Gypsum recommendations for a typical Dystrophic Red Argisol cropped with *Phaseolus vulgaris*[1]

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10.1590/0034-737X2024710014

ABSTRACT

Paraná leads the Brazilian production of beans so that the cultivation system can restrain the root development of the plants. Limestone and agricultural gypsum can be alternatives to stimulate the development of roots, and it is necessary to establish criteria for their use. The objective of this work was to evaluate the development of bean plants subjected to liming and gypsum doses in a typical Dystrophic Red Argisol. The experiment was carried out in Umuarama, state of Paraná in PVC tubes (80 x 15 cm), growing *Phaseolus vulgaris* cultivar Pérola for 90 days. Treatments consisted of gypsum doses (0, 420, 670, 950, 1140, 1430, 3000, and 5320 kg ha^{-1}) combined or not with lime application, in a factorial design (8 x 2) with four replications. At the end of the cycle, the aerial part of the plants and soil samples were collected for analysis. Gypsum doses benefited bean development, especially when associated with liming, which raised pH, Ca^{+2}, and Mg^{+2} and reduced Al^{+3} in the soil. The doses of maximum technical efficiency of gypsum were 3291 and 2991 kg ha^{-1} for the treatments with and without liming, respectively, also increasing the Ca^{+2} and available P concentration in the soil.

Keywords: agricultural gypsum; bean; fertilization; liming.

INTRODUCTION

The common bean (*Phaseolus vulgaris*) is an important crop for the state of Paraná as it has been the leading produced in Brazil in recent years, with the southern region holding 20% of the total cropped area and 30.8% of national production in 2022 (SIDRA, 2022). The form of bean cultivation may imply factors capable of optimizing or reducing crop productivity. In conventional systems, where the soil is turned with a plow and harrow, the reduction in the productive potential can occur due to the chemical, physical and biological degradation of the soil, so the search for conservationist systems capable of minimizing soil mobilization is justified (Torres *et al.*, 2018).

The direct seeding system revolutionized Brazilian agricultural production. This system is characterized by maintaining the cover of crop residues on the surface, which enables to maintain and/or increase of the organic matter and cation exchange capacity (CEC) of the soil. In addition, the effects of erosion are minimized, and the availability of water and nutrients increases, therefore optimizing plant development (Brown *et al.*, 2018). Over time, the surface action of fertilizers and acidity correctors tends to concentrate on the surface layer (0-10 cm), as these inputs are applied without incorporation into the subsurface, which restrains root growth (Batista *et al.*, 2018).

Agricultural gypsum can be an alternative to improve soil conditions and increase plant productivity, as it can promote the development of the root system of plants in depth, ensuring better crop performance,

Submitted on December 08th, 2022 and accepted on November 14th, 2023.
[1] Part of the first author's final paper as a requirement for obtaining the title of Agronomist Engineer at the State University of Maringá.
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because it is capable of providing calcium and sulfur in subsurface layers of the soil due to mobility on soil profile (Zandoná *et al.*, 2015). Liming promotes an increase in base saturation and soil pH, and gypsum can increase the subsurface calcium and sulfur concentration (Batista *et al.*, 2018).

Commonly, the result of the chemical analysis of the 20 - 40 cm layer of the soil must be observed for decision-making as to the need or not to apply gypsum, for most crops. The main indicators of the need for gypsum application are the levels of calcium (< 0.4 $cmol_c$ dm^{-3}), exchangeable aluminum (> 0.5 $cmol_c$ dm^{-3}), and aluminum saturation (> 20%) (Caires & Guimarães, 2018; Lopes & Guimarães, 1999; Raij *et al.*, 2022; Sousa *et al.*, 2005). To explain gypsum, the most used parameters for recommending agricultural gypsum doses are the need for liming, clay percentage, and base saturation (Lopes & Guimarães, 1999; Raij *et al.*, 2022; Ribeiro *et al.*, 1999; Sousa *et al.*, 2005; Vitti *et al.*, 2008). Caires & Guimarães (2018) describe calcium saturation in the effective CEC (< 54%) as an indicator of the need for gypsum application in soils under no-tillage in southern Brazil, which differs from other criteria for the application of agricultural gypsum developed before the conventional system.

Thus, the criteria established for the application of agricultural gypsum may imply a reduction in the doses, which reduces root development and exploration of the profile in greater depth (> 20 cm), enabling the Optimization of the productive potential of the crop. On the other hand, very high doses of gypsum can cause a chemical imbalance in the soil, which can harm plant development, as observed by Mota Neto *et al.* (2017), which explains the need for research capable of establishing the dose of maximum technical efficiency for bean cultivation.

For the crop to reach its maximum productive potential, the use of inputs such as agricultural gypsum and limestone in an adequate and complementary way is justified. Thus, the objective of this work was to evaluate the development of beans submitted to the application of limestone and doses of agricultural gypsum, to establish gypsum criteria in an Argisol with a sandy texture in the northwest region of Paraná, Brazil.

