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Effect of liming in plinthic and petroplinthic soils for soybean cultivation in the Brazilian Savanna

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Abstract

Agricultural expansion is advancing on marginal soils (Plinthic soils), but the liming recommendation for this soil, especially for soybean cultivation, remains unknown. This study aimed to evaluate soybean (*Glycine max*) responses to limestone doses in concretionary soils (plinthic and/or petroplinthic). The experiment was carried out in the greenhouse, in randomized blocks, with four soil types and six limestone doses (4x6 factorial scheme), with four replicates. Soils were: RYO: Red-Yellow Oxisols; CPP-29, CPP-72, CPP-82 corresponds to the Concretionary Petric Plinthosol with 29, 72, and 82% concretions, respectively. Limestone doses varied from 0 to 4 times for each soil, based on the recommendation of regional bulletins. Soil temperature, crop emergence, development, and soybean yield characteristics were evaluated. Results were evaluated by ANOVA, followed by the LSD test or polynomial regression adjustment ($p \leq 0.05$). Soybean response to liming varied with soil types. Seedlings showed lower vigor in Plinthic soils with plinthite contents ≥72%. These soils showed higher thermal accumulation (°C), and this increase showed a strong negative correlation with soybean development and reproductive characteristics. Evidence of liming response was observed after crop stage V5. Limestone substantially improved soybean growth and development in Plinthic soils with high plinthite levels, although they had lower yield potential than low plinthite levels and Oxisol. In general, the maximum response of the crop occurred at doses ~2 times higher than that practiced in the Brazilian Savanna region, especially in Plinthic soils.

Keywords: Plinthosol, limestone, ironstone concretions, Murundu, Cerrado Region.

Introduction

Soybean (*Glycine max*) is currently the most cultivated crop in the world. Brazil reached the first position in production, with 37% of world production, 124 million tons, and average yield of 3.379 kg ha^{-1}. The planted area is in full expansion, fueled by the rise in commodities at 3% compared to the 2021/22 harvest (CONAB, 2022; USDA, 2022). This expansion is taking place in soils with a low aptitude for agriculture (marginal soils) of the Brazilian Savanna, with restrictions on annual cultivation (e.g., soybean and corn) (Almeida et al., 2020; Souza et al., 2019).
Plinthic soils have been increasingly used for the production of crops without the necessary technological package for long-term sustainable production (Almeida et al., 2020; Ibrahim and Fatondji, 2020; Leite et al., 2022). Plinthic soils are hydromorphic soils, where wetting and drying cycles promote the formation of ferruginous concretions of variable dimensions and shapes, which can be agglomerated or individualized with the presence of gravel, formed from the chemical dynamics of iron in the soil (Eze et al., 2014; Martins et al., 2018; WRB, 2015).
The presence of plinthites or petroplinthites in the horizons limits the rooting volume and the soil water and nutrient storage capacity, consequently limiting crop yield. In addition, its source material has low fertility, favors the increase in soil temperature, and presents the low response to fertilizer application (Ibrahim and Fatondji, 2020; Ikazaki et al., 2018; Kiwia et al., 2022).
Liming is often used to overcome these limitations, as it reduces active (Al^{3-}) and potential acidity (H+Al) and increases exchangeable Ca^{2+} and Mg^{2+} levels. These

attributes favor root development and crop yield using fertilizers (Li et al., 2019; Weil and Brady, 2017). However, the practice of liming for annual crops in Plinthic soils has not yet been well established, is not very assertive and the low levels of fine soil limit traditional recommendation methods (Carvalho et al., 2020; Teixeira et al., 2020)

In previous studies (Leite et al., 2022), our group evaluated the dissolution dynamics of limestone doses in concretionary soils. However, the main limitation of the previous study was that it did not assess the responses of annual crops to this practice in Plinthic soils. Thus, this study aimed to evaluate soybean responses to limestone doses in concretionary soils (plinthic and/or petroplinthic soils) cultivated in the Brazilian Savanna.

Results and discussion

Soil temperature and seeding

Liming did not influence soil temperature and soybean germination ($p > 0.05$), but strongly increased soybean development and yield in different soils ($p \leq 0.05$). The temperature was influenced only by soil types ($p>0.005$) (Fig. 1 A-B). There was no difference in the first two times (9 and 11 am, $p = 0.07$ and 0.056), but they were strongly different from 2 pm onwards, and at 4 pm, only RYO showed a slight reduction of -0.61 °C (Fig. 1-A).

