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Liming in soils with plinthic materials of the Brazilian Savanna: potentials and limitations

Olavo da Costa Leite[1], Saulo de Oliveira lima[1*], João Henrique Silva da Luz[2]*, Rubens Ribeiro da Silva[1], Rodrigo Ribeiro Fidelis[1], Rodrigo de Castro Tavares[1], Juliana Barilli[1], Ângela Franciely Machado[1]

[1]Federal University of Tocantins, Campus Gurupi, Gurupi, TO, Brazil
[2]University of Sao Paulo, "Luiz de Queiroz" College of Agriculture, Piracicaba, SP, Brazil

***Corresponding author: saulolima@uft.edu.br or jhluz@usp.br**

Abstract

The expansion of agriculture has been taking place in marginal soils with low productive potential, such as Plinthosols. The liming can increase the economic and environmental sustainability of agriculture. However, there are no studies on the dissolution or recommendation of limestone for Plinthosols. The objective was to evaluate the effect of limestone doses on the chemical attributes of three soils with different gravel contents (ironstone concretions). The soils were collected (0-20 cm layer) in native areas of the central region of the Brazilian Savanna. They were classified as Red-Yellow Latosol (RYO) and two Concretionary Pétric Plinthosol (with 29% [CPP-29] and 72.8% [CPP-72] of soil volume with gravel). A factorial scheme (3x6) with the three soils (RYO, CPP-29, and CPP-72), six limestone doses, and four replications. The evolution of pH was verified at 10, 20, 30, and 40 days after the beginning of incubation (DAI), and determined the chemical attributes (Al, H+Al, Ca, Mg, BS, V%, P, and K) at 40 DAI. The doses to reach pH 6 were 1.4 t ha^{-1} for RYO, 3.9 t ha^{-1} for CPP-29, and 2.7 t ha^{-1} for CPP-72. Al^{3+} neutralization was 100% with doses above 3.5, 2.5 and 0.5 t ha^{-1} for CPP-29, CPP-72, RYO. There was a significant increase in Ca and Mg contents in all soils. However, the Soil CPP-72 did not reach a critical level for Ca (>2.41 $cmol_c$ dm^{-3}) and Mg (>0.91 $cmol_c$ dm^{-3}) for Plinthosols with higher plinthite content. Thus, we recommend using agricultural practices that increase the capacity of the soil to retain and recycle nutrients.

Keywords: Plinthosol; limestone; ironstone concretions; soil fertility; Cerrado Region.
Abbreviations: RYO_Dystrophic Red-Yellow Latosol, CPP-29_Concretionary Petric Plinthosol endico with 29.3% gravel, CPP-72_ Concretionary Petric Plinthosol endico with 72.8% gravel, CEC_ cationic exchange capability, BS_ base sum, P-rem_ Phosphorus buffer capacity.

Introduction

Land expansion for agricultural production occurs in soils considered marginal and with low productive potential. This expansion is mainly encouraged by the price of commodities, availability, and the price of land. In Brazil, this is happening in the last agricultural frontier, called MATOPIBA (Brazilian states), in the Savanna biome (Almeida et al., 2020).
Plinthosols (WRB: World Reference Base for Soil Resources, 2015), or Plinthosols in Brazil (Santos et al., 2018), soils with excess gravel in their composition (Eze et al., 2014). Historically, they were considered unfit for agriculture due to physical and chemical limitations (low water retention and low natural fertility) (Santos et al., 2018). However, farmers are often increasingly inserting these soils into the production system, without scientific information or management practices aimed at sustainability, with low risks of soil degradation (Martins et al., 2018; Oluwatosin et al., 2019).
The global extent of Plinthosols is estimated at ~60 million hectares, with higher occurrence in tropical regions such as Brazil, Nigeria, China, and others (Eze et al., 2014; FAO, 2015). Plinthite consists of a mixture of clay material with low organic carbon, rich in iron, or iron and aluminum, with quartz grains and other minerals (Garcia et al., 2013).
The formation is always associated with processes that lead to the segregation, mobilization, and transport of Fe2+, either by the lateral flow of the infiltration waters or by the oscillations of the water table loaded with this element, precipitation, and concentration of iron compounds (laterization or plintization) (Santos et al., 2018; Yaro et al., 2006).
The reduction of moisture of these soils promotes irreversible hardening of plinthite, forming nodules (gravel) or plinthite ironstone concretions called petroplinthites (Martins et al., 2018). Gravel content in all horizons of these soils can range from 5 to 90% (Oluwatosin et al., 2019). Because of these characteristics, these soils have low soil quality (structure, texture, water retention, cation exchange capability) (Lopes and Guimarães-Guilherme, 2016; Santos et al., 2018), reduced total volume of soil exploited/used by the roots of agricultural. In the latter case, the reduction of the adequate depth of the soil directly affects the performance of crops in regions with the occurrence of Indian summer (short-term water stress), common in savannas regions (Alvares et al., 2013).

