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Lime requirement in tropical soils: a study in the brazilian amazon savannah

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ABSTRACT

Liming positively impacts soil quality, such as increasing pH and nutrient availability. In the state of Roraima, arable soils, for the most part, are under the domain of the savannah biome, with an acidic pH and low sum of bases, conditioning agricultural use to investments in fertility correction. Thus, the study aimed to evaluate different limestone recommendation methods and their effects on the chemical characteristics of three soil classes, using corn as an indicator plant in pot cultivation. The lower doses were considered to neutralize exchangeable acidity, and the higher doses aimed at neutralizing exchangeable acidity and increasing calcium and magnesium levels. In the more clayey soil, the different doses of lime did not affect the initial production of dry matter; therefore, a method that guarantees the supply of calcium and magnesium to the crop, in addition to neutralizing the toxic forms of aluminum, is the most appropriate. In sandy soils with low buffering power, predominant in the savannah, the highest doses of limestone reduced dry matter production. In these soils, the method based on the neutralization of exchangeable aluminum was efficient in raising the pH and reducing the exchangeable Al^{3+}, but it did not guarantee adequate levels of calcium and magnesium for the crop's needs. The results show the importance of an individualized approach in lime requirement determination for liming in Roraima soils.

Keywords: Limestone, Soil fertility, Soil pH, Base saturation.

Necessidade de calagem em solos tropicais: um estudo na savana amazônica brasileira

RESUMO

A calagem apresenta impactos positivos na qualidade dos solos, como o aumento do pH e na disponibilidade de nutrientes. No estado de Roraima, solos agricultáveis, em grande parte, estão sob domínios do bioma savana e apresentam pH ácido e distrofia, condicionando o uso agrícola a investimentos na correção da fertilidade. Assim, objetivou-se avaliar diferentes métodos de recomendação de calcário e seus efeitos nas características químicas de três tipos de solo, tendo o milho como planta indicadora em um cultivo em vasos. As menores doses consideraram a neutralização da acidez trocável e as maiores a neutralização da acidez trocável e o aumento dos níveis de cálcio e magnésio. No solo mais argiloso, as diferentes doses de calcário não afetaram a produção inicial de biomassa seca; dessa forma, um método que garanta o fornecimento de cálcio e magnésio para a cultura, além de neutralizar as formas tóxicas de alumínio, é o mais adequado. Nos solos mais arenosos e com baixo poder tampão, predominantes na savana, as maiores doses de calcário reduziram a produção de biomassa. Nesses solos, o método baseado na neutralização do alumínio trocável foi eficiente em elevar o pH e reduzir o Al trocável, mas não garantiu teores de cálcio e magnésio adequados para a necessidade da cultura. Os resultados obtidos evidenciam a importância de uma abordagem individualizada na determinação da necessidade de calagem para os solos de Roraima.

Palavras-chave: Calcário, Fertilidade do solo, pH do solo, Saturação por bases.

1. Introduction

Liming acidic soils has far reaching positive impacts on soil and plant processes and functions in terms of chemistry, physics, nutrition, and biota quality (Holland et al., 2018). The main methods for lime requirement determination for liming tropical soils in Brazil aim to increase pH and Ca (calcitic limestone) or Ca and Mg (dolomitic limestone) content, indirectly reducing Al and Mn activity to non-toxic levels, increasing P availability, effective CEC and cation adsorption (Sousa et al., 2007; SBCS-CQFS-RS/SC, 2004; Raij, 2011).

The main lime requirement determination methods are based on the neutralization of exchangeable acidity (Al^{3+}), the neutralization of Al^{3+} combined with calcium and magnesium contents, the decrease in pH in the SMP buffer solution, and the base saturation of the cation-exchange capacity of the soil (Sousa et al., 2007; Sousa and Lobato, 2004; Raij, 2011). Other methods, complementary to those considered traditional, have been proposed to avoid under or overestimation of liming, such as the methodologies proposed by Guarçoni and Sobreira (2017) and Teixeira et al. (2020), which use algorithms to decide on a recommendation that meets the supply of calcium and magnesium, with a recommendation limited to the neutralization of potential soil acidity loads.

Excessive application of lime can alter the solubility/availability of micronutrients such as iron, manganese, zinc, copper, and boron (Fageria and Baligar, 2008) and affect the soil base balance (Silva Carneiro et al., 2018). Excessive liming can also affect soil structure, increasing the number of small aggregates due to the breakdown of larger aggregates stabilized by Fe and Al sesquioxides, resulting in reduced permeability and a lack of adequate drainage and, consequently, a change in the ecosystem (Harter, 2007). On the other hand, recommendation methods, such as those based on exchangeable acidity, use a conversion factor to compensate for part of the limestone spent on neutralizing the H^+ that dissociates from the functional groups of organic matter, clay, minerals, and oxides (Kaminski et al., 2007) to avoid underdosing and meet liming objectives.

In the savannah domains of the state of Roraima, the arable soils are found on the flattened surfaces of the central and northeastern regions, where deep, weathered, and not very fertile soils predominate, represented by Latossolos and Argissolos (Vale Júnior and Schaefer, 2010). Due to their mineralogical composition and sedimentary origin, the soils have low pH values, low sum of bases and base saturation, and low activity of the clay fraction (Benedetti et al., 2011). The agricultural use of these soils depends on investments in correcting their natural fertility, adequate fertilization of crops, and an understanding of their physical properties (Melo et al., 2003).

The lime requirement (LR) definition for the state of Roraima still follows consolidated methods for other regions. The aim was, therefore, to evaluate the methods used to determine the LR in three classes of low CEC soils in the Amazon savannah, with corn as the indicator crop.

2. Material and Methods

The experiment was conducted in the experimental area of the Center for Agricultural Sciences (CCA) of the Federal University of Roraima - UFRR, in Boa Vista - RR. The climate of the region is Aw-type, according to the Köppen classification, belonging to the Tropical Rainy climate domain, hot and humid, with a clear dry period (Barni et al., 2020).

For the study, samples were collected from three soil classes, already described and present on the Cauamé campus of the Federal University of Roraima, in the 0-0.20 m layer. The three soil profiles selected are classified as Latossolo Amarelo Distrocoeso Típico (LA), Latossolo Vermelho Distrófico (LV), and Argissolo Vermelho-Amarelo Distrófico (PVA) (Benedetti et al., 2011).

