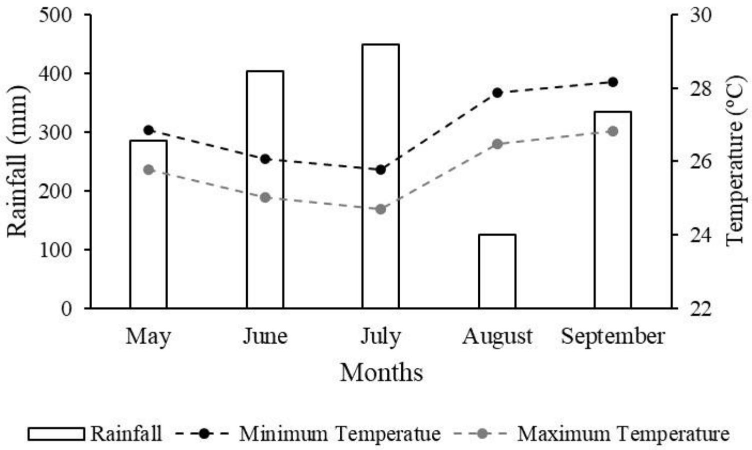

Figure 2. Total rainfall (mm) and mean daily minimum and maximum temperature (ºC) in each month of the study period (May to September 2018) in the experimental area of the Centre for Agricultural Sciences, Campus of Cauamé, Federal University of Roraima, Boa Vista, Roraima, Brazil.

The parameters used in the calculation were: a) sowing date of May 20, 2018; b) soybean crop with a cycle of 110 days (similar to the cycle of the chosen cultivar in this research); c) automatic weather station in Boa Vista RR A135; d) medium-textured soil according to soil analysis. Soil in the experimental area is classified as a Latossolo Amarelo Distrófico típico, according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to Xanthic Haplustox in Soil Taxonomy (Soil Survey Staff, 2014). Table 1 displays the chemical and textural properties of the soil before the experiment, categorized into four layers of up to 0.60 m.

The study was conducted under rainfed conditions, and the area was converted from a native savannah to a no-till system in 2017. The cultivation in the experimental area began with the planting of cowpeas during the 2017/18 harvest. Before sowing, the soil was prepared using minimum cultivation with a harrow. The soil was corrected with 800 kg ha^{-1} of lime, ECCE 92%, and 130 kg ha^{-1} of P_2O_5 using simple superphosphate as the source. Both were applied in the total area without incorporation.

Subsequently, the area remained fallow until the present experiment was set up with soybean planting in the 2018/2019 crop season. The experimental design consisted of randomized blocks with three replications. The plots were randomized with five gypsum rates: 0, 1.5, 3, 6, and 12 t ha^{-1}. Each plot comprised six rows, which were spaced 0.50 m apart and 4 m long, totaling 12 m^2. The soybean was cultivated under a no-tillage system, using the spontaneous vegetation resulting from the fallow period of the previous crop as mulch. Fifteen days before sowing (DBS), the area was treated with Glyphosate herbicide (480 g L^{-1}) at a rate of 1,200 g ha^{-1} of active ingredient (a.i.), resulting in desiccation. To neutralize all exchangeable acidity and part of the non-exchangeable acidity in the 0-0.20 m layer, dolomitic limestone with PRNT 92.3%, CaO 32%, and MgO 15% was applied at a rate of 225 kg ha^{-1}, correcting the soil by 30 DBS (Sousa and Lobato, 2004).

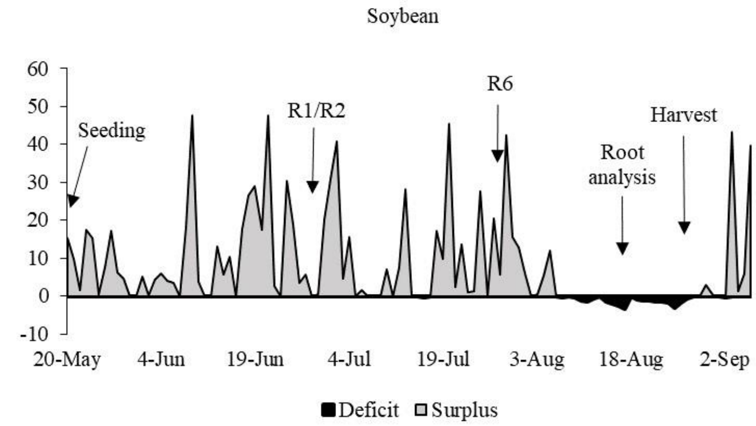

Figure 3. Climatological water balance in each month of the study period (May to September 2018) in the experimental area of the Centre for Agricultural Sciences, Campus of Cauamé, Federal University of Roraima, Boa Vista, Roraima, Brazil. R1/R2 stage (full bloom); R6 stage (full seed).