The practice of liming can effectively promote improvement in this soil (Almeida et al., 2020). Since the dredging increases the pH of the soil, it increases the levels of $Ca2^{+}$ and $Mg2^{+}$ and the saturation based on CEC on soil (Bossolani et al., 2021; Li et al., 2019; Novais et al., 2007). Consequently, it decreases the toxicities of $Al3^{+}$ and Mn favors root growth, enhancing crop yield (Carvalho et al., 2020; Neto et al., 2019). However, we did not find studies on cared soil with ironstone concretions (or Plinthosols).

Thus, we hypothesize that the limestone recommendation in this soil is underestimated due to the chemical analysis of the soil being performed only at the <2 mm (fine earth), overestimating nutrient content sums by not considering the total volume of the soil. The objective of this study was to evaluate the effect of limestone doses on the chemical attributes of three native soils with different ironstone concretions.

Results and discussion

Limestone dissolution and acidity correction

Plinthite contents strongly influenced the dissolution of limestone ($p < 0.05$), and only the Plinthosol with 72.8% gravel (CPP-72) did not reach the critical limits of Ca and Mg for agricultural cultivation, according to bulletins for the Brazilian Savanna (Ribeiro et al., 1999; Sousa and Lobato, 2004).

The evolution of pH was slightly faster ($p = 0.002$) for CPP-72, followed by CPP-29 and RYO (Fig. 1-A-B-C). The maximum pH value on the response surface occurred at 28.5 (± 0.2) days, regardless of soil ($p < 0.05$), at doses of 10, 8.04 and 7.79 t ha-1 of limestone with values of 7.05, 7.19 and 7.15 pH for CPP-29 ($p = 0.011$), RYO ($p < 0.0001$), CPP-72 ($p < 0.0001$), respectively. After the 28 days, at these same doses, there was a decrease in the pH to 6.73, 6.89, and 6.86 (i.e., -4.5, -4.2, and -4.1%), respectively. This is due to the buffering capacity of the soil, as well as the low solubility of limestone (0.0038 g L-1 CO32-), which has its dissolution, short-term, governed by the concentration of protons in the solution (Carvalho et al., 2020; Sousa and Lobato, 2004).

The maximum pH values obtained with adjustment of simple regressions after 40 days of incubation were 7.02 ($p = 0.0002$), 6.94 ($p = 0.001$) and 6.84 ($p = 0.009$) at doses 8.18, 9.44 and 7.83 t ha-1 limestone for CPP-29, CPP-72 and RYO, respectively (Fig. 1-D). These doses increased the pH by 47.6, 51.7, and 27.1% when compared to the control, respectively, and we highlight that the low increase in RYO may have occurred because the pH before incubation was close to the ideal range (5.5 to 6.5) (Weil and Brady, 2017). A recent meta-analysis by Li et al. (2019) describes similar results.

Their pedogenesis can explain the initial pH values of Plinthosols (CPP-29 and CPP-72) being lower than RYO, which is always associated with the leaching of exchangeable bases. In addition, the high levels of iron and/or aluminum that act in the formation of ferruginous nodules (isomorphic substitution) and because their mineralogical constitution is, mainly, oxyhydroxides Fe and Al (Eze et al., 2014; Martins et al., 2018; Santos et al., 2018).

The increase in pH is desired because it indicates that the liming reduces the excess of free H^{+} in the soil solution. This effect is mainly conditioned by the complex soil-plant-environment interactions and the heterogeneity of the physical and chemical properties of the soil (Pagani and Mallarino, 2015). However, for the recommendation of limestone, it is not usual to use a dose that represents maximum technical efficiency, that is, doses that can lead to an over-liming but strongly reduce the availability of cationic micronutrients and P (Weil and Brady, 2017).

Thus, the doses required to reach pH 6.0 (value where maximum nutrient availability occurs (Novais et al., 2007) were 1.4 t ha^{-1} for RYO, 3.9 t ha^{-1} for CPP-29, and 2.7 t ha^{-1} for CPP-72. We highlight that the method of recommendation of liming by Ribeiro et al. (1999) (widely used in the Brazilian Savanna), which considers the premise of neutralization of Al^{3+} and elevation of the contents of exchangeable bases, estimate doses in 1.57, 1.42, and 1.3 t ha^{-1} limestone (PRNT = 97%) for RYO, CPP-29, and CPP-72, respectively. These doses were assertive only for RYO, while for CPP-29 and CPP-72, the error was -174.6 and -119.5% compared to our incubation results.