After field collection, the soils were air dried, pulverized, and sieved (4 mm mesh), the field capacity was determined using the drainage method, and the soil moisture was determined using the oven drying method at 105 ºC. Part of the sample from each soil class was sent to the laboratory for physical and chemical analysis. A randomized block design was adopted for the experiment in a 3x5 factorial scheme, with four replications, where each soil class received five lime doses.

Table 1 shows the soil classes and their chemical and physical attributes. The pH in water and KCl (1 mol L^{-1} KCl solution) were measured using soil:solution ratios of 1:2.5 (weight/volume) (Embrapa, 1997). The exchangeable Ca, Mg, and Al levels were extracted using a 1 mol L^{-1} KCl solution. Al^{3+} was measured using a standardized NaOH base. Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry (Embrapa, 1997). K and P were extracted using the Mehlich-1 extractant (HCl 0.05 mol L^{-1} and H_2SO_4 0.0125 mol L^{-1}). Flame photometry was used to determine K, and calorimetry to determine P. Potential acidity (H + Al) was extracted in a 1.0 mol L^{-1} calcium acetate solution at pH 7.0 and quantified using standardized NaOH (Embrapa, 1997). The sum of bases (SB), cation exchange capacity at pH 7 (CEC), and base saturation (BS) were estimated from the results of the sorption complex. Particle size distribution was determined using the pipette method (Embrapa, 1997).

P-rem was determined in solution after 5 cm^3 of soil had been shaken for 1 h with 50 mL of $CaCl_2$ 0.01 mol L^{-1} (Alvarez et al., 2000). The organic matter content of the soil was determined by oxidizing potassium dichromate 0.2 mol L^{-1} (Embrapa, 2009).

Based on the data in Table 1, the liming requirements were calculated using the method of neutralizing exchangeable acidity (Catani and Alonso, 1969) to define the minimum dose. To establish the highest dose, the neutralization of exchangeable acidity and elevation of Ca and Mg were used (Alvarez and Ribeiro, 1999). The values obtained were converted into doses per hectare and calculated for the volume of the pots (Table 2), which had a capacity of 11 liters.

The intermediate doses were defined at equal intervals and transformed into values equivalent to the recommendation using the base saturation method (Raij, 1981) (Table 2). A mixture of $CaCO_3$ (p.a.) and $MgCO_3$ (p.a.) in a 4:1 ratio was used as the corrective agent with an ECCE of 100%. The experimental unit was a black polyethylene pot with a volume of 11 dm^3, filled with soil and a corn plant. Before planting the corn, liming was conducted by manually incorporating lime into the entire soil volume in each pot. Water was added to maintain humidity at nearly 80% of field capacity. The pots were kept in a protected environment, and the soil from each class that had received the lowest lime dose was sampled weekly to determine the pH. At 21 days after the start of incubation, it was found that the pH of the sampled soils had reached a value equal to or greater than 5.5, and incubation ended. A soil sample was also taken from all the units to determine the pH on this date. This sampling was repeated three more times, according to the corn growth stages (V4, V10, and V16-R1), for the chemical analysis of macronutrients and soil fertility assessment during the crop cycle (Table 3).

Before sowing the corn, 220 kg ha^{-1} of triple superphosphate was applied, with the application concentrated in the center line of the pot at a depth of approximately 5 cm. Also, 50 kg ha^{-1} of urea and 40 kg ha^{-1} of potassium chloride were diluted in water and applied over the entire surface of pots, and 50 kg ha^{-1} of FTE Br was homogenized over the entire soil volume. The corn hybrid 30F35VYHR® was sown using three seeds per pot, and after ten days, the seedlings were thinned out, leaving the most vigorous. Throughout the crop cycle, three topdressings were conducted at V3 (300 kg ha^{-1} of ammonium sulfate, 70 kg ha^{-1} of potassium chloride), V7, and V9 (100 kg ha^{-1} of urea, 30 kg ha^{-1} of potassium chloride)

Table 1. Physical and chemical attributes of the soils studied.

Soil	pH		P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC_{pH7}	BS
	H_2O	KCl	mg kg^{-1}		cmol$_c$ dm^{-3}					(%)
LA	4.83	3.95	0.9	12	0.24	0.08	0.68	2.30	2.65	13.2
LV	5.10	4.17	0.7	-	0.16	0.16	0.29	1.60	1.92	16.7
PVA	4.89	4.02	0.7	2	0.15	0.08	0.29	1.10	1.34	17.9

Soil	Clay (%)	Silt (%)	Sand (%)	P-rem (mg L^{-1})	SOM (dag kg^{-1})
LA	27.4	7.9	64.7	35.3	0.53
LV	19.9	8.6	71.5	42.2	0.66
PVA	12.7	4.8	82.5	47.8	0.26

LA: Latossolo Amarelo Distrocoeso Típico. LV: Latossolo Vermelho Distrófico. PVA: Argissolo Vermelho-Amarelo Distrófico.

Table 2. Equivalent doses of calcium carbonate ($CaCO_3$) applied per pot for soil correction and expected base saturation values in the soils for each liming recommendation.

Soil	Dose (kg ha^{-1}) and Base saturation expected (BS%)				
	T1[2/]	T2	T3	T4	T5
LA[1/]	910 (48[3/])	1220 (59)	1531 (71)	1842 (83)	2153 (94)
LV	434 (39)	773 (57)	1113 (75)	1452 (92)	1792 (110)
PVA	434 (50)	786 (77)	1138 (103)	1490 (129)	1842 (155)

[1/]LA: Latossolo Amarelo Distrocoeso Típico. LV: Latossolo Vermelho Distrófico. PVA: Argissolo Vermelho-Amarelo Distrófico. [2/]T1: Exchangeable acidity neutralization method ($LR = 0.08+1.22*Al^{3+}$) Catani & Alonso (1969). T2: T1 + 25% of the difference between T1 and T5. T3: T1 + 50% of the difference between T1 and T5. T4: T1 + 75 % of the difference between T1 and T5. T5: method for neutralizing exchangeable acidity and raising Ca and Mg ($LR = \{Y [Al^{3+} - (mt \times t/100)]\} + [x -(Ca^{2+} + Mg^{2+})]$) Alvarez & Ribeiro (1999), where Y is determined by the equation Y = 4.002 - 0.125901 P-rem + 0.001205 P-rem2 - 0.00000362 P-rem3, t is the effective cation exchange capacity, X is equal to 2 cmol$_c$ dm^{-3} and mt is equal to 15 for the corn crop. [3/]Expected base saturation for the dose applied within each soil.