Higher concretion levels promoted greater thermal accumulation throughout the day; in CPP-82, 40.3°C was recorded, followed by 39.49 °C for CPP-72 and 39.13 °C for CPP-29, and did not differ from each other at 4 pm. This trend also occurred in the average of the 744 observations (Fig. 1-B, $p = 0.00001$), RYO was 32.9 ±0.88 °C, and concretions promoted the thermal increase of 0.88, 1.45, and 1.70 °C for CPP-29, 72 and 82, respectively, in relation to RYO. The low resilience of Plinthic soils to temperature is strong evidence to explain the impact on crop vigor (Fig. 1-C-D).

Soybean seedling vigor was strongly influenced only by soil type (Fig. 1-C-D). The highest emergence velocity index (4.28) and emergence percentage (70.7%) occurred for Plinthic soils with 29% of gravel (CPP-29), followed by RYO with 3.86 of EVI and 65.8% of emergence percentage. Soils with gravel content ≥72% (CPP-72 E 82) did not differ, with ~1.99 EVI and ~44.2% emergence percentage. Both variables were inversely proportional to the average soil temperature (correlation of -0.80 for EVI and -0.79 for emergence percentage). In Plinthic soils with 65% of gravel, Nikkel and Lima (2019) also reported reduced growth, and there was no influence of liming in the initial soybean phase.

After the period of higher solar irradiation, which for the Brazilian Savanna region is from 11 am to 2 pm, Plinthic soil showed high thermal accumulation and low temperature resilience compared to Latosols. Similar reports or those that explain these results for Plinthic soils were not found in the literature, but we believe that thermal accumulation occurred due to concretions' size and dark color (dark colors reflect less and absorb more solar radiation). These factors associated with low water holding capacity strongly impacted plasticity and negatively the vigor of soybean seeds during emergence.

Thermal stress affects all stages of plant development, but the germination and emergence rate is a critical phenomenon for achieving optimal planting density and crop performance (Ahmad et al., 2021). In this phase, the reserve carbohydrates of seeds are metabolized to favor embryo development. However, germination with heat stress allocates part of this finite reserve to maintain the homeostatic stability of cells, fighting or mitigating the effects of oxygen and nitrogen free radicals that are produced in greater quantities under stress conditions (Rengel, Cakmak and White, 2022). While this defense mechanism is crucial for the survival of seedlings, it also signifies that fewer resources are accessible for embryo growth and seedling formation. Consequently, the vigor of seedlings is diminished, potentially exerting adverse effects on plant density and crop performance (Taiz et al., 2017).

The adoption of cover crops and no-till (conservation tillage) systems in these areas with Plinthosols can be an effective management strategy to mitigate the rise in soil temperature (Ramos, 2022). This is attributed to the residue cover, which induces a mulching effect (e.g., shielding the soil from solar radiation, reducing evapotranspiration, and elevating soil temperature), along with an increase in soil organic matter content (Krupek et al., 2022). However, we did not find literature reporting these responses in Plinthic soils, thus encouraging further field studies to validate this management strategy aimed at enhancing the sustainability of soybean cultivation in Plinthosols.

Soybean development

Throughout the soybean cycle, soils differentiated plant height at stage V3 ($p=0.02$), where CPP-72 and 82 were ~2.9 cm higher than RYO and CPP-29 (Fig. 2-A). In V5, there was no influence, but from R2, there was an inversion of soil groups. RYO and CPP-29 were similar and superior to CPP-72 and 82, with plants higher by 5.8 (29%), 8.7 (32%), and 6.7 (21%) cm for R2, R4, and R5, respectively. After R5, there was no significant increase, so the final average plant height was 40.0 cm for CPP-29, 39.3 cm for RYO, 32.7 cm for CPP-82, and 32.3 cm for CPP-72. At R5, responses to limestone doses were quadratic, except for CPP-82, which was null (~32.74 cm) (Fig. 2-B). The greatest response was for CPP-72, with increase of 66% at dose of 1.13 t ha^{-1} ($R^2 = 0.90$, $p = 0.02$) with 43.7 cm, followed by RYO and CPP-29, with 54 and 33% increase at doses of 1.16 t ha^{-1} ($R^2 = 0.97$, $p = 0.01$) and 3.06 t ha^{-1} ($R^2 = 0.85$, $p = 0.001$).

The evolution of stem diameter differed among soils after V5 (Fig. 2-D). At this stage, CPP-29 was 14% higher than RYO, and 34% higher than CPP-72 and 82 (both similar to each other). A similar response to height occurred after this stage for diameter. In R5, RYO and CPP-29 did not differ (~6.7 mm, $p = 0.0005$) and were superior by 32% compared to CPP-72 and 82 (~5.1 cm). As for the effect of limestone, all responses were quadratic ($R^2 \geq 0.72$). The best responses, in ascending order, were: RYO>CPP-72>CPP-29>CPP-82, with increments of 84, 82, 65 and 34% at doses of 1.09, 1.18, 3.72, and 1.45 t ha^{-1}, respectively (Fig. 2-C).