Liming was conducted manually by plowing the surface of the total area without incorporation into the soil. After 20 DBS, the five gypsum rates were applied manually on the surface and without incorporation, according to each treatment. Before planting, the planting rows were fertilized with 120 kg ha^{-1} of P_2O_5 (triple superphosphate) and 50 kg ha^{-1} of FTE-BR12 to supply micronutrients. Potassium was applied at a rate of 120 kg ha^{-1} of K_2O, sourced from potassium chloride (KCl), with 40% applied at sowing and the remaining amount applied 25 days after emergence (DAE). The soybean seeds were inoculated with 500 g of peat inoculant per 50 kg of seed at the sowing time to supply nitrogen.

The inoculant contained the Semia 5079 and Semia 5080 strains of *Bradyrhizobium japonicum*, with a minimum *Bradyrhizobium* concentration of $5x10^9$ viable cells per gram of inoculant. Before inoculation, the seeds were moistened with a sugar solution at a rate of 6 ml per kilogram of seed.

Table 1. Chemical attributes of the Xanthic Haplustox at the 0-0.60 m soil layer before setting up the experiment in the Amazon savannah in Roraima state (Brazil). Ca = exchangeable calcium; Mg = exchangeable magnesium; Al = exchangeable aluminum; H+Al = potential acidity; SB = sum of bases; t = cation capacity at pH soil; T = cation capacity at pH 7; K = exchangeable potassium; P = available phosphorus; S.O.M. = soil organic matter; P-Rem = remaining phosphorus; Zn = zinc; Fe = iron; Mn = manganese; Cu = copper; B = boron; S = sulfur; V = base saturation; m = aluminum saturation.

Layers	pH										
	KCl	Water	Ca	Mg	Al	H+Al	SB	t	T	K	P
--- m ---			-------------------------cmol$_c$ dm^{-3}-------------------------							---mg dm^{-3}---	
0.00 – 0.10	5.0	5.9	1.73	0.54	0.05	1.36	2.33	2.38	3.69	24.31	11.15
0.10 – 0.20	4.5	5.2	1.23	0.34	0.16	1.56	1.61	1.77	3.17	14.06	6.46
0.20 – 0.40	4.3	4.9	0.56	0.15	0.39	1.64	0.73	1.12	2.37	7.91	1.67
0.40 – 0.60	4.4	5.0	0.34	0.10	0.48	1.59	0.46	0.94	2.05	6.88	0.67
	S.O.M.		P-Rem			Zn	Fe	Mn	Cu	B	S
	--dag kg^{-1}--		--mg L^{-1}--			------------------------mg dm^{-3}------------------------					
0.00 – 0.10	0.94		51.41			3.35	84.12	4.32	0.95	0.21	21.08
0.10 – 0.20	0.67		45.63			1.18	192.1	2.17	0.65	0.11	23.98
0.20 – 0.40	0.38		36.10			0.86	70.14	0.48	0.53	0.06	37.34
0.40 – 0.60	0.26		27.29			1.10	46.36	0.13	0.54	0.01	39.08
	Textural classification					Clay	Silt	Sand		V	m
						--------dag kg^{-1}--------				-------%-------	
0.00 – 0.10	Sandy clay loam					27	1	72		63.21	2.10
0.10 – 0.20	Sandy clay loam					29	1	70		50.66	9.04
0.20 – 0.40	Sandy clay loam					30	1	69		30.81	34.82
0.40 – 0.60	Sandy clay loam					28	2	70		22.32	51.06

pH in water and KCl - ratio 1:2.5; Ca – Mg – Al: extractor – KC l mol L^{-1}; S: extractor – monocalcium phosphate in acetic acid; P – K – Zn – Fe – Mn – Cu: extractor – Mehlich 1; B: extractor: hot water; H+AL: extractor – SMP; S.O.M.: oxidation: $Na_2Cr_2O_7$ 4N + H_2SO_4 10 N; Clay – Silt – Sand: pipette method.

On May 20, 2018, soybeans were sown with a density of 25 seeds per meter. At 14 DAE, manual thinning was performed, leaving 15 plants per meter (a population of 300.000 plants ha^{-1}). Weeds were controlled manually, and pests and diseases were managed as necessary. To chemically control the caterpillars *Agrotis ipsilon* and *Rachiplusia* spp., Lannate BR® (a.i. methomyl) was used, and to prevent anthracnose, the commercial product Cercobin 700 WP® (a.i. thiophanate-methyl) was applied.