MATERIAL AND METHODS

The experiment was conducted in 2021, in an open experimental area, at the State University of Maringá, Regional Campus of Umuarama, state of Paraná. The geographical coordinates of the place are 23°47'26.7 "S and 53°15'24.5" W and an altitude of 401 m. The climate is characterized as Cfa, according to the Köppen classification, with high temperatures and poorly distributed rainfall throughout the year (Aparecido *et al.*, 2016).

The soil was collected in a native pasture area, with no history of agricultural activities, it was used in the experiment classified as a typical Dystrophic Red Argisol with a sandy texture (Santos *et al.*, 2018), which originally had pH in $CaCl_2$ = 4.04; Al^{+3}, Ca^{+2}, Mg^{+2}, and T (cation exchange capacity at pH 7.0) concentration of 0.9; 0.75; 0.25 and 5.41 $cmol_c$ dm^{-3} respectively, and potential acidity = 4.28 $cmol_c$ dm^{-3}, available P concentration = 4.7 mg dm^{-3}, K = 50.8 mg dm^{-3}, BS = 20.86%, m (aluminum saturation) = 16.64%, sand, silt and clay = 80.75; 0.25 and 19% respectively. Argisol samples were collected at the layer of 0-20 cm and used to fill PVC tubes 80 cm high and 15 cm in diameter, which constituted the experimental units.

The treatments consisted of eight doses of agricultural gypsum (equivalent to 0, 420, 670, 950, 1140, 1430, 3000, and 5320 kg ha^{-1}), established according to the methodologies described in Table 1 for soil layering 20-40 cm deep, combined or not with the lime application. The

Table 1: Methodologies used for the agricultural gypsum dose calculation

Authorship	Methodology	Dose (kg ha^{-1})
Ribeiro *et al.*, (1999)	$NG = 0.00034 – 0.002445x^{0,5} + 0.0338886x – 0.00176366x^{1,5}$	420
Vitti *et al.*, (2008)	NG = 0.25 x Need for liming	670
Sousa *et al.*, (2005)	NG = 50 x clay %	950
Raij *et al.*, (2022)	NG = 60 x clay %	1140
Sousa *et al.*, (2005)	NG = 75 x clay %	1430
Caires & Guimarães (2018)	NG = (0,6 x t -Ca concentration, in $cmol_c$ dm^{-3}) x 6.4	3000
Vitti *et al.*, (2008)	NG = (BS2-BS1) x T ($cmol_c$ dm^{-3})/50	5320

NG = need for gypsum; t = effective CEC; B2 = desired base saturation; B1 = real base saturation; T = CEC at pH 7.0.

experimental design was in randomized blocks, arranged in a factorial model (eight doses of agricultural gypsum and two forms of limestone application) with four replications. The application of an acidity corrector occurred together with the application of agricultural gypsum doses, with an incubation period of thirty days until sowing.

The agricultural gypsum used presented 259 g dm^{-3} CaO, 151 g dm^{-3} S, 7,48 g dm^{-3} P_2O_5 and 17,43% humidity. The acidity corrector used was dolomitic limestone (PRNT 100%), wich presented 25% CaO and 17% MgO, at a dose equivalent to 2680 kg ha^{-1} to raise the base saturation to 70%, according to the methodology proposed by Pauletti & Motta (2019) for the crop of beans in Paraná.

At sowing, all vases received the same doses of nitrogen, phosphorus, and potassium, equivalent to 205 kg ha^{-1} of urea, 670 kg ha^{-1} of simple superphosphate, and 70 kg ha^{-1} of potassium chloride, as recommended by Pauletti & Motta (2019) for bean cultivation. Bean cultivar BRS Pérola was sown in February 2021, maintaining a population of two plants per tube, which were cultivated for a cycle of 90 days. Soil moisture was maintained through watering using a watering can during dry periods and weed control was carried out by manual pulling, when necessary. The occurrence of anthracnose (*Colletotrichum lindemuthianum*) was observed 40 days after emergence (DAE), where control was carried out with two fortnightly applications of the combination of strobilurin and triazole at a dose of 500 mL ha^{-1} with the aid of a manual sprayer, according to the manufacturer's recommendations.

During the harvest period (90 DAE), the aerial part of the plants was collected and analyzed for aerial part height, stem diameter, fresh and dry mass (dried in an oven at 65 ºC for 72 hours), the mass of one thousand grains, and estimated grain yield. The economic efficiency dose for the application of agricultural gypsum was obtained through the model adapted from Michaelis-Meten (Srinivasan, 2022), according to $y = \frac{V_{max} \times x}{K + x}$, where: y = grain yield (kg ha^{-1}); x = gypsium doses (kg ha^{-1}); V_{max} = max speed of reaction and K = Michaelis-Menten constant. The determination of V_{max} and K where ajusted by the Non-linear least squares (NLS), folowing transformations described by Caroll *et al.* (1987), using R statistical software.