Height has a strong relationship with soybean yield due to the increase in the number of nodes that originate the reproductive structures, and collar diameter indicates potential carbohydrate reserves that could collaborate with grain filling. Pearson's correlation of height and diameter were -0.78 and -0.89 with soil temperature so they may have consequences on soybean reproductive characteristics.

Our study revealed a direct relationship between the increase in gravel content in Plinthic soils and the reduction in soybean plant height, as well as the attenuation of the

Table 1. Chemical and physical characterization of the original soils used in the incubation experiment. Gurupi – TO, 2020.

Soils	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS[2]	CEC_T[1]	CEC_t[3]	V[4]	m[5]	OM[6]	P-rem	pH $CaCl_2$
	.... $cmol_c\ dm^{-3}$							.... (%)			$mg\ dm^{-3}$	
RYO	0.8	0.4	0.0	2.0	1.2	3.2	1.2	37.5	0.0	1.2	4.41	5.5
CPP-29	0.7	0.3	0.5	4.2	1.0	5.2	1.5	19.2	33.3	2.2	6.08	4.2
CPP-72	0.6	0.2	0.6	2.0	0.8	2.8	1.4	28.6	42.9	1.9	4.68	4.4
CPP-82	0.6	0.2	0.3	2.2	0.8	3.0	1.1	26.7	27.3	1.4	4.68	4.5
Soils	P	K	B	Cu	Fe	Mn	Zn	Silt	Clay	Sand	Gravel	Fine Earth
	.... $mg\ dm^{-3}$							.... $g\ kg^{-1}$				
RYO	0.7	0.06	0.12	0.6	14.0	0.2	0.8	75	325	600	0	1000
CPP-29	1.3	0.07	0.2	1.1	72.0	7.6	0.4	75	350	575	293	707
CPP-72	1.2	0.08	0.2	1.0	71.0	6.3	0.6	75	275	650	728	272
CPP-82	5.0	0.07	0.15	0.5	23.0	3.3	0.3	25	100	875	820	180

RYO: Red-Yellow Oxisols; CPP-29: Concretionary Petric Plinthosol with 29% concretions; CPP-72 Concretionary Petric Plinthosol with 72% concretions; CPP-82: Concretionary Petric Plinthosol with 82% concretions. [1]CEC full; [2]Sum of bases; [3]effective cation exchange capacity; [4]Base saturation; [5]Aluminium saturation; [6]Organic matter.