At 35 DAE, when the plants were in the R1 (beginning bloom) to R2 (full bloom) phenological stage, we sampled 30 plants per plot and collected the third trefoil from the apex to the base to determine the contents of macro (N, P, K, Ca, Mg, and S) and micronutrients (B, Cu, Mn, Zn, and Fe). The samples were washed and dried in an oven at 65 ºC until they reached a constant mass. The leaves were ground in a Willey TE-650 mill and sent for duplicate leaf analysis.

At 80 DAE, during the R7 stage (beginning maturity), soil profiles were sampled according to Melo et al. (2019). To analyze the root system, 15 trenches were sampled in each treatment and their respective repetitions at 0.70 m from the soybean planting row. The trenches were 1.0 m wide, 0.75 m long, and 0.75 m deep.

The vertical leveling of the profile allowed for the observation of root distribution in the trench wall beneath the plant apex. A 0.02 m layer of soil was removed along the vertical section containing the roots, followed by using a water jet to expose the roots. Following the procedure, the roots were painted green to enhance the contrast with the soil of the trench wall. Then, a tape measure with the dimensions of the trench was placed next to the roots to take photographs.

The images were captured using a semi-professional digital camera with a resolution of 32 megapixels and a flash. A black cloth was used to cover the trench and avoid the contrast from reflected sunlight to improve image quality. The images were then corrected and aligned. Grid lines were created with the same dimensions as the trench (0.60 m wide x 0.60 m deep). The grid consisted of squares measuring 0.60 m x 0.20 m. Volume (measured in cubic millimeters), surface area (measured in square millimeters), and length (measured in millimeters) were quantified at 0.0-0.20 m, 0.20-0.40 m, and 0.40-0.60 m soil layers using Safira software (Jorge and Silva, 2010).

At R8 stage (full maturity), at the end of the 90-day cycle, 10 plants from the useful area of the plot were evaluated for the following variables: first pod insertion height (from ground level to the insertion of the first pod), plant height, collar diameter (at the height of the collar), number of pods per plant (measured by counting pods and dividing by the number of the plants evaluated), number of empty locules (measured by counting empty locules and dividing by the number of plants evaluated), and number of seeds per pod (measured by counting the number of seeds in 100 randomly selected pods and dividing by the same value, in triplicate). Following the sampling, the plants within the useful area were harvested manually, and the pods were threshed using a mechanized harvester. We considered a harvested area of 3 m^2 and grains with approximately 13% moisture to estimate yield. We expressed the mass ratio to the useful area size in kg ha^{-1}.

The normality, heteroscedasticity, and variance of the data were tested through graphical visualization (Kozak and Piepho, 2018) and numerical tests (Peña and Slate, 2006) using linear models to check the distribution of the indicators. When necessary, quadratic and logarithmic transformations were applied to the data (Menke, 2015). Quadratic transformations were necessary for leaf sulfur content, yield, and number of pods per plant. Logarithmic transformation was necessary for leaf boron content. Following the premises, all the variables underwent analysis of variance using an F-test ($P<0.05$) based on the experimental design (five quantitative treatments – gypsum rates – in three randomized blocks). The averages were subjected to regression analysis ($P<0.05$) when significant. The data were analyzed using linear models with the support of the following libraries in the RStudio development environment (RStudio Team, 2024): gvlma version 1.0.0.3, vegan version 2.6-4, devtools version 2.4.5, and tidyverse version 1.3.2.

3. Results and Discussion

The application of gypsum resulted in increased leaf contents of N by 7.3%, S by 18.6%, and Zn by 36.7% compared to the control treatment (Table 2) (Figure 4B, 4C, and 4D), demonstrating the chemical benefit of gypsum. However, the effect of gypsum rates on Mg resulted in a reduction of up to 24.9% in leaf Mg content according to the linear regression analysis ($P<0.05$) (Figure 4A). The contents of the remaining nutrients were not affected by applying gypsum, but they showed values within the range considered adequate for soybean nutrition.

Leaf Mg contents decreased as gypsum application rates increased, which is consistent with findings in other soil and climate conditions in Brazil (Besen et al., 2021; Brignoli et al., 2023; Caires et al., 1999; Fontoura et al., 2019).