Teixeira et al. (2020) describe similar results for the method of Ribeiro et al. (1999), where this method underestimated limestone doses for soils with high cation exchange capacity at pH 7.0 (CEC >12 cmo^{lc} dm^{-3}) and overestimated in soils with low CEC (<4 cmo^{lc} dm^{-3}). Bossolani et al. (2021) also describe that method underestimated doses in a long-term experiment with limestone in Oxisols. We highlight those further studies need to be carried out to improve the limestone recommendation system for Brazilian Savanna conditions, especially for soils with plinthite ironstone concretions.

The reduction of exchangeable Al^{3+} was exponentially decreasing, regardless of soil ($p = 0.000049$), and this reduction was less pronounced in soils with higher plinthite content (CPP-72<CPP-29<RYO) (Fig. 1-A). Al^{3+} neutralization was 100% with doses above 3.5, 2.5 and 0.5 t ha^{-1} for CPP-29, CPP-72, RYO, respectively. As observed in Fig. $^{1-}$D, at these doses, the pH was above 5.5, a point where the solubility of Al3+ tends to be null (Novais et al., 2007; Weil and Brady, 2017).

Although the Al^{3+} values of these soils are not initially considered high, their phytotoxic effects can become very expressive for crops with low tolerance. The soils had low Ca levels, and Mg initially with this Al^{3+} tends to be the dominant cation in effective CEC, thus confirming the importance of liming for the soils in the first year of cultivation (Lopes and Guimarães-Guilherme, 2016). The use of limestone as an acidity corrective doubles the elimination of toxicity caused by Al^{3+}. The first, by increasing the pH of the soil (fig. 1) in sufficient quantities to neutralize the Al^{+3} (<5.5); the second by increasing the levels of Ca^{+2}, which mitigates the effects of toxicity because it is responsible for maintaining the integrity of the plasma membrane of cells (Weil and Brady, 2017).

The increase in limestone doses had an inversely proportional impact on the potential acidity values (H+Al, $p < 0.00001$) (Fig. 2-B). As expected, this effect can be explained by the direct relationship of the increase in basic cations (originated from the dissolution of corrective acidity) occupying the CEC, reducing H+Al levels (Sousa and Lobato, 2004). The reduction occurred in the order CPP-72>RYO>CCP-29. The doses required for H+Al to occupy 10% of CEC were 4.0, 4.35, and 7.3 t ha^{-1} for RYO, CPP-72, and CPP-29, respectively.

The highest dose of limestone for CPP-29 required to reduce H+Al can be explained by the high pH buffer capacity of this soil because it presents higher levels of initial organic matter (OM) (2.2% - the main fraction of the soil that generates CEC in tropical soils) and P-rem (6.08 mg de P dm-3 - represents the sorption sites of anionic exchange capacity) that the other soils (Tab. 1). A meta-analysis performed by Li et al. (2019) confirms our observations that the response to liming tends to be higher in conditions where the soils pH, clay, and OM are initially lower, so they have lower buffering capacity. In addition, the authors report that the ideal duration of the liming frequency should be ~3 years because the maximum effect of pH was ten up to this period.

Base dynamics (Ca, Mg and K)

As expected, doses and soils strongly influenced Ca contents (Fig. 3-A, p = 0.0001). Compared with control, the most significant increase was for CPP-29 with an increase of 1253% (p = 0.00002), a dose of 10.0 t ha^{-1}, with 2.87 cmolc dm^{-3} of Ca. Next was for CPP-72, which increased by 1058% compared to the control, with a maximum dose of 6.15 t ha^{-1} (1.10 cmolc dm^{-3} Ca, p = 0.04), and for RYO with the lower value among soils (in percentage terms) with an increase of 608% in the dose of 6.98 t ha^{-1}, with 3.9 cmolc dm^{-3} Ca. It is noteworthy that RYO presented a higher accumulation of Ca in absolute values, and CPP-72 did not reach the critical level of 2.41 cmolc dm-3 of Ca defined for soybean crop (Ribeiro et al., 1999), one of the primary commodities the Brazilian Savanna.