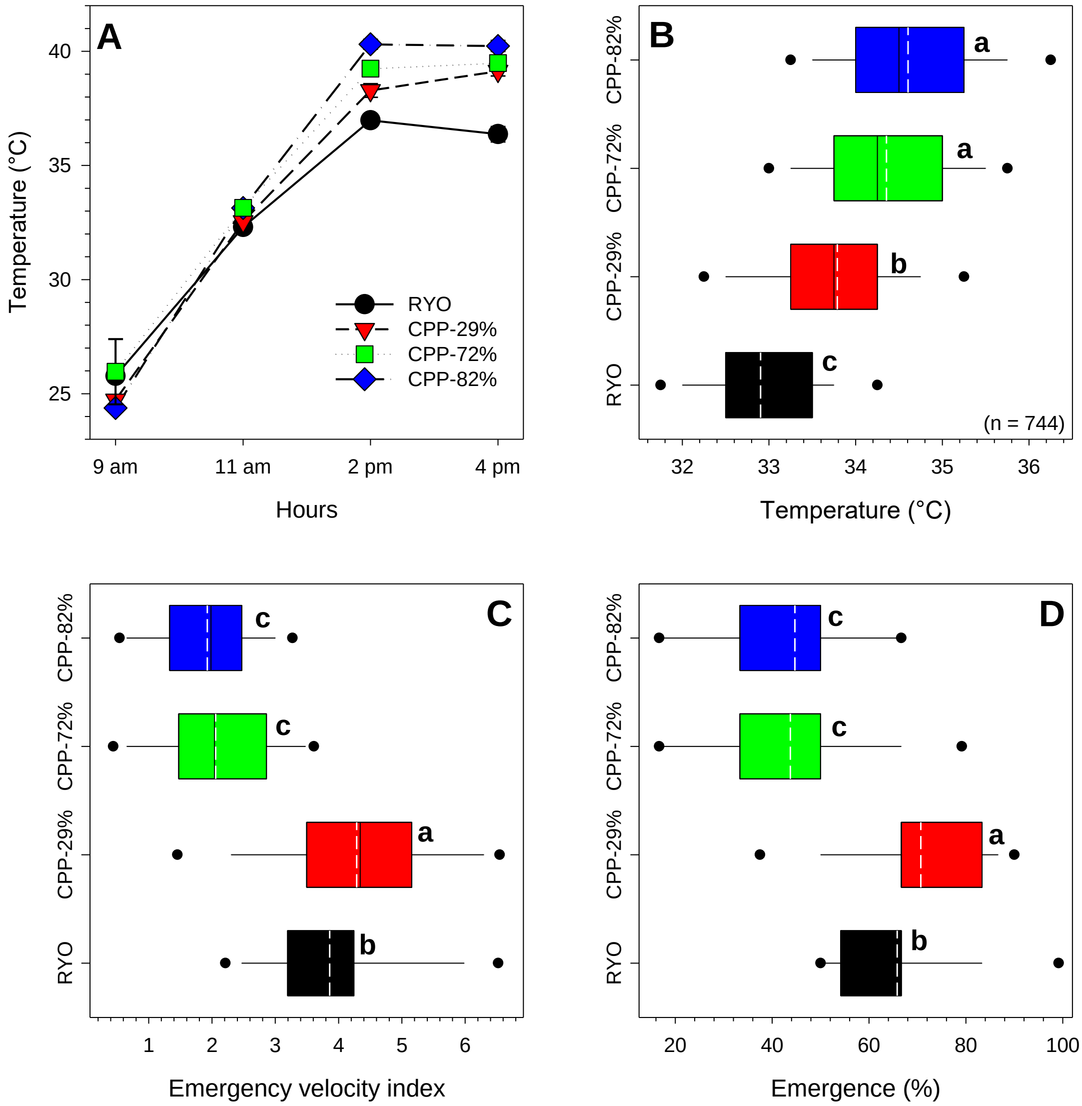

Figure 1. Soil temperature throughout the day (A), general mean (B), emergence velocity index (C), and emergence percentage (D) of soybean cultivated in soils with concretions. RYO: Red-Yellow Oxisols; CPP-29, CPP-72, and CPP-82 correspond to the Concretionary Petric Plinthosol with 29, 72, and 82% concretions, respectively. Boxplots with the same letters do not differ by LSD test ($p \leq 0.05$). Dashed lines indicate the mean. The error bars indicate the standard error of the mean.

Table 2. Limestone doses were applied to the soils of the experiment. A value of 1 represents the recommendation of Ribeiro et al. (1999).

Soils	Limestone doses (t ha^{-1})					
	0%	50%	100%	200%	300%	400%
RYO	Non-limestone	0.35	0.70	1.41	2.11	2.82
CPP-29		1.08	2.17	4.34	6.51	8.67
CPP-72		0.42	0.85	1.70	2.55	3.40
CPP-82		0.51	1.01	2.02	3.03	4.04

RYO: Red-Yellow Oxisols; CPP-29: Concretionary Petric Plinthosol with 29% concretions; CPP-72 Concretionary Petric Plinthosol with 72% concretions; CPP-82: Concretionary Petric Plinthosol with 82% concretions.