The decrease in leaf Mg content is attributed to the movement of Mg^{2+} in the soil profile, which was caused by high gypsum rates in this study. This mobility is due to the lower oxygen-binding energy of the functional groups in the soil colloids. During the reaction process, there is no change in the effective CEC, so the Ca^{2+} supplied by the gypsum competes with Mg^{2+} on the exchange surface, taking precedence (Besen et al., 2021; Brignoli et al., 2023; Fontoura et al., 2019). The accumulation of Mg^{2+} ions in the soil solution is facilitated, leading to their leaching into deeper soil layers, especially when water is available.

Table 2. Nitrogen content (N), Phosphorus content (P), Potassium content (K), Calcium content (Ca), Magnesium content (Mg), Sulfur content (S), Boron content (B), Copper content (Cu), Manganese content (Mn), Zinc content (Zn) and Iron content (Fe) in the leaves of soybean cultivar BRS 8381, collected at the R1/R2 stage (beginning bloom/full bloom), under gypsum rate in no-tillage in the Amazon savannah in Roraima state, Brazil. MSE = mean standard error; CV = coefficient of variation; ns= not significant

Element	Gypsum rate (t ha^{-1})					Contrast	Mean	MSE	CV
	0	1.5	3	6	12				
	---------------------g kg^{-1}---------------------								%
Mg	3.9	3.8	3.6	3.4	2.9	L	3.5	0.11	11.7
Ca	13.3	13.6	12.8	15.4	14.8	ns	14.0	0.37	10.3
K	20.0	21.2	20.8	20.8	21.6	ns	20.9	0.38	7.0
P	4.3	4.2	4.8	4.6	4.9	ns	4.6	0.11	9.3
N	55.9	55.6	57.6	58.6	60.0	L	57.5	0.69	4.1
S	3.6	3.6	3.8	4.2	4.3	L	3.9	0.13	12.5
	--------------------mg kg^{-1}--------------------								
B	61.3	51.4	50.6	56.5	56.1	ns	55.2	2.11	14.8
Cu	13.8	14.0	13.9	13.8	15.5	ns	14.2	0.47	12.7
Mn	27.2	23.3	25.3	27.2	27.4	ns	26.1	1.76	26.2
Zn	54.7	59.5	51.3	80.5	82.0	L	65.6	5.09	30.1
Fe	183.6	178.0	169.0	191.2	180.3	ns	180.4	3.44	7.4

Additionally, the use of gypsum promotes the formation of neutral ionic pairs SO_4^{2-}, with the $MgSO_4^0$ form taking priority over the other ionic pairs, indicating that Mg^{2+} is carried to the subsurface soil layers (Rampim et al., 2011). Although the study found a reduction in leaf Mg contents in soybean leaves at the highest rate applied, it is well known that gypsum has positive effects on increasing crop productivity, particularly under conditions of water deficit and m% above 10% (Nora et al., 2017; Serafim et al., 2023; Tiecher et al., 2018). To prevent reductions in leaf Mg levels and crop yields (Besen et al., 2021; Pauletti et al., 2014; Tiecher et al., 2018), when high doses of gypsum are applied, it is recommended that it only be applied in combination with the use of dolomitic limestone with a more balanced Ca:Mg ratio to avoid Mg^{2+} deficiency, since the movement of Ca^{2+} and Mg^{2+} from the surface layer to the subsoil is evident and liming maintains high levels of Mg^{2+} (Caires et al., 1998; Costa and Crusciol 2016; Soratto and Crusciol 2008).

This is because gypsum has more beneficial effects when the acidity of the soil surface is neutralized by liming (Bortoluzzi et al., 2014; Fontoura et al., 2019; Joris et al., 2016; Nora et al., 2017; Tiritan et al., 2016).