Table 3. Summary of the main operations and evaluations conducted.

Date	DAE[1/]	Operation/Evaluation	Growth stage
06/04/22	_	Liming	_
06/25/22	_	Soil sampling/Sowing/Fertilization	_
06/29/22	_	Emergence	Ve
07/06/22	7	Topdressing	V3
07/13/22	14	Soil sampling	V4
07/20/22	21	Topdressing	V7
08/03/22	35	Topdressing	V9
08/06/22	38	Soil sampling	V10
08/24/22	56	Soil sampling	V16-R1

[1/]Days after emergence.

Fertilization recommendations were based on and adapted from Sousa and Lobato (2004). Evaluations were made 56 days after the crop emerged when the plants were at the R1 stage. The shoot was separated from the roots to assess the plant dry matter. The shoots were washed, separated into leaves and stalks, and taken to an air-forced circulation oven to be dried at 65 °C until they reached a constant weight, and then the dry matter was quantified.

The same procedure was conducted on the roots after manually separating them from the soil, washing them in tap water under pressure, and sieving them through a 2 mm mesh sieve. The results were subjected to analysis of variance, and the means were compared using the Tukey test at 5% probability or regression analysis.

3. Results and Discussion

Considering the average contents in the period from 21 days after incubation to the final sampling, the treatments with liming recommendations higher than T3 neutralized the exchangeable Al^{3+} in the LA and LV, while in the PVA, all the doses applied were effective in neutralizing Al^{3+} (Figure 1A). It was expected that the lowest lime dose (T1) would neutralize the exchangeable Al^{+} in the soils, as proposed by Catani and Alonso (1969), to raise the pH (H_2O) of the soil to 5.7.

However, the mixture of corrective agents was underdosed in the more clayey soil. Likely, the method proposed by Sousa and Lobato (2004) for neutralizing aluminum in Cerrado soils is more effective, as it increases the liming recommendation using the equation LR = 2 x Al^{3+}, which is ideal for soils with Al^{3+}. The Catani and Alonso (1969) method provides for the correction of soils without Al^{3+}, intending to desorb non-exchangeable H, increasing the effective CEC and the Ca and Mg contents. However, it underestimates the dose in soils with Al^{3+}.

The average pH for all liming recommendations and soil classes was close to the range suitable for the growth of most crops, between 5.5 and 6.5. However, treatments with a lime dose equal to or higher than T4 achieved pH values close to (LA) or above 7 (LV and PVA) (Figure 1B). The results observed align with Alvarez and Ribeiro (1999), who predicted this behavior in low CEC soils, leading to over-calcification and its negative effects. The Ca and Mg contents increased with the increase in the doses of correctives in the soils, but with average contents lower than those considered critical sufficiency of 1.5 $cmol_c\ dm^{-3}$ for Ca and 0.5 $cmol_c\ dm^{-3}$ for Mg (Figure 2A and 2B) recommended by Alvarez and Ribeiro (1999).

Considering the low CEC of the soils, only the LV (Table 1) would have charges to maintain 2 $cmol_c\ dm^{-3}$ of Ca and 0.6 $cmol_c\ dm^{-3}$ of Mg, to the detriment of the other bases. In LA and LV soils, with T5, the Ca+Mg content reached 2 $cmol_c\ dm^{-3}$ 21 days after liming. Still, it was ineffective in maintaining this average soil level during the period evaluated (Figure 2C) due to competition with other bases (K and $NH4^{+}$) from fertilization and leaching. The dystrophic condition of the soils was not altered by the lower doses of lime (T1 and T2), with base saturation values between 25 and 50%. In treatments equal to or greater than T3, base saturation reached 50 to 80% (Figure 2D). These values were lower than expected, especially for PVA, where base saturation was expected to be close to 100% (Table 2).

The average available K content was below 0.08 $cmol_c\ dm^{-3}$, with most of the values being below 0.05 $cmol_c\ dm^{-3}$, falling within the medium and low interpretation ranges according to Vilela et al. (2004) for Cerrado soils with a CEC less than 4 $cmol_c\ dm^{-3}$ (Figure 3A). The P contents were dispersed, indicating no influence from liming, probably due to the localized application in a row, while sampling was conducted at random points in the pots (Figure 3B). It should be considered that P in acidic soils remains strongly retained by iron and aluminum hydroxides, while in alkaline soils, it is held in less soluble magnesium and calcium mineral compounds, making it poorly mobile in the soil and unavailable to plants when the pH of the soil solution is below or above 6 and 6.5, respectively (Ibrahim et al., 2022).

In LV and PVA soils, the average Ca/Mg ratio values ranged from 4 to 6/1 at lime doses equal to or greater than T2. In LA, the Ca/Mg ratio ranged from 5 to 6/1 (Figure 4A). These results may be due to the greater outflow of Mg from the system, either through leaching or plant absorption. The use of the Ca/Mg ratio is still debated and is not unequivocally defined (Chaganti and Culman, 2017; Culman et al., 2021; Kopittke and Menzies, 2007), but better results have been found when Ca predominates over Mg (Silva, 1980; Lange et al., 2021; Veloso et al., 2001) up to a ratio of 10:1 while maintaining a minimum content of 0.5 $cmol_c\ dm^{-3}$ for Mg (Sousa and Lobato, 2004).

As expected, the average concentration of Ca and Mg in the CEC throughout the experiment increased as the recommended doses increased (Figure 5A and 5B). For K, the average values in the CEC (31 to 81 days after lime application) were below 3% (Figure 5C). According to Culman et al. (2021), the most desirable ranges of the CEC saturation ratio with basic cations are 60-75% for Ca, 10-20% for Mg, and 3-5% for K, values close to those obtained by liming at dose T5 for all soils.

The average ratio between the sum of the exchangeable Ca and Mg contents and K $(Ca^{2+}+Mg^{2+})/K^{+}$ from 31 to 81 days after the lime application was higher than 30 for the correction of the three soils with doses equal to or higher than T3. Values of this ratio above 30 are considered high, according to Sousa and Lobato (2004).