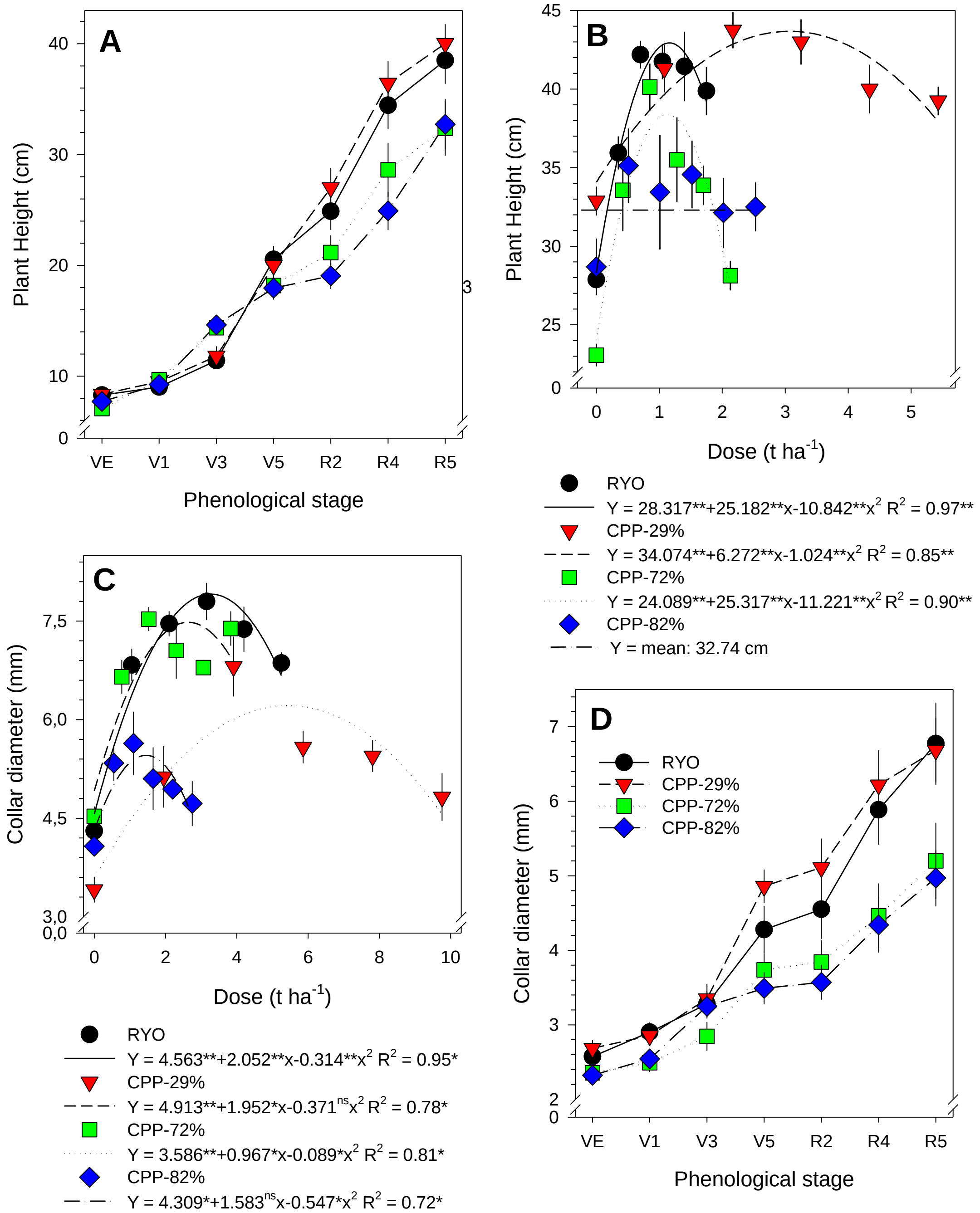

Figure 2. Height and collar diameter by phenological stage (A, D) and function of limestone doses (B, C) of soybean cultivated in soils with concretions. The results of figure A and B refer to the R5 stage. RYO: Red-Yellow Oxisols; CPP-29, CPP-72, and CPP-82 correspond to the Concretionary Petric Plinthosol with 29, 72, and 82% concretions, respectively. **: $p<0.01$; *: $p<0.05$; ns: $p>0.05$. The error bars indicate the standard error of the mean.