The soil of the plots was sampled (0-20 cm) with the aid of a soil auger, because this is where most of the bean root system is concentrated. The soil was dried and sieved (2 mm), and analyzed for pH in $CaCl_2$, exchangeable aluminum concentration, P, K^+, $Ca^{+2,}$ and Mg^{+2}, according to the methodology proposed by Teixeira *et al.* (2017).

The results obtained in this experiment were submitted to analysis of variance (F test). When a significant difference was found, the gypsum doses were subjected to regression analysis, and the forms of limestone application were compared by the T test, both at 5% error probability, using the SISVAR computational package computational (Ferreira, 2019).

RESULTS AND DISCUSSION

The use of limestone as an acidity corrector and the doses of agricultural gypsum increased the height of the aerial part, fresh and dry mass of the aerial part, one thousand-grain mass, and grain yeld (Table 2). This is the result of the soil acidity correction, making nutrients such as calcium and sulfur available by gypsum to bind to the CEC and be absorbed by the common bean plant, being an acidity-sensitive crop, promoted by the application of the acidity corrective (Galindo *et al.,* 2017).

The limestone increased the Ca^{+2} and Mg^{+2} concentrations, raised the pH and reduced the Al concentration, with no difference for the available P and K concentrations in the soil (Table 2), as the acidity corrective provides Ca^{+2} and Mg^{+2}, releasing OH^-, therefore neutralizing Al^{+3} and H^+, and it does not have available P or K^+ in its composition for availability in the soil (Eckert *et al.*, 2022). The doses of agricultural gypsum did not change the levels of K^+, pH and Al^{+3} in the soil, raising only the concentration of available P, as gypsum does not act as an acidity corrector, but provides Ca^{+2} and may present low available P concentrations (0.6-0.75%) as it is a residue from the phosphate fertilizer industry (Brignoli *et al.*, 2022). The interaction was significant between gypsum doses and limestone application for P, $Ca^{+2,}$ and Mg^{+2} concentrations (Table 2). This is because the acidity neutralization in low fertility soils increases the availability of these nutrients in the solution, by reducing the activity of Fe and Al oxides, responsible for irreversible P fixation of phytotoxic elements (Al^{+3} and H^+) in acidic soils, and makes Ca^{+2} and Mg^{+2} available, promoting their adsorption in the colloidal system and root absorption of nutrients in solution (Melo *et al.*, 2019).

Even in the treatments without liming, agricultural gypsum increased the height of the aerial part of the plants by up to 55.8%, in 85.8% and 70.5% the fresh and dry mass of the aerial part of the plants that did not receive liming (Figure 1A, C and D). The doses of agricultural gypsum increased grain yeld by more than 10 times

Table 2: Summary of pH variance analysis on pH, aluminum, available phosphorus, potassium, calcium and magnesium concentrations of a typical Dystrophic Red Argisol after *Phaseolus vulgaris* cultivation; the height of the aerial part, stem diameter, fresh and dry mass of aerial part, grain yeld and mass of a thousand bean grains subjected to doses of agricultural gypsum with and without lime application

F test	Height (cm)	Diameter (cm)	Fresh mass (g)	Dry mass (g)	Grain yeld (kg ha^{-1})	1,000 grain mass (g)
Block	0.4328	0.1184	0.5981	0.2546	0.0190	0.3985
L	0.0002*	0.0626ns	0.0001*	0.0001*	0.0002*	0.0002*
G	0.0001*	0.3075ns	0.0001*	0.0001*	0.0003*	0.0001*
L x G	0.0344ns	0.9982ns	0.1038ns	1461ns	0.1752ns	0.2722ns
CV (%)	11.94	15.35	10.01	18.37	17.19	12.74
F test	**pH ($CaCl_2$)**	**Al ($cmol_c$ kg^{-1})**	**P (mg kg^{-1})**	**K (mg kg^{-1})**	**Ca ($cmol_c$ kg^{-1})**	**Mg ($cmol_c$ kg^{-1})**
Block	0.9230	0.4537	0.6502	0.0162	0.6801	0.7080
L	0.0001*	0.0001*	0.5210ns	0.2088ns	0.0002*	0.0001*
G	0.5942ns	0.2591ns	0.0001*	0.4040ns	0.0001*	0.0002*
L x G	0.4606ns	0.2482ns	0.0004*	0.9884ns	0.0001*	0.0002*
CV (%)	4.00	21.47	14.86	17.36	7.18	3.97