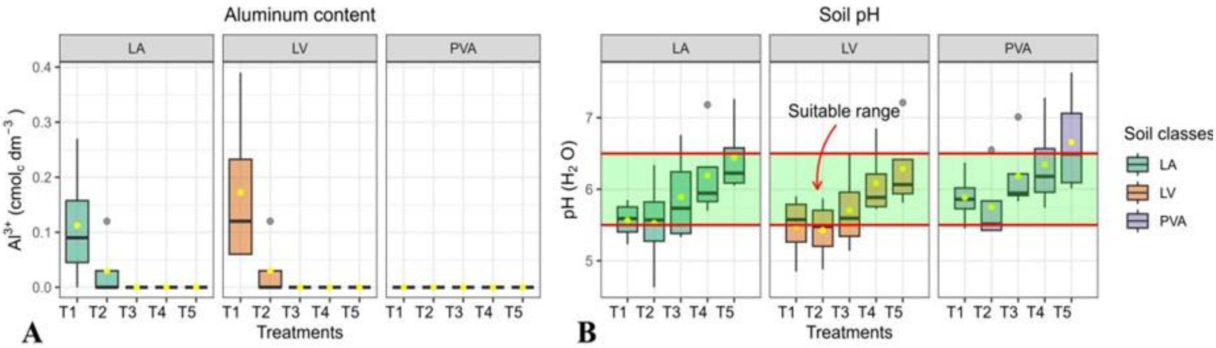

Figure 1. Distribution of aluminum content (A) and soil pH (B) according to the liming based on different lime requirements determination methods and soil classes.

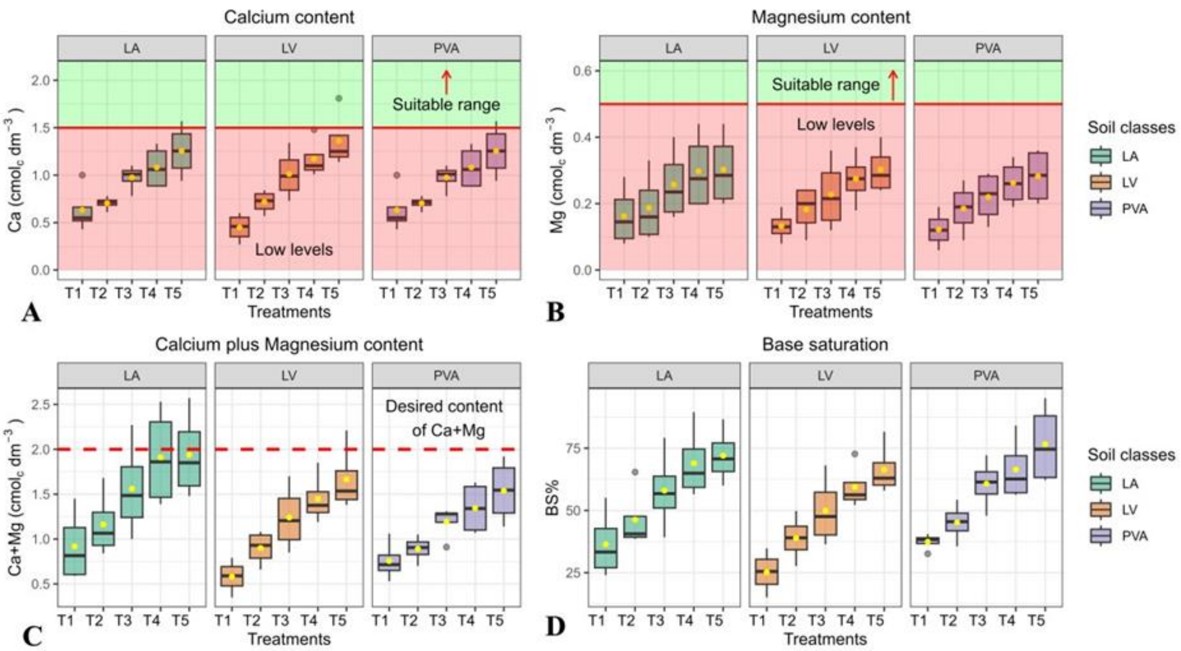

Figure 2. Distribution of calcium content (A), magnesium content (B), sum of calcium and magnesium content (C), and base saturation of CEC (D) according to the liming based on different lime requirements determination methods and soil classes.

At doses equal to or lower than T2, this ratio was between 15 and 25, 20 and 30, and 18 and 30 in the LA, LV, and PVA soils, respectively (Figure 5D), close to 20 to 30 considered adequate by Sousa and Lobato (2004). The biological response to the treatments, assessed by the total dry matter of the corn plant, ranged among soils. There was a significant interaction among the three soil classes and liming recommendation methods for the total dry matter production variable.

The treatments with different recommended lime doses did not cause significant changes in the total dry matter production of corn in LA soil; however, in LV and PVA soils, there was a significant decrease as the recommended lime dose for each soil increased (Table 4). A significant decrease in corn grain yield with increased lime doses was also observed by Liebhardt (1979) in sandy soils with low CEC (4 $cmol_c\ kg^{-1}$) in the coastal plain of the state of Delaware (USA) with the application of calcitic limestone (31% Ca, 1% Mg), dolomitic limestone (21% Ca, 12% Mg) and a mixture of both (29% Ca, 6% Mg); it increased the soil pH from 5.7 to 6.4.

In later studies, Liebhardt (1981) suggested adopting a liming program for these weakly buffered soils to keep the soil pH between 5.5 and 6.0, values similar to those obtained in this study using the LR determination method based on neutralizing exchangeable acidity. According to the authors, in the conditions of sandy soil and low CEC studied by Liebhardt (1981), the cause of the reduction in productivity was probably due to the lower absorption of manganese by the plants in the higher pH conditions. Considering that the $(Ca^{2+}+Mg^{2+})/K^{+}$ ratio was within the appropriate range, being close to the values of 20 to 30 considered adequate by Sousa and Lobato (2004), there are other hypotheses for the low results of dry matter of corn.