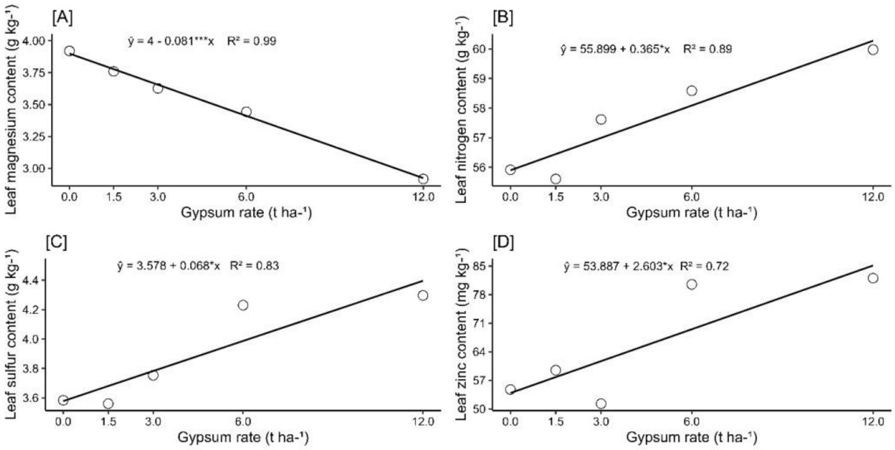

Figure 4. Magnesium content (g kg^{-1}) (A), Nitrogen content (g kg^{-1}) (B), Sulfur content (g kg^{-1}) (C), and Zinc content (mg kg^{-1}) (D) in the leaves of soybean cultivar BRS 8381, collected at the R1/R2 stage (beginning bloom/full bloom), under gypsum rate in no-tillage in the Amazon savannah in Roraima state, Brazil.

Using gypsum to manage soil can lead to changes in the chemical properties that promote favorable conditions for root growth. This was confirmed in this study that observed an increase in N, Zn and S contents in soybean leaves. The findings of Fageria et al. (2014), Pauletti et al. (2014), and Rampim et al. (2011) also support this conclusion. It is worth noting that N in soybean plants is mostly obtained through symbiotic fixation, and the use of gypsum can improve the conditions for this process by promoting symbiosis with bacteria (Santos et al., 2008; Schenfert et al., 2020). For Zn, the increase may be attributed to the presence of micronutrients in the gypsum. Significant amounts of this micronutrient are added when high rates are applied (Soares et al., 2018). In conditions of lower buffering power, such as the soil in this study, P, S, and Zn are more easily released into the solution, leading to greater absorption of these elements by plants and resulting in higher leaf contents (Santos et al., 2008). However, soybeans grown in medium-textured soil were inefficient in utilizing P, as evidenced by the unaltered leaf content despite applying gypsum in one crop season.

Regarding S in soybean leaves, the contents of this nutrient increased with increasing gypsum rates (Figure 4C). This is because gypsum is a mineral source of S in the soil. Similar increases were also observed by Caires et al. (1998, 2003) during the first soybean crop. In successive crops, the S associated with sulfate ions (SO_4^{2-}) may be redistributed throughout the soil profile rather than accumulating in a specific layer. This phenomenon has been observed by Caires et al. (2003), Pauletti et al. (2014), and Schenfert et al. (2020), who reported regular distribution of S over the soil profile.

The effects of gypsum on the increase in leaf Ca content were not observed in the soybean crop following application. This result may be related to the slower movement of Ca^{2+} in soils with a predominantly negative net charge (Caires et al., 2003). Although soil K^+ was low before the study, according to Ribeiro et al. (1999), high fertilization was conducted with K^+ application installments during soybean cultivation. This helped prevent possible reductions in foliar contents and/or deficiencies. Gypsum can promote the movement of K^+ to subsurface soil layers, reducing its availability in more superficial soil layers (Borgmann et al., 2021; Tiecher et al., 2018). This phenomenon did not occur in this research.

According to Ribeiro et al. (1999), the contents of all the macronutrients, except for Mg, remained at sufficient levels for soybeans. Gypsum application did not cause significant changes ($P<0.05$) in foliar contents of the micronutrients B, Cu, Fe, and Mn, regardless of the rates applied. However, the leaf contents also remained sufficient for soybean crops (Ribeiro et al., 1999).

The intensity of solubilization and interference of gypsum with early liming on the chemical attributes of the soil was verified in just one soybean crop in the Amazon savannah. Rampim et al. (2011) observed this solubilization and change in chemical properties just six months after application. This promotes root development, redistributes nutrients, and provides greater SO_4^{2-} mobility in the profile.

The results of the visual analysis of root distribution in the soil profile indicate that soybean root growth in the deeper soil layers (40-60 cm) increased with increasing gypsum rates (Figures 5 and 6). The fitted linear models showed a reduction in root growth in terms of volume, surface area, and root length in the 20-40 cm soil layer and an increase in the 40-60 cm soil layer with increasing gypsum rates ($P<0.05$) (Figure 6). No significant ($P<0.05$) influence on root growth was observed at the 0-20 cm soil layer.

The growth of soybean roots in the soil profile is influenced by the chemical and physical-chemical conditions of the soil. According to Bossolani et al. (2022), soybean roots' growth is improved in the short term due to the improvement in the chemical condition of the soil, while in the long term, the physical-chemical condition of the soil plays a crucial role. Rampim et al. (2011) found that surface-applied gypsum in a no-till system helps mobilize Al in the form of $AlSO_4^+$ and redistribute exchangeable bases throughout the profile.