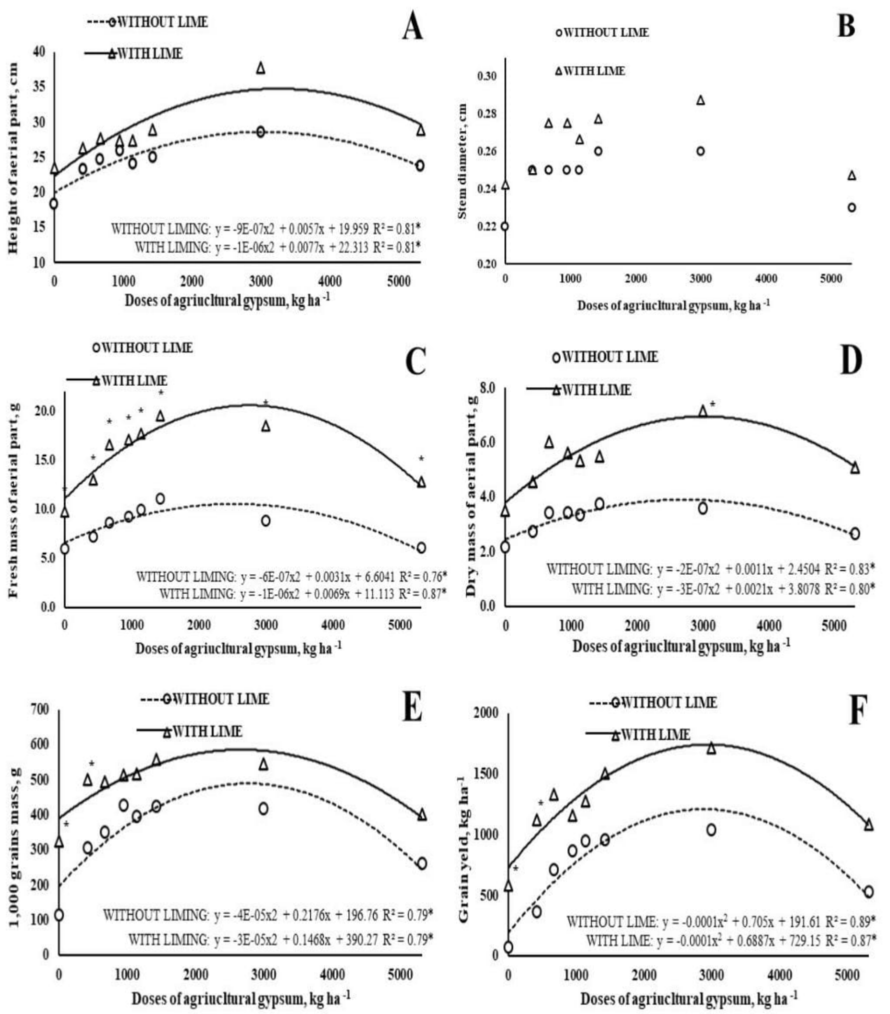
"L" represents the limestone variables, "G" is the agricultural gypsum variables, and "L x G" is the interaction between agricultural gypsum and limestone; CV = coefficient of variation; * and ns = significant and not significant at 5% probability, respectively.

and the mass of a thousand bean grains by up to 293% (Figure 1 E and F), highlighting the dose of 3000 kg ha^{-1} of gypsum. This is because of the high mobility of agricultural gypsum in the subsurface layers of the soil, allowing it to act below the arable layer, enhancing the exploration of the soil profile by the root system of crops with greater use of the nutrients applied to improve the performance of the plants in adverse conditions, such as drought (Amaral *et al.*, 2017).

Liming potentiated the effect of agricultural gypsum (Figure 1). In the treatments that received the doses of agricultural gypsum associated with the acidity corrector, a gain of 60.6% in plant height, 99.6%, and 104.3% in fresh and dry mass of aerial parts was observed respectively, in addition to a rise of up 191% in the grain yeld and 70.6% in the mass of a thousand grains of the common bean compared to the control (0 kg ha^{-1} of agricultural gypsum + liming). In addition, gypsum application promoted an increase in grain mass of up to 3.85 times when compared to the results obtained with the application of gypsum without liming. This demonstrates that agricultural gypsum does not replace liming as soil conditioners and acidity correctors have distinct and complementary action mechanisms. Lime promotes the neutralization of Al^{+3} and H^{+} in the soil top layer and makes Ca^{+2} and Mg^{+2} available. Gypsum, in turn, conditions the soil in depth by making Ca^{+2} and SO_4^{-2} available, which stimulates the deepening of roots, optimizes nutrient absorption capacity and favors plant development under conditions of water stress (Duart *et al.*, 2021).

Higher doses of agricultural gypsum impaired bean development, with a reduction of up to 45.3% and 28.7% in the fresh and dry mass of aerial parts, respectively, and by up to 42% in the mass of a thousand grains when