In Brazilian Cerrado soils, the most common micronutrient deficiencies are B, Cu, and Zn, with Zn deficiency evident in conditions of base saturation greater than 60%, even in perennial crops (Sousa and Lobato, 2004). As Zn availability is highly reduced in sandy textured soils (lower CEC) and with a pH above 6 (Suganya et al., 2020), its deficiency may be one of the factors involved in the reduction of dry matter accumulation in the treatments with higher lime doses, corroborated by the substantial positive correlation (correlation coefficient (r) equal to 0.76 with statistical significance validated at a significance level of α equal to 0.05) obtained between total dry matter production and CEC_{pH7} of the soils in our study.

This occurs too in the results obtained by Agyin-Birikorang et al. (2022), where a balanced nutrient treatment, but without Zn, associated with the lime application resulted in a 30% decrease in corn grain yield compared to complete balanced fertilization, in acid soils in northern Ghana.

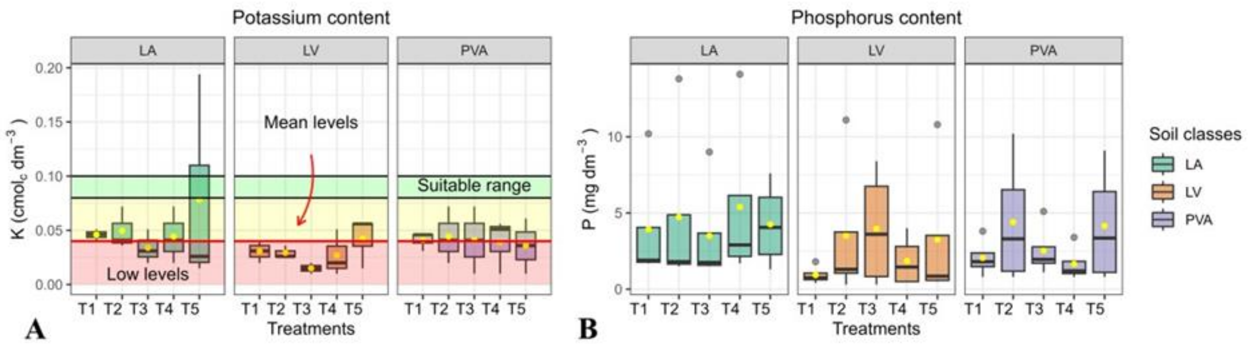

Figure 3. Distribution of potassium (A) and phosphorus (B) contents according to the liming based on different lime requirements determination methods and soil classes between 31 and 81 days after liming

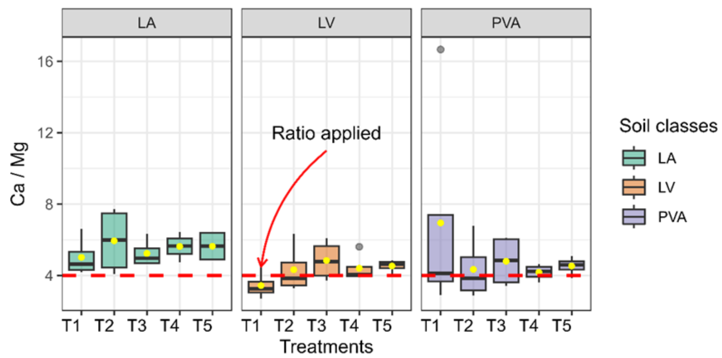

Figure 4. Ca/Mg ratio according to the liming based on different lime requirements determination methods and soil classes.

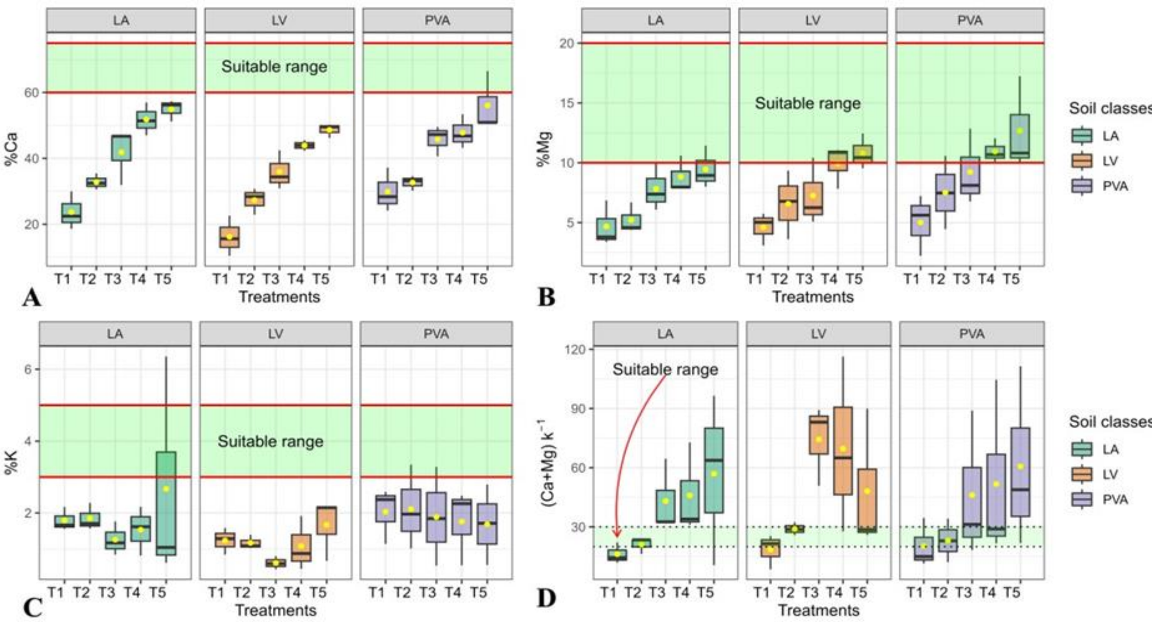

Figure 5. Calcium (A), magnesium (B), and potassium saturation in the total soil CEC (C) and the ratio $(Ca^{2+}+Mg^{2+})/K^{+}$ (D) according to the liming based on different lime requirements determination methods and soil classes between 31 and 81 days after liming.