The chemical changes in the plant favored soybean rooting and increased water absorption, particularly in the 40-60 cm soil layer, as evidenced by root growth. Higher rates of gypsum were positively correlated with increases in root volume, length, and surface area (Figure 6). Aluminum toxicity and nutrient deficiency are the primary chemical factors that limit root development in acidic tropical soils (Bossolani et al., 2022; Fageria et al., 2014; Moraes et al., 2023; Rampim et al., 2011). This is particularly true for Amazonian savannah soils (Benedetti et al., 2011; Vale Júnior et al., 2011). Changes in the soil's chemical properties can create favorable conditions for better root growth, leading to greater absorption of water and nutrients and increased productivity (Fageria et al., 2014; Souza et al., 2023).

Gypsum application promoted greater root growth in depth, which may explain the yield of 2.9 t ha^{-1} of soybean in dystrophic soil, achieving a level of productivity compatible with the cultivar used (Smiderle et al., 2016). The increasing gypsum rates significantly impacted the first pod insertion height ($P<0.05$).

The other variables related to soybean production, such as plant height, collar diameter, number of pods per plant, number of empty locules, number of seeds per pod, and yield, did not show any effects ($P<0.05$) in terms of the rates under study. Their average values are presented in Table 3.

The first pod insertion height is a crucial factor for soybean cultivation. This determines the adjustment of the harvester's cutting bar, ensuring maximum efficiency during the process (Mauad et al., 2010). Therefore, soybean cultivars with a first pod insertion height ranging from 10 to 15 cm are preferred (Monteiro et al., 2016).