The Mg contents obtained a response similar to Ca (p = 0.00003), except for the YRO soil that presented a linear response (Fig. 3-B). In this soil, there was the highest accumulation of Mg (1.94 cmo^{lc} dm^{-3}), as occurred for Ca, with an increase of 265% (R^2 = 0.83, p = 0.005) relating to control at a dose of 10 t ha^{-1}. This soil can explain these results has a higher content of fine earth, that is, only 5% of its volume was plinthite, so among the evaluated soils, it was the only one with a high probability of presenting higher specific surface (unmeasured data) for retention of cations (Lopes and Guimarães-Guilherme, 2016).

For CPP-29, the increase was 0.47 cmo^{lc} dm^{-3} of Mg (R^2 = 0.88, p = 0.003), i.e., 141% when purchased at the dose of 4.62 t ha^{-1}, and the lowest response in absolute value was for CPP-72 at a dose of 7.0 t ha^{-1} with only 0.54 cmo^{lc} dm^{-3} of Mg (R^2 = 0.85, p = 0.015). As observed for Ca, CPP-72 did not reach the critical level for Mg (0.91 cmo^{lc} dm^{-3}), this evidences that soils with high plinthite contents do not retain and provide sufficient nutrients to meet the demand of annual crops, as argued by Oluwatosin et al. (2019) and Yaro et al. (2006).

These soils are rich in low-activity clay minerals, such as hematite, goethite, gibbsite, and magnetite. The soils are describ with extremely low chemical fertility. Because they have a low volume of exploitable soil, they are considered marginal (or low agricultural capacity) (Garcia et al., 2013; Neto et al., 2019). However, these soils are increasingly being cultivated with annual crops, so several studies need to be carried out to define management and the threshold of plinthite contents in the soil that allows the sustainable and economical use of Plinthosols (Almeida et al., 2020).

The sum of exchangeable bases (BS) were positively influenced by limestone doses and soils (p = 0.0001) (Fig. 4-A). The response to the doses increased the sum of bases by 1.15, 0.76 and 0.42 cmo^{lc} dm^{-3} for each ton of limestone applied to RYO (R^2 = 0.97, p = 0.002), CPP-29 (R^2 = 0.97, p = 0.0001) and (R^2 = 0.98, p = 0.002), respectively. Therefore, the maximum technical efficiency was at doses 9.07, 8.08 and 7.76 t ha^{-1} with an increase of 611, 757 and 396%, for CPP-29 and RYO, respectively.

Although there were significant increments ($p<0.05$), Plinthosols presented, in absolute values, low BS. Yaro et al. (2006) describe similar effects when comparing plintic soils with no-plintics from Nigeria. Soils with plinthites often have a high content of gravel and sand (fractions > 2 mm), low clay content, and soil organic matter (colloidal fractions), so it contains a low ability to retain cations naturally (Neto et al., 2019; Santos et al., 2018).

Although the initial base saturation (V%) of each soil was distinct (before incubation), the responses to the limestone doses were similar, with an average elevation of 20.9% (± 1.9) for each ton applied ($p < 0.000001$, Fig. 4-B). However, it cannot reach above 80% since limestone tends to reprecipitate. How can reduce the availability of cationic micronutrients and precipitation of Ca with P and Mo (Carvalho et al., 2020). By reducing its dissolution and mainly by causing the saturation of the harmful loading sites of the soil colloids, which reduces cation retention and favors the leaching of exchangeable bases (Novais et al., 2007; Weil and Brady, 2017).

Thus, according to our results, to achieve 80% (value that is widely practiced for soybean crop grown in the Savanna) it is necessary to apply 4.14 t ha-1 (R2 = 0.98, p = 0.004) for CPP-29, 2.85 t ha^{-1} (R2 = 0.97, p = 0.00001) for CPP-72 and 2.34 t ha^{-1} (R2 = 0.97, p = 0.00005) for YRO.

Although we did not carry phosphate fertilization, we observed a slight response of the P available in the soil (Fig. 5-A). This same effect was recorded in a global compilation on liming scaling by Li et al. (2019). They generally recorded an increase in available P after the liming by 9.3% (ranging from 4 to 14% to 95% confidence). This increase after the liming is well documented in the literature since the OH- released during the limestone dissolution react precipitates Al and Fe releasing P for plant absorption or adsorption in soil colloids (Pavinato et al., 2020).

There was no difference in the limestone doses in the available K contents ($p>0.05$) (Fig. 5-B), only for soils that initially differed (Tab. 1). In the literature, the effect of the liming on the available K is not apparent, only speculations that the liming can reduce its leaching and promote increased absorption of K by plants, which can be an indirect effect caused by nutritional interaction (Sousa and Lobato, 2004). We encourage future studies that perform limestone incubation with potassium fertilization to validate or reject this hypothesis for these uncertainties.