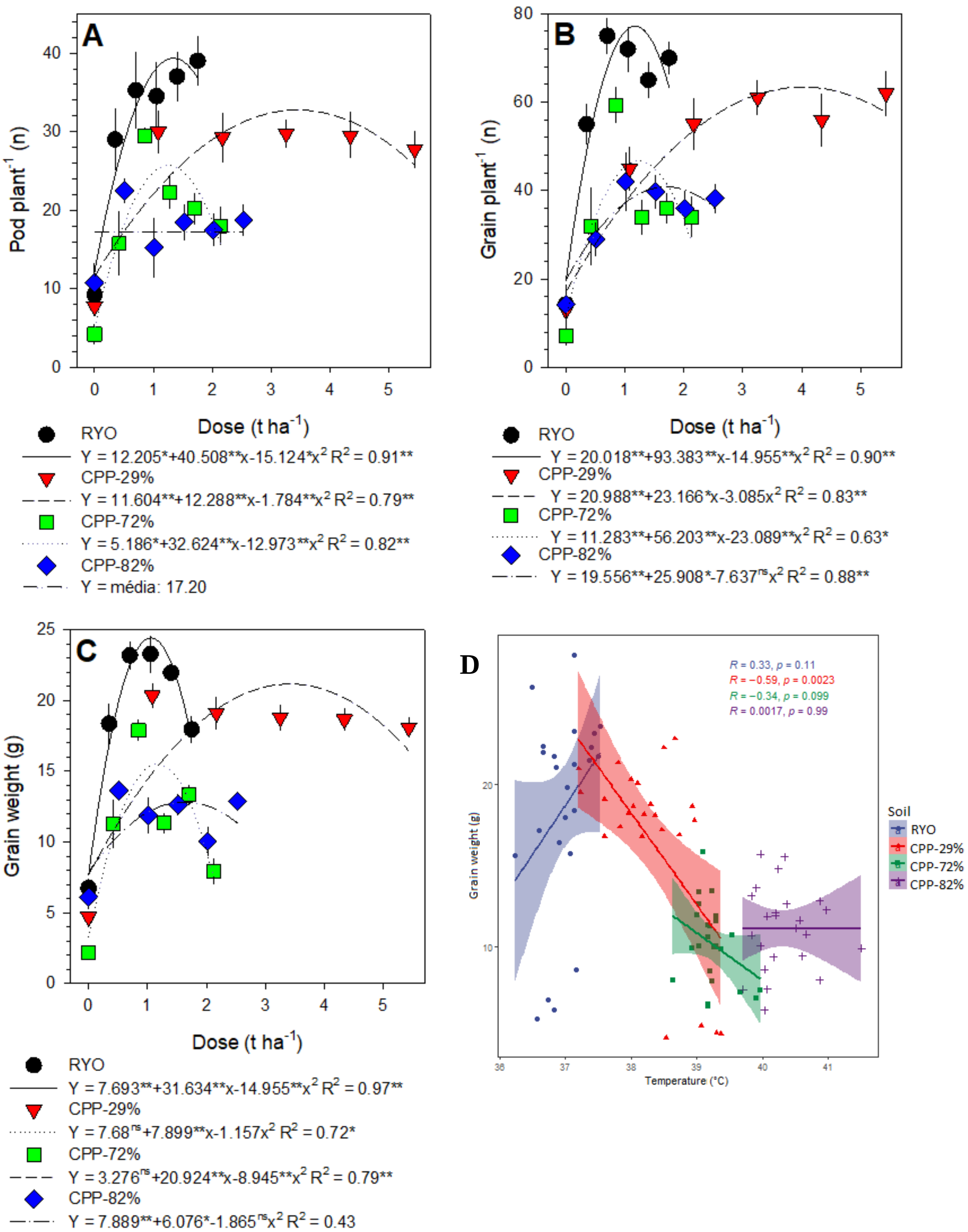

Figure 3. The number of pods (A), grain (B), grain weight per plant (C), and correlation of temperature vs. grain weight (D) of soybean grown in soils with concretions. RYO: Red-Yellow Oxisols; CPP-29, CPP-72, and CPP-82 correspond to the Concretionary Petric Plinthosol with 29, 72, and 82% concretions, respectively. **: $p<0.01$; *: $p<0.05$; ns: $p>0.05$.

response to liming for this variable. Findings consistent with ours were previously observed by Nikkel and Lima (2019) when evaluating soybeans at three stages of development in Plinthic soils. These authors reported a reduction of 18% in the height of plants cultivated in Plinthic soils, and this effect intensified to 47% at the R2 stage of the crop cycle. It is possible that the lack of liming response in plant height, observed in soils with higher gravel content, such as in the case of CPP-82, may have been masked by the increased temperature associated with these soils (see Figure 1-A-B). Waraich et al. (2021) also described similar responses, including reduced plant height and biomass accumulation, associating these effects with a decrease in photosynthetic rate and stomatal conductance of the crop. These findings related to temperature variation in agricultural crops were recently reviewed by Ahmad et al. (2021), who demonstrated the higher sensitivity of oilseed crops to thermal stress.

Reproductive characteristics of soybeans

The number of pods plant^{-1} was strongly influenced by soils and limestone doses ($p = 0.002$), and the maximum technical efficiency (MTE), was almost always higher than recommended by Ribeiro et al. (1999) and Sousa and Lobato (2004), except for CPP-82, which was unresponsive to limestone doses (Fig. 3-A). Regardless of dose, plants in RYO and CPP-29 produced more pods, mainly with limestone doses of 1.34 and 3.44 t ha^{-1} (39.3 and 32.8 un $plant^{-1}$). However, plants in CPP-72 had a higher percentage increase (505%) with 1.26 t ha-1 of limestone compared to the control.

Similar results were observed for the number of grains (p = 0.002) (Fig. 3-B). RYO and CPP-29 were superior to CPP-72 and 82, with 74.7 and 64.5 vs. 46.7 and 41.6 grains $plant^{-1}$, respectively. These results are in MTE, which were estimated at 1.17, 1.75, 1.24, and 3.64 t ha^{-1} with increments of 422, 396, 544, and 192% compared to controls, respectively. The substantial effects of limestone for CPP-72 must be highlighted, which presented only 7.3 grains $plant^{-1}$ without liming and in the first dose, increased to 32 grains $plant^{-1}$. This soil showed the highest saturation by Al^{3+}, 43%, and soybean tolerates up to ~20%, so it showed the highest response to liming (Ribeiro et al., 1999). This response was observed in all agronomic variables.