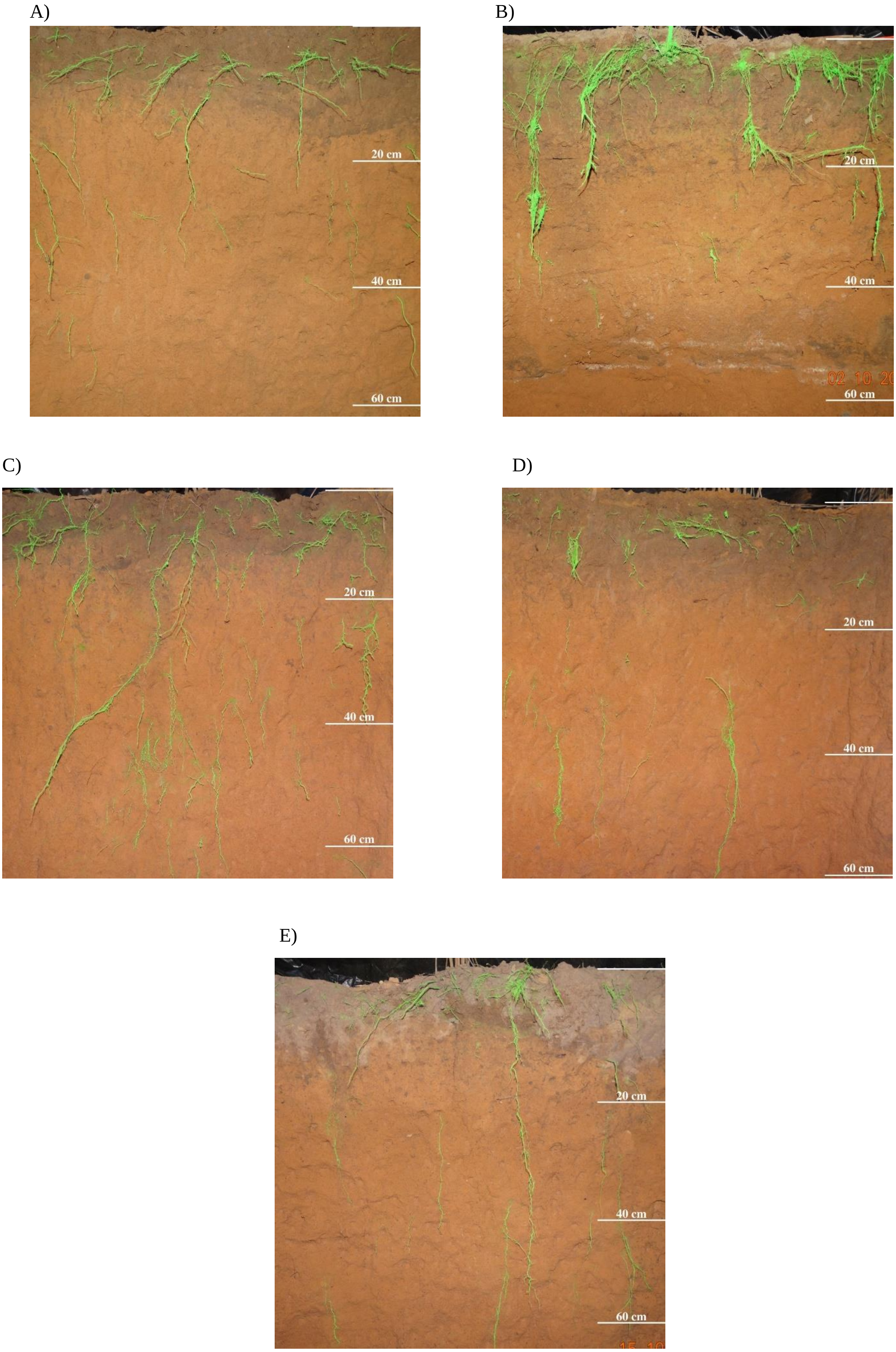

Figure 5. Soybean root distribution in the soil profile as a function of the gypsum rate (A = 0 t ha^{-1}; B = 1.5 t ha^{-1}; C = 3.0 t ha^{-1}; D = 6 t ha^{-1}; E = 12 t ha^{-1}) on the surface.

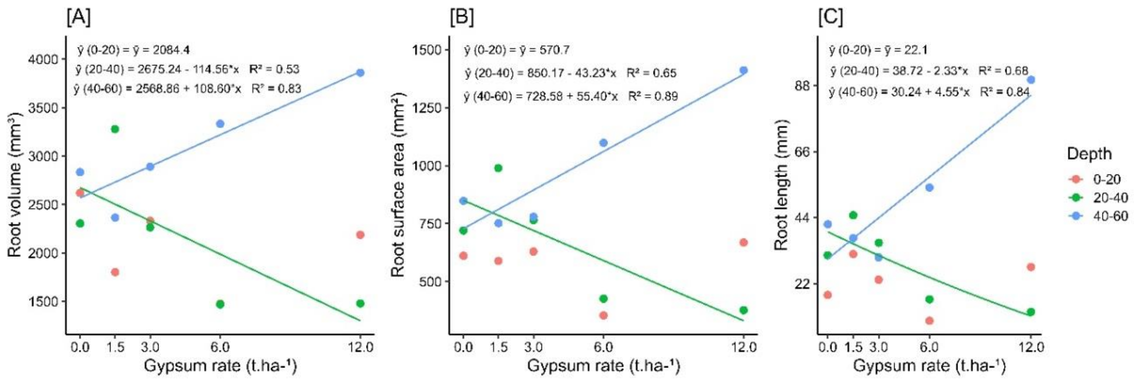

Figure 6. Volume (mm³), surface area (mm²), and length (mm) of roots of soybean by soil layer according to the gypsum rate on the surface.

In this study, losses related to the minimum pod insertion height for harvesting were not observed for soybean cultivar BRS 8381, even without gypsum. The impact of gypsum rates on the first pod insertion height was most accurately described by a positive linear function, with an average increase of 0.245 cm per ton of gypsum applied (Figure 7).

Abiotic stresses, such as drought, heat, and acidity, can lead to a greater reduction in the first pod insertion height due to a lower number of nodes and shorter internode length. This characteristic is located in the lower part of the stem and develops earlier (Kuzbakova et al., 2022). Therefore, gypsum, which contributed to the development of the root system of soybean plants by increasing the leaf nutrients content, combined with the absence of episodes of water stress, did not affect the number of nodes or the length of the internode in the soybean plants in this study.

1

Table 3. Phytotechnical characteristics of soybean leaves (cultivar BRS 8381), collected at the R8 stage (full maturity), under gypsum rate in no-tillage in the Amazon savannah in Roraima state, Brazil. FPIH = first pod insertion height; TPH = total plant height; CD = collar diameter; NPP = number of pods per plant; NEL = number of empty locules; NSP = number of seeds per pod; Prod = productivity; MSE = mean standard error; CV = coefficient of variation; ns= not significant.