In general, there was a reduction in increments in Ca, Mg, BS, and V% available responding to limestone doses after ~6 t ha^{-1}, where all soils at 40 DAI presented pH>6.5(Fig. 1-D). This response may have occurred due to the dissolution of limestone being governed by the presence of protons in contact with the molecule/carbonate particle (CO^{32-} ion) dissolved in the soil solution. In other words, the limestone effects are restricted to the volume of soil where it was applied in the. This indicates that the protons of the solution accentuate the dissolution and possible dissociation of limestone and as the pH of the soil solution increases, given the consumption of limestone, the concentration of CO^{3-2} ions in the solution available neutralize other protons decreases. Consequently, the concentrations of ions CO^{32-}, Ca^{2+}, and Mg^{2+} in solution no longer vary, stopping the consumption of solid limestone (Bossolani et al., 2021; Sousa and Lobato, 2004).

Our results indicate that even with lime application, Ca and Mg contents may be production limiting for Plinthosols (Fig. 3). These soils have reduced root exploration volume, which

Table 1. Chemical and physical characterization of the original soils used in the incubation experiment. Gurupi – TO, 2019.

Soils	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS[2]	CEC[1]	ECEC[3]	V[4]	m[5]	MO[6]	P-rem	pH
	.... $cmol_c$ dm^{-3}							.... (%)			mg dm^{-3}	$CaCl_2$
RYO	0.8	0.4	0.8	2.0	1.26	3.26	2.1	39	39	1.2	4.41	5.5
CPP-29	0.7	0.3	0.6	4.2	1.07	5.27	1.6	20	35	2.2	6.08	4.2
CPP-72	0.6	0.2	0.2	2.0	0.95	2.88	1.1	31	17	1.9	2.68	4.4
Soils	P	K	B	Cu	Fe	Mn	Zn	Silt	Clay	Sand	Gravel	Fine Earth
	.... mg dm^{-3}							.... g kg^{-1}				
RYO	0.7	23.4	0.12	0.6	14.0	0.2	0.8	75	325	600	50	950
CPP-29	1.3	27.3	0.2	1.1	72.0	7.6	0.4	75	350	575	293	707
CPP-72	1.2	31.2	0.2	1.0	71.0	6.3	0.6	75	275	650	728	272

RYO: Red-Yellow Oxisols; CPP-29: Concretionary Petric Plinthosol with 29% concretions; CPP-72 Concretionary Petric Plinthosol with 72% concretions; [1]CEC full; ²Sum bases; [3]effective cation exchange capacity; [4]Base saturation; [5]Aluminium saturation; [6]Organic matter; P-rem: Phosphorus buffer capacity.

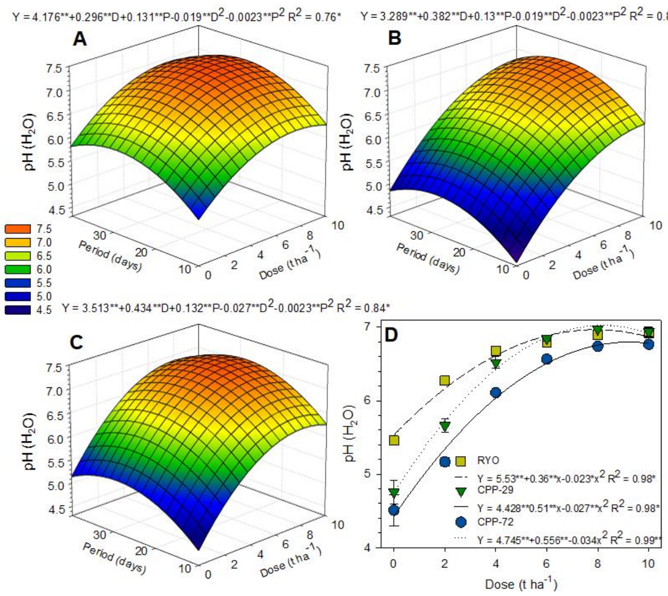

Figure 1. pH evolution as a function of limestone doses and incubation time para Oxisols (RYO) (A), Plinthosol with 29.3% gravel (CPP-29) (B), Plinthosol with 72.8% gravel (CPP-72) (C) and for the three soils at 40 days after incubation (D). **: significant to 1% ($p \leq 0,01$); *: significant to 5% ($0.01 \leq p < 0.05$); ns: not significant ($p > 0.05$). The error bars indicate the standard error of the mean.