The mass of grain $plant^{-1}$ (yield indicator) varied inversely proportional to gravel contents (p = 0.0003). RYO had the highest grain mass, 17.7 g in 1.06 t ha^{-1}, followed by CPP-29, with 16.5 g in 3.41 t $ha^{-1,}$ and CPP-72, with 15.3 g in 1.17 t ha^{-1} (Fig.3- C). The MTE for CPP-82 had a smaller increase (6.7 g, ~110%) with control, justified by the low quadratic adjustment (R^2= 0.43), although significant (p = 0.02), or because the high gravel contents limit the crop potential.

Pearson's correlation showed that the increase in temperature also had a negative effect on grain mass, except for RYO, where the lowest temperature occurred (Fig. 1-A-B) and CPP-82% with no effect (r = 0.0017, p = 0.99) (Fig. 3-D). The increase in temperature mainly reduced the grain mass of CPP-29 (r = -0.59, p = 0.0023), followed by CPP-72 (r = -0.36, p = 0.088).

The lower level of gravel (CPP-29) presented satisfactory results compared to CPP-72 and 82. In these soils, liming was essential to improve soil chemistry (Leite et al., 2022), and consequently, increase the productive potential for levels similar to other more cultivated Brazilian Savanna soil classes (e.g., Oxisol). These results corroborate those Ikazaki et al. (2018), where Plinthic soils contributed to sorghum yield, but the reduction in adequate soil depth was limited (this occurred for CPP-72 and 82 in this study).

Previous studies have reported the presence of plinthite from Plinthic soils on soybean growth and development (Nikkel and Lima, 2019). There was a 20% reduction in root biomass and 36% in total biomass, although the authors did not show the mechanisms involved. In this study, soil temperature at 5 cm strongly correlated with reduced growth since germination and higher plinthite contents resulted in increased thermal accumulation (Fig-1-3). This variable was not manipulated and the correction does not imply causality, so this test cannot validate this hypothesis, and in this sense, further studies should be carried out.

Temperature significantly affects soybean growth, development, yield, and composition. The temperature stimulus with the grain mass for RYO may be because the increase in temperature favors transpiration, absorption, and translocation of nutrients in the plant. However, there is a threshold (~35 °C), mainly in the reproductive phase, where cells lose membrane stability. The heat stress results in a cascade effect with reduced chlorophyll content, photosynthetic rate, and leaf water status, compared to the ideal temperature. This causes pod and grain abortion and decreases grain weight and yield (Ahmad et al., 2021).

This problem can be overcome by adopting the no-tillage system in straw. Costa et al. (2015) reported that forage straw adequately reduced soil temperature, contributing to soybean development and yield. In addition, it can increase soil fertility and biological activity since concretionary soils have low water and nutrient storage capacity. This was confirmed by Souza et al. (2019) after evaluating the conversion of native forests into no-till in Plinthic soils. In the long term, no-till system considerably improved soil quality attributes (nutrient cycling and storage), soil aggregation, and biological activity superior to native forest.

In a previous study, liming significantly altered pH, Ca^{+2} and Mg^{+2} in Plinthic soils (Leite et al., 2022). This favors more significant root growth by reducing potential acidity and increasing the sum of bases, increasing the volume of explored soil and, consequently, the productive potential of soybean. In general, the doses recommended by the Brazilian Savanna soil fertility bulletins (Ribeiro et al., 1999; Sousa and Lobato, 2004) were not assertive, regardless of soil type. The best response for soybean mass occurred with ~2 times higher doses. However, these results must be validated with field experiments.

Materials and methods

Experimental conditions

The experiment was conducted in the greenhouse of the Federal University of Tocantins (UFT - Gurupi), in the southern region of the state of Tocantins, Brazil (11°44’44.16” S and 49°03’04.17” W) at 280 m. The regional climate is of B1wA'a' type, humid with moderate water deficiency. The average annual rainfall is 1600 mm, concentrated from November to May, with an average annual temperature of 27 °C (Alvares et al., 2013).