The increase or non-decrease in the productive response of crops under different lime doses in soils was expected for all soils, not just LA, considering the contribution of Ca and Mg made by liming and the low levels of these nutrients in the soil. This response was obtained in more clayey soils than LA in research carried out in the north of the Brazilian Amazon, which showed that increasing the dose of lime resulted in a linear increase in dry matter production in pepper (Cardoso et al., 2014) and sugar cane (Silva et al., 2014), and also indicated the possibility of a response for applications higher than 2,000 and 6,000 kg ha^{-1} of lime, respectively.

From the point of view of base balance, for the LV and PVA soils, the highest dry matter production occurred in the treatments with the lowest dose applied (T1 and T2), whose average ratio $(Ca^{2+}+Mg^{2+})/K^{+}$ was between 18 and 30. This result is similar to that of Veloso et al. (2001), who obtained the highest dry matter production of corn harvested 45 days after planting, with a ratio of 19.8 for the crop grown in pots under greenhouse conditions.

The relationships between basic cations during the period when the effect of liming was evaluated (from 31 to 81 days after lime application) showed a negative correlation for the LV and PVA soils (correlation coefficient (r) equal to -0.59 with statistical significance validated at a significance level of α equal to 0.05) with total dry matter production. However, this value is lower (correlation coefficient (r) equal to -0.45 with statistical significance validated with a significance level of α equal to 0.05) if the correlation includes the LA results since this soil showed productive stability under different ratio values among these cations.

A predictive multiple regression model, which considers the cation exchange capacity (CEC_{pH7}) and the ratio between cations $(Ca^{2+}+Mg^{2+})/K^{+}$), provided the best explanation for the behavior of plant dry matter production for the three soils evaluated, considering the period from 31 to 81 days after lime application (Figure 6). This relationship is probably established because when there is an increase in the lime dose (Ca and Mg) compared to potassium (K) or other cationic nutrients (Zn, Cu, Co, Ni, Fe, and Mn) supplied at constant doses, saturation of the exchange sites can occur, which prevents adequate absorption of these other cations. This saturation of the exchange sites will be greater as the lower cation exchange capacity (CEC) of soil.

Considering the conditions under which this study was conducted, it was not possible to determine an unequivocal lime requirement determination method for liming the soils of Roraima. However, the results indicate the need to consider texture and CEC when defining lime doses. In the case of the more clayey soil with a higher CEC, as the different liming recommendations did not reduce the initial dry matter production of the corn crop, the methodology for lime requirement calculation can be more flexible, allowing the use of limestone as a source of Ca and Mg and raising base saturation to levels of around 60%, as recommended by Fageria (2001) for corn growing in Brazilian Cerrado soils.

Table 4. Total dry matter of corn plants according to the liming based on different lime requirements determination methods and soil classes.

	Total dry matter (g per plant)				
Soil/Treatments	T1	T2	T3	T4	T5
LA	100.2 aA	89.4 aA	104.6 aA	99.5 aA	104.6 aA
LV	109.9 aA	81.5 aA	47.2 bB	47.0 bB	23.6 bC
PVA	60.3 bA	41.7 bAB	34.2 bB	28.7 bBC	15.1 bC

Means followed by the same lowercase letter in the columns and uppercase letter in the lines do not differ by the Tukey test ($p \leq 0.05$). CV:13.76. LA: Latossolo Amarelo Distrocoeso Típico. LV: Latossolo Vermelho Distrófico. PVA: Argissolo Vermelho-Amarelo Distrófico. [2/]T1: Exchangeable acidity neutralization method ($LR = 0.08+1.22*Al^{3+}$) Catani & Alonso (1969). T2: T1 + 25% of the difference between T1 and T5. T3: T1 + 50% of the difference between T1 and T5. T4: T1 + 75 % of the difference between T1 and T5. T5: method for neutralizing exchangeable acidity and raising Ca and Mg ($LR = \{Y [Al^{3+} - (mt \times t/100)]\} + [x - (Ca^{2+} + Mg^{2+})]$) Alvarez & Ribeiro (1999), where Y is determined by the equation Y = 4.002 - 0.125901 P-rem + 0.001205 P-rem2 - 0.00000362 P-rem3, t is the effective cation exchange capacity, X is equal to 2 $cmol_c\ dm^{-3}$ and mt is equal to 15 for the corn crop. [3]/Expected base saturation for the dose applied within each soil.

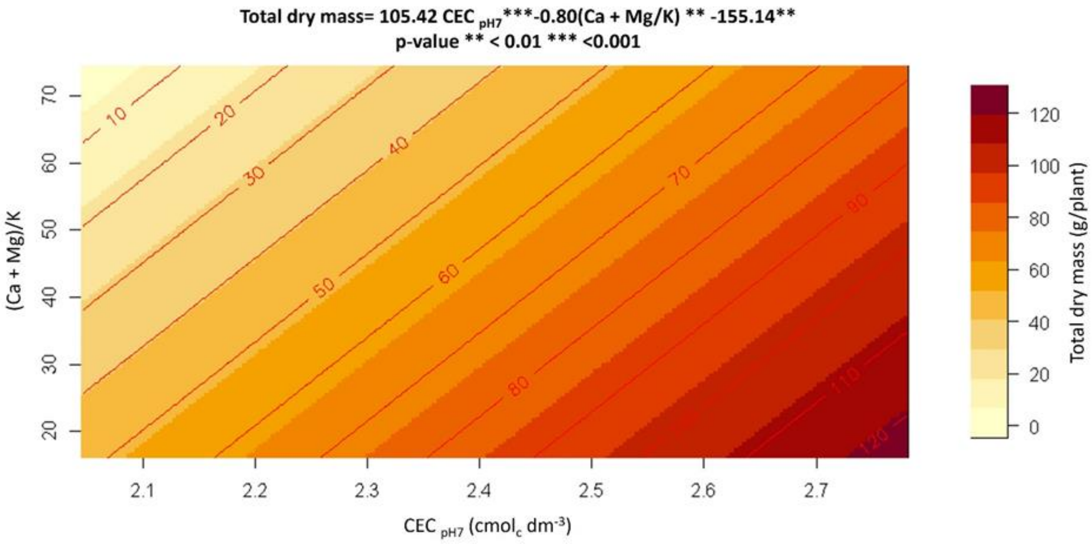

Figure 6. Total dry matter production of corn according to the $(Ca^{2+}+Mg^{2+})/K^{+}$ratio and CEC_{pH7} of the soil between 31 and 81 days after lime application.