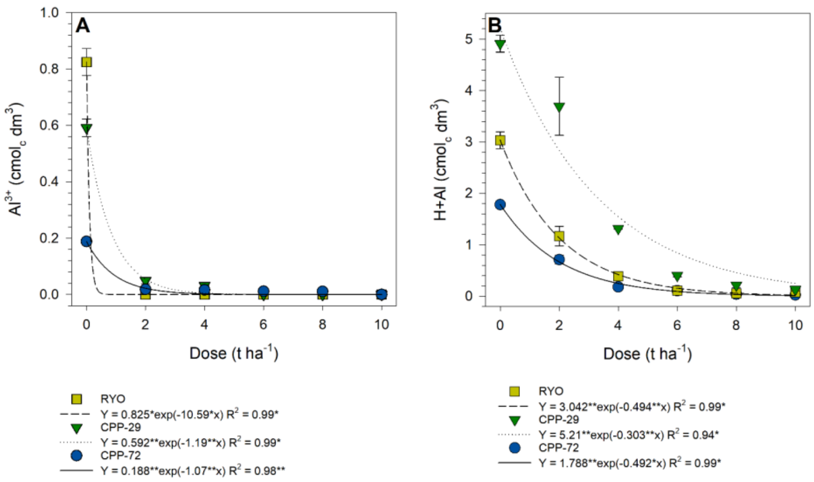

Figure 2. Exchangeable aluminium (A) and potential acidity (B) for Oxisols (RYO), Plinthosol with 29.3% (CPP-29) e 72.8% (CPP-72) gravel after 40 days of incubation with doses of limestone. **: significant to 1% ($p \leq 0,01$); *: significant to 5% ($0.01 \leq p < 0.05$); ns: not significant ($p > 0.05$). The error bars indicate the standard error of the mean.

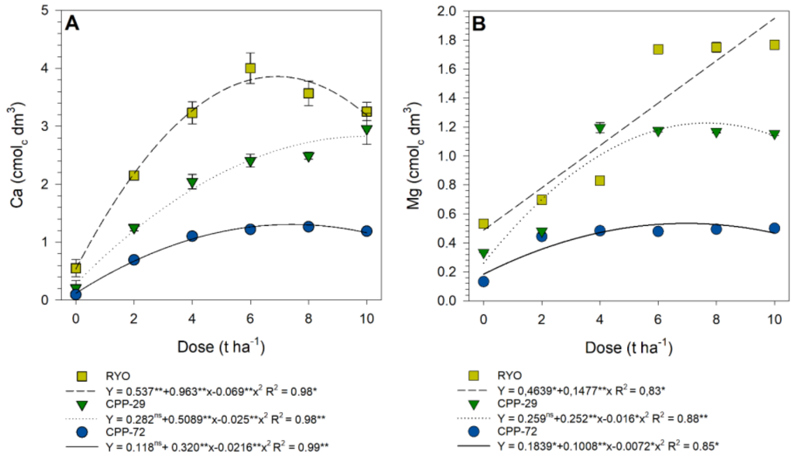

Figure 3. Exchangeable calcium (A) and magnesium (B) contents for Oxisols (RYO), Plinthosol with 29.3% (CPP-29) e 72.8% (CPP-72) gravel after 40 days of incubation with doses of limestone. **: significant to 1% ($p \leq 0{,}01$); *: significant to 5% ($0.01 \leq p < 0.05$); ns: not significant ($p > 0.05$). The error bars indicate the standard error of the mean.