The soils used in the trial were the same as those used by Leite et al. (2022), with the addition of another with higher gravel content. The Brazilian soil classification system classified soils as: Dystrophic Red-Yellow Oxisol (WRB, 2015) with 5% gravel (RYO, 11°43’20” S and 49°03’22” W), concretionary Petric Plinthosol endico (WRB, 2015) with 29.3% gravel (CPP-29, 11°46’09” S and 49°03’18” W), concretionary Petric Plinthosol argisolic with 72.8% gravel (CPP-72, 11° 44' 49 " S and 49°03’04” W) and concretionary Petric Plinthosol argisolic with 82.3% gravel (11°46'12'' S and 49°03'22''W).

Soils were collected in the 0–20 cm layer and air dried without sieving to ensure identical amounts of concretion as the original soil. All soils were under native vegetation, in other words, without anthropic intervention, and their chemical and physical attributes were characterized (Table 1). The fine soil was separated from the gravel after passing 200 g of soil in the sieve with mesh of 2 mm, and the material retained in the sieve was classified as gravel (Teixeira et al., 2017).

Experimental design

The experiment was conducted in randomized blocks, with four soil types and six limestone doses (4x6 factorial scheme), with four replicates. Soils were: RYO: Red-Yellow Oxisols; CPP-29, CPP-72, CPP-82 corresponds to the Concretionary Petric Plinthosol with 29, 72 and 82% concretions, respectively. Six limestone doses varied from 0 to 4 times (0, 50, 100, 200, 300 and 400%) the recommendation of the regional bulletins for each soil (Ribeiro et al., 1999; Sousa and Lobato, 2004). The dose corresponding to 100% of recommendation was 0.70, 2.17, 0.85, and 1.01 t ha^{-1} for RYO, CPP-29, CPP-72, and CPP-82, respectively (Table 2).

Experimental units (EU) were composed of 12 dm^3 pots. Filler limestone doses (PRNT = 99.7%) were applied according to the respective soils and incubated at 70% of field capacity for 30 days before crop sowing. The fertilization recommendation was according to Ribeiro et al. (1999) for soybean, with an application of 44 kg ha^{-1} of P via single superphosphate (18% P_2O_5, 16% Ca, and 8% S) and 100 kg ha^{-1} of K via potassium chloride (58% of K_2O) with 50% applied at sowing and 50% after stage V5. Next to sowing, seeds were inoculated with commercial *Bradyrhizobium japonicum* strains.

Fifteen 'Bônus IPRO 8579 RSF' soybean variety seeds (popular among producers in the region due to their high yield potential) were sown in each EU. After the germination test (15 days after emergence -DAE), only one seedling per UE was left. Aerial microsprinklers irrigated the test with flow rate of 100 L h^{-1}, with ~8 mm day^{-1} divided at the beginning and end of the day. Accumulated simulated precipitation was ~800 mm of water, similar to what occurs under field conditions in the region. Agricultural pesticides were used to control pests and diseases as recommended for the crop.

Soil and plant evaluations

In the first 30 DAE, the soil temperature of each EU was measured at a depth of 5 cm at 9 am, 11 am, 2, and 4 pm with a digital thermometer (Simpla model - TE07). This was performed to verify if gravel contents altered the soil temperature, which surprisingly explained many responses of soybean in Plinthic soils. Seedling emergence was determined daily for 15 days after the emergence of the first seedling. The emergence velocity index (EVI) and the emergence percentage were determined according to official Brazilian methods (MAPA, 2009).

Plant height and stem diameter were evaluated using a ruler (cm) and digital caliper (mm) at seven crop stages (VE, V1, V2, V3, V5, R2, R4 and R5). In R8, stage of crop maturity, the number of pods and grains $plant^{-1}$ was determined by direct counting, and the weight of grains $plant^{-1}$ was measured on a digital scale (g).

Statistical analysis

Results were evaluated by ANOVA (Fisher test, $p \leq 0.05$); soils were compared by post-hoc LSD, and the doses were adjusted by polynomial regressions according to the model significance ($p \leq 0.05$). Pearson's correlation analysis was used to quantify the effects of temperature on soybean grain mass in the different soils. Statistical analyses were performed using the R® version 4.0 and graphics using SigmaPlot version 10.0®.

Conclusions

Soybean crop response to liming varied with different soil types. Evidence of the liming response was observed after crop stage V5. Limestone substantially improved soybean growth and development in Plinthic soils with high levels of plinthites, although they presented lower yield potential compared to low levels of plinthite and Oxisol. The maximum crop response occurred at doses ~2 times higher than that practiced in the Brazilian Savanna region, especially in Plinthic soils.

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Contributions

OCL, SOL, and RSS planned the experiment, OCL, JHL, MGS and JOJ conducted the experiment and statistical analyses, OCL, JHL, and SOL wrote the first draft. All authors reviewed and approved the latest version of the manuscript.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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