Lower lime doses in more sandy soils with low CEC led to higher dry matter production, indicating the need to pay attention to the chemical changes caused by liming in this soil type. As the improvement in the soil chemical attributes (base saturation, pH, and neutralization of exchangeable Al) was not related to the increase in total dry matter production of corn during the period evaluated, other factors, probably related to over-liming, may have affected dry matter production. Therefore, the initial aim of liming these soils should be to raise the pH and neutralize aluminum, followed by the supply of Ca and Mg, considering the effects of raising the pH on the availability of other nutrients.

Fageria and Baligar (2008) pointed out that over-liming in tropical soils can lead to deficiencies in micronutrients such as Fe, Mn, Zn, Cu, and B, especially in sandy soils. This condition requires that, in parallel with liming, micronutrient correction is conducted in the soil or complementary fertilization during the cultivation of crops, possibly by foliar application.

4. Conclusions

For soils with more than 20% clay, methods of recommending lime that guarantee the supply of calcium and magnesium to the crop and neutralize toxic forms of aluminum are suitable since they improve soil fertility and, as a result, the response of the corn crop. In soils with less than 20% clay (more sandy), the method based on neutralizing exchangeable aluminum effectively raises pH and reduces exchangeable Al. However, it does not guarantee adequate levels of calcium and magnesium in the soil to develop the complete corn cycle. It may be necessary to use soluble sources of Ca and Mg without raising the pH.

Authors' Contribution

Maurício Lourenzoni Augusti and Iasmin Kele Amâncio Costa da Silva contributed mainly to the statistical analysis, interpretation of the results, and manuscript writing. Richard Alcides Álvarez Molina and Cássia Rejane do Nascimento contributed mainly to planning, setting up, and conducting the experiment and collecting the data. Sandra Cátia Pereira Uchoa and Paulo Roberto Ribeiro Rocha contributed mainly to the strategic orientation of the research, organization, and critical revision of the manuscript. All the authors participated in experimenting and revised the final version of the manuscript.

Bibliographic References

Agyin-Birikorang, S., Adu-Gyamfi, R., Tindjina, I., Fugice, J., Dauda, H.W., Singh, U., Sanabria, J. 2022. Ameliorating incongruent effects of balanced fertilization on maize productivity in strongly acid soils with liming. Journal of Plant Nutrition, 45(17), 2597–2610. DOI: https://doi.org/10.1080/01904167.2022.2064293.

Alvarez, V.V.H., Novais, R.F., Dias, L.E., Oliveira, J.A. 2000. Determinação e uso do fósforo remanescente. Boletim Informativo da Sociedade Brasileira de Ciência do Solo, 25, 27–34.

Alvarez, V.H.V., RIBEIRO, A.C., 1999. Calagem. In: Ribeiro, A.C., Guimarães, P.T.G., Alvarez V.H.V. (Eds.), Recomendação para o uso de corretivos e fertilizantes em Minas Gerais - 5ª aproximação. Comissão de Fertilidade do Solo do Estado de Minas Gerais, Viçosa, p. 43-60.

Barni, P.E., Barbosa, R.I., Xaud, H.A.M., Xaud, M.R., Fearnside, P.M., 2020. Precipitação no extremo norte da Amazônia: distribuição espacial no estado de Roraima, Brasil. Sociedade Natureza, 32, 439-456. DOI: https://doi.org/10.14393/sn-v32-2020-52769.

Benedetti, U.G., Vale Júnior, J.F., Schaefer, C.E.G.R., Melo, V.F., Uchôa, S.C.P., 2011. Gênese, química e mineralogia de solos derivados de sedimentos pliopleistocênicos e de rochas vulcânicas básicas em Roraima, Norte Amazônico. Revista Brasileira de Ciência do Solo, 35(2), 299–312. DOI: https://doi.org/10.1590/S0100-06832011000200002.

Cardoso, A.A.S., Santos, J.Z.L., Tucci, C.A.F., Barbosa, T.M.B. 2014. Acúmulo de nutrientes e crescimento da pimenta-de-cheiro em função de doses de calcário. Revista Agro@mbiente On-Line, 8(2), 165-174. DOI: https://doi.org/10.18227/1982-8470ragro.v8i2.1881.

Carneiro, J.S.C., Alves de Sousa, S., Nikkel, M., Teixeira Deusdará, T., Franciely Machado, Â., Ribeiro da Silva, R., 2018. Supercalagem: alterações em atributos químicos de um Latossolo Vermelho amarelo distrófico. Revista de Ciências Agroambientais, 16(1), 31–38. https://doi.org/10.5327/rcaa.v16i1.1522.

Catani, R.A., Alonso, O., 1969. Avaliação da exigência de calcário do solo. Anais da Escola Superior de Agricultura Luiz de Queiroz, 26, 141–156. DOI: https://doi.org/10.1590/S0071-12761969000100013.

Chaganti, V.N., Culman, S.W., 2017. Historical Perspective of Soil Balancing Theory and Identifying Knowledge Gaps: A Review. Crop, Forage Turfgrass Management, 3(1), 1-7. DOI: https://doi.org/10.2134/cftm2016.10.0072.

Culman, S.W., Brock, C., Doohan, D., Jackson-Smith, D., Herms, C., Chaganti, V.N., Kleinhenz, M., Sprunger, C.D., Spargo, J. 2021. Base cation saturation ratios vs. sufficiency level of nutrients: A false dichotomy in practice. Agronomy Journal, 113(6), 5623–5634. DOI: https://doi.org/10.1002/agj2.20787.

EMBRAPA. EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. 1997. Manual de métodos de análises do solo, 2 ed. Centro Nacional de Pesquisa de Solos, Rio de Janeiro.

EMBRAPA. EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. 2009. Manual de análises químicas de solos, plantas e fertilizantes. In: Embrapa Informação Tecnológica, 2 ed. revisada ampliada. Embrapa Informação Tecnológica, Brasília.

Fageria, N.K. 2001. Resposta de arroz de terras altas, feijão, milho e soja à saturação por base em solo de cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental, 5(3), 416–424. DOI: https://doi.org/10.1590/S1415-43662001000300009

Fageria, N.K., Baligar, V.C. 2008. Ameliorating Soil Acidity of Tropical Oxisols by Liming for sustainable crop production. Advances in Agronomy, 99, 345-399. DOI: https://doi.org/10.1016/S0065-2113(08)00407-0.