Variable	Gypsum rate (t ha^{-1})					Contrast	Mean	MSE	CV (%)
	0	1.5	3	6	12				
FPIH	15.6	15.3	17.0	17.1	18.4	L	16.7	0.44	10.3
TPH	68.7	69.8	70.3	75.5	70.4	ns	70.9	0.94	5.2
CD	0.60	0.66	0.63	0.60	0.60	ns	0.6	0.02	9.8
NPP	39.3	60.6	44.9	38.6	40.5	ns	44.8	2.99	25.9
NEL	1.4	1.5	1.0	1.2	1.3	ns	1.3	0.16	48.5
NSP	2.7	2.7	2.8	2.8	2.7	ns	2.7	0.04	6.1
Prod	2722.2	3133.3	2646.3	3211.1	3055.6	ns	2953.7	89.83	11.8

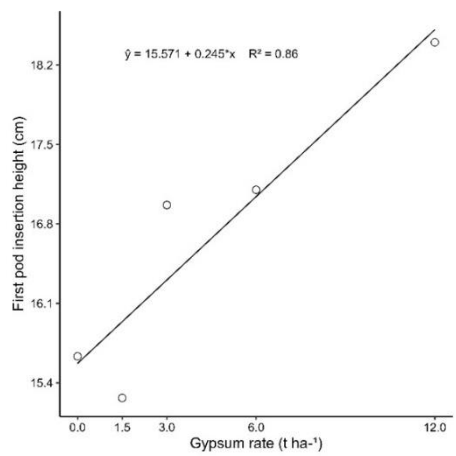

Figure 7. First pod insertion height of Soybean cultivar BRS 8381 plants as a function of gypsum rate in the Amazon savannah, in Roraima, Brazil.

As a result, the first pod insertion height was increased with higher gypsum rates, promoting better growth of the soybean plants.

The study did not find any increase in productivity or changes in the other production components of the soybean crop due to the applied gypsum rates. This result confirms previous studies that have reported the low response of this species to applied gypsum (Benart et al., 2020; Borgmann et al., 2021; Caires et al., 1999; Caires et al., 2003; Minato et al., 2023; Raut et al., 2020; Soares et al., 2018), even under favorable water balance conditions without water deficit. According to Pias et al. (2020), soybean grain yields respond twice as much to gypsum application under water deficit conditions compared to normal conditions.

Additionally, Tiecher et al. (2018) found that the subsurface acidity of the soil affects soybean growth. In this study, no water deficiency occurred from sowing to the phenological stage corresponding to full seed (R6 stage) (Figure 3). The soil analysis indicates a pH of 5.2 and low m% content in the 0.10–0.20 m soil layer before applying gypsum, which helped attenuate gypsum's effects on soybean production components. The negative effects of soil acidity components were mitigated by the combination of favorable rainfall and adequate levels of macronutrients (Brignoli et al., 2023).

Species belonging to the Fabaceae family, such as soybeans, are more efficient at absorbing Ca^{2+} from the soil solution than those from the Poaceae family. This is due to their roots having a higher cation exchange capacity, which allows them to absorb cations present in low contents in the soil (Borgmann et al., 2021). Therefore, applying gypsum is less likely to cause positive responses in the soybean crop than an increase in the saturation and availability of Ca^{2+} in the soil, as observed in this research.

The long-term combination of liming and gypsum application reduces soil active and exchangeable acidity while increasing the availability of P, Ca^{2+}, Mg^{2+}, and S throughout the soil profile (Bossolani et al., 2021; Bossolani et al., 2022). This positively affects fertility and crop yields, particularly during drought periods. Although the soybean crop responded with increased foliar levels of N, S, and Zn with increasing gypsum rates, the increase in nutrient absorption does not always result in gains in crop productivity (Table 3). Instead, soybean plants exhibit 'luxury absorption' (Fontoura et al., 2019).

4. Conclusions

The research results provide valuable insights into the effective application of gypsum to enhance the chemical properties of a Xanthic Haplustox and the root environment of soybean plants. The use of gypsum resulted in a more uniform distribution of the soybean root system over the soil profile. The increase in volume, surface area, and length at depth improved soil exploration and allowed the extraction of water and nutrients from deeper soil layers during periods of water deficit. Additionally, it increased the nutrient contents in the leaves, except for Mg, and resulted in an average yield of 2.9 t ha^{-1} of soybean grains in the Amazon savannah. This level of productivity is compatible with the cultivar used.

Authors' Contribution

Eduardo Medeiros Severo: Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation, Methodology, Investigation, Formal Analysis, Project Administration. Gabriele Medeiros Hermógenes: Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal Analysis. Sandra Cátia Pereira Uchoa: Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal Analysis. José Maria Arcanjo Alves: Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal Analysis, Resources. Glauber Ferreira Barreto: Writing – review & editing, Visualization, Investigation. Carlos Enrique Canche Iuit: Writing – review & editing, Visualization, Investigation. Silvino Guimarães Moreira: Writing – review & editing, Visualization, Validation, Formal Analysis.

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