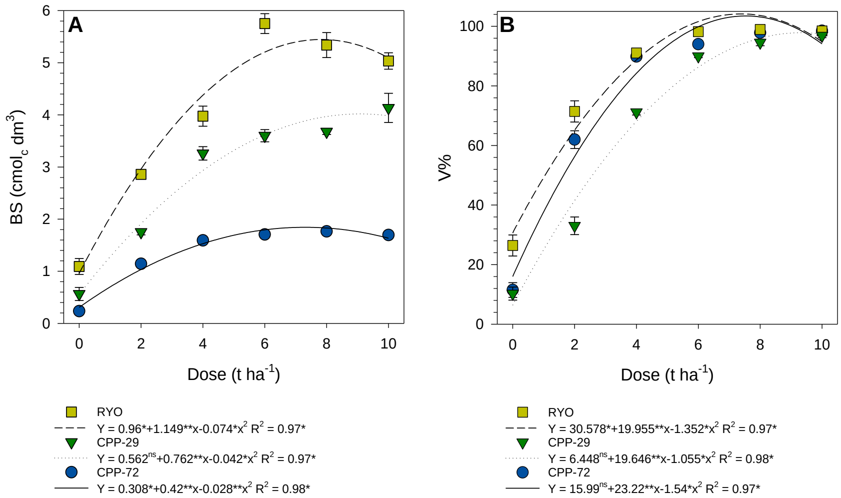

Figure 4. Sum of bases (A) and base saturation (B)for Oxisols (RYO), Plinthosol with 29.3% (CPP-29) e 72.8% (CPP-72) gravel after 40 days of incubation with doses of limestone. **: significant to 1% ($p \leq 0{,}01$); *: significant to 5% ($0.01 \leq p < 0.05$); ns: not significant ($p > 0.05$). The error bars indicate the standard error of the mean.

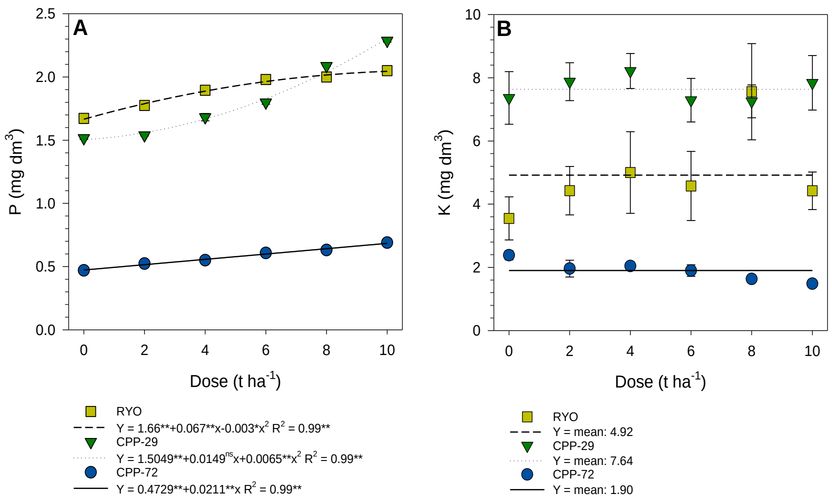

Figure 5. Phosphorus (A) and potassium (B)for Oxisols (RYO), Plinthosol with 29.3% (CPP-29) e 72.8% (CPP-72) gravel after 40 days of incubation with doses of limestone. **: significant to 1% ($p \leq 0{,}01$); *: significant to 5% ($0.01 \leq p < 0.05$); ns: not significant ($p >$ 0.05). The error bars indicate the standard error of the mean.

favors the leaching process of the bases provided by the liming, especially for K^+ can be easily leached mainly under conditions of a relative increase in the other bases in the soil CEC (Novais et al., 2007).

The increase in CEC is favored by increasing and conserving soil organic matter. Thus, conservation management practices are mandatory to promote sustainability in Plinthosols. Practices such as crop rotation, green fertilization, proper crop residue management, use of organic waste, no-tillage and minimum tillage, crop-livestock integration or crop-livestock-forest, etc., will undoubtedly contribute to maintaining the balance of these soils (Lopes and Guimarães-Guilherme, 2016).

Although Plinthosols are frequently inserted to cultivate annual plants (Almeida et al., 2020; Martins et al., 2018; Oluwatosin et al., 2019), however, studies of Plinthosols have been limited to their pedogenesis (Eze et al., 2014), chemical, physical and mineralogical characterization (Garcia et al., 2013; Yaro et al., 2006). Here we describe the first study, as far as we know, under the potentials and limitations of the use of lime in plintic soils. However, our results have methodological, technical limitations due to incubation not being performed in leaching columns without plant cultivation. Thus, we encourage new studies with Plinthosols and limestone sources that collect and quantify the nutrient contents of the leached solution, especially with the inclusion of cultivation of expressive agricultural for the Brazilian Savanna.

Materials and methods

Experimental design and used soils

The experiment was conducted in a greenhouse of the Federal University of Tocantins (UFT – Gurupi), the southern region of Tocantins state, Brazil (11° 44’ 44,16” S e 49° 03’ 04,17” W) at 280 meters of altitude. The regional climate is of type B1wA'a' humid with moderate water deficiency. The average annual rainfall is 1600 mm, concentrated in November to May, with an average annual temperature of 27 °C (Alvares et al., 2013).

The soils used in incubation were classified by the Brazilian soil classification system, how: Dystrophic Red-Yellow Latosol (or Oxisol (WRB: World Reference Base for Soil Resources, 2015) with 5% gravel (RYO, 11° 43’ 20” S e 49° 03’ 22” W), Concretionary Petric Plinthosol endico (or Plinthosol (WRB: World Reference Base for Soil Resources, 2015)) with 29,3% gravel (CPP-29, 11° 46’ 09” S e 49° 03’ 18” W), and concretionary Petric Plinthosol argissolic with 72.8% gravel (CPP-72, 11° 44' 49" S e 49° 03’ 04” W). All soils were under native vegetation, in other words, without anthropic intervention, and their chemical and physical attributes were characterized (Tab. 1)

Treatments and experimental conditions

The incubation assay was carried out in a completely randomized design, the treatments were distributed in a 3x6 factorial scheme, with four replications. The first factor corresponds to the soils (RYO, CPP-29, and CPP-72) and the second to six doses equivalent to 0, 2, 4, 6, 8, and 10 t ha^{-1} limestone filler (Caltins©) containing 30% CaO and 18% MgO and total relative neutralization power of 97.2%.

The soils were collected in the 0–20 cm layer, distorted and air-dried. The experimental units (EU) consisted of resistant plastic bags of 2 dm^3 containing 0.5 dm^3 of soil without removing the plinthites. The limestone was carefully mixed with the entire soil bulk in the plastic bags. The soil moisture from the EU was kept close to 70% of field capacity, moisture was returned every two days with deionized water, and then plots were turned over for complete homogenization. The plastic bags were closed with wire, leaving an opening that allowed the gas exchange.

Samples from the EU were collected at 10, 20, 30, and 40 days after the incubation (DAI) to evaluate the pH evolution, and the other attributes were quantified only at 40 days, a period equivalent to the end assay.

Chemical analysis of the soil

After incubation of the soil, the samples were initially air dried, distorted, and passed in the 2 mm sieve, thus obtaining the fine ground dried in the air. According to Teixeira et al. (2017) determined the chemical attributes.

The pH was determined in $CaCl^2$ (ratio 1:2.5) with a pHmeter; P and K were extracted by Mehlich-1 (0.0125 mol L^{-1} of H^2SO^4 and 0.05 mol L^{-1} of HCl), and P is quantified by colorimetry and K by flame photometer. The exchangeable Al, Ca, Mg were extracted by KCl at 1 mol L^{-1}, the Al+H, extracted by 0.5 mol L^{-1} calcium acetate solution at pH 7 and titled with NaOH 0,0606 mol L^{-1} (Teixeira et al., 2017). The sum of Ca, Mg, and K determined the base sum (BS). Already total CEC by the sum of BS+(H+Al), and base saturation (V%) calculated by the formula: (BS/CEC) x100 (Ribeiro et al., 1999; Sousa and Lobato, 2004). We highlight that the chemical attributes were determined only in the soil fraction <2 mm according to standard Brazilian methods. However, this fraction does not represent the entire soil volume due to plinthites. Therefore, to avoid overestimating the chemical attributes that cultivated crops can exploit, we corrected the values to be expressed according to the volume of fine land that each soil contained. Namely: RYO attributes were multiplied by 0.95, CPP-29 by 0.707, and CPP-72 by 0.272.

Statistical analysis

The results were evaluated by normality test (Shapiro-Wilks) and homoscedasticity of variance (Bartlett), when the assumptions were not met, the Box-Cox transformation was applied. Then, the results were submitted to variance analysis ($p \leq 0.05$), and the regression models were adjusted according to the level of significance (Student t-test, $p \leq 0.05$ and $p \leq 0.01$). All analyses were performed in the software R version 4.0 (TEAM, 2021).

Conclusions

The use of limestone has improved soil fertility in general, and we confirm the hypothesis that the limestone dose is being underestimated for Plinthosols with 29% and 72% of soil volume with plinthite ironstone. The highest doses of limestone were not sufficient to reach critical limits of Ca and Mg for Plinthosols with higher plinthite content. Thus, we recommend using agricultural practices that increase the capacity of the soil to retain and recycle nutrients. Further studies should be carried out to update the limestone recommendation for Plinthosols. These studies should consider nutrient leaching with plant crops in Plinthosols.

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Contributions

O.L., S.L., and R.S. planned the experiment, O.L., J.L. and A.M. conducted the experiment and analyses statistics, O.L. J.L. and S.L. writing the first draft. All authors reviewed and approved the latest version of the paper.

Compliance with ethical standards

The authors declare that they have no conflict of interest.

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