Guarçoni, A., Sobreira, F.M., 2017. Classical methods and calculation algorithms for determining lime requirements. Revista Brasileira de Ciência do Solo, 41, 1-11. DOI: https://doi.org/10.1590/18069657rbcs20160069.

Harter, R.D. 2007. Acid soils of the tropics. ECHO Technical Note, North Fort Myers ECHO, 11.

Holland, J.E., Bennett, A.E., Newton, A.C., White, P.J., McKenzie, B.M., George, T.S., Pakeman, R.J., Bailey, J.S., Fornara, D.A., Hayes, R.C., 2018. Liming impacts on soils, crops and biodiversity in the UK: A review. Science of The Total Environment, (610–611), 316–332. DOI: https://doi.org/10.1016/J.SCITOTENV.2017.08.020.

Ibrahim, M., Iqbal, M., Tang, Yu-Ting, Khan, S., Guan, Dong-Xing, Li, G. 2022. Phosphorus Mobilization in Plant–Soil Environments and Inspired Strategies for Managing Phosphorus: A Review. Agronomy, 12(10), 2539. DOI: https://doi.org/10.3390/agronomy12102539.

Kaminski, J., Silva, L.S., Ceretta, C.A., Rheinheimer, D.S., 2007. Acidez e calagem no sul do Brasil: Aspectos históricos e perspectivas futuras. Tópicos em ciência do solo. Sociedade Brasileira de Ciência do Solo, Viçosa, 5, 307–332.

Kopittke, P.M., Menzies, N.W. 2007. A Review of the Use of the Basic Cation Saturation Ratio and the “Ideal” Soil. Soil Science Society of America Journal, 71(2), 259–265. DOI: https://doi.org/10.2136/sssaj2006.0186.

Lange, A., Cavalli, E., Spaziani Pereira, C., Vinicius Chapla, M., Da Silva Freddi, O., 2021. Relações cálcio: magnésio e características químicas do solo sob cultivo de soja e milho. Nativa, 9(3), 294–301. DOI: https://doi.org/10.31413/nativa.v9i3.11526.

Liebhardt, W.C., 1979. Corn Yield as Affected by Lime Rate and Type on a Coastal Plain Soil. Soil Science Society of

America Journal, 43(5), 985–988. DOI: https://doi.org/10.2136/sssaj1979.03615995004300050035x.

Liebhardt, W.C., 1981. The Basic Cation Saturation Ratio Concept and Lime and Potassium Recommendations on Delaware's Coastal Plain Soils. Soil Science Society of America Journal, 45(3), 544–549. DOI: https://doi.org/10.2136/sssaj1981.03615995004500030022x.

Melo, V.F., Gianluppi, D., Uchôa, S.C.P. 2003. Características edafológicas dos solos do estado de Roraima. Embrapa Roraima, Boa Vista.

Raij, B. van. 1981. Avaliação da fertilidade do solo. Associação Brasileira para Pesquisa da Potassa e do Fosfato, Piracicaba.

Raij, B. van, 2011. Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute, Piracicaba.

SBCS. SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO. 2004. Fertilidade do Solo. Comissão de Química e Fertilidade do Solo. In: Manual de adubação e calagem para os estados do Rio Grande do Sul e Santa Catarina. 10 ed. SBCS, Porto Alegre, p. 57-71.

Silva, J.E., 1980. Balanço de cálcio e magnésio e desenvolvimento do milho em solos sob cerrado. Pesquisa Agropecuaria Brasileira, 15(3), 329–333.

Silva, S.V., Zilton, J., Santos, L., Alberto, C., Tucci, F., Afonso, A., Cardoso, S. 2014. Efeito de doses de calcário e cultivares na produtividade e qualidade agroindustrial da cana-de-açúcar em solo da Amazônia. Revista Agro@mbiente On-Line, 8(3), 298–305. DOI: https://doi.org/ :10.5327/Z1982-8470201400031785.

Sousa. D.M.G., Lobato, E. (org.). Cerrado: correção do solo e adubação. Embrapa Informação Tecnológica, Brasília.

Sousa, D.M.G., Lobato, E. 2004. Correção da acidez do solo. In: Sousa, D.M.G., Lobato, E. (org.). Cerrado: correção do solo e adubação. Embrapa Informação Tecnológica, Brasília, p. 81–96.

Sousa, D.M.G., Miranda, L.N., Oliveira, S.A. 2007. Acidez do solo e sua correção. In: Novais, R.F., Alvarez, V.H.V., Barros, N.F., Fontes, R.L.F., Cantarutti, R.B., Neves, J.C.L. (Eds.), Fertilidade do solo. SBCS, Viçosa. p. 205–276.

Suganya, A., Saravanan, A., Manivannan, N. 2020. Role of Zinc Nutrition for Increasing Zinc Availability, Uptake, Yield, and Quality of Maize (Zea Mays L.) Grains: An Overview. Communications in Soil Science and Plant Analysis, 51(15), 2001–2021. DOI: https://doi.org/10.1080/00103624.2020.1820030.

Teixeira, W.G., Víctor Hugo Alvarez, V., Neves, J.C.L., 2020. New methods for estimating lime requirement to attain desirable pH values in Brazilian soils. Revista Brasileira de Ciência do Solo, 44, 1-21. DOI: https://doi.org/10.36783/18069657rbcs20200008.

Vale Júnior, J.F., Schaefer, C. 2010. Solos sob savanas de Roraima: gênese, classificação e relações ambientais. Gráfica Ioris, Boa Vista.

Veloso, C.A.C., Souza, F.R.S., Pereira, W.L.M., Tenório, A.R.M. 2001. Relações cálcio, magnésio e potássio sobre a produção de matéria seca de milho. Acta Amazonica, 31(2), 193–193. DOI: https://doi.org/10.1590/1809-43922001312204

Vilela, L., Sousa, D.M.G., Silva, J.E. 2004. Adubação potássica. In: Sousa. D. M. G., Lobato, E. (org.). Cerrado: correção do solo e adubação. Embrapa Informação Tecnológica, Brasília. p. 169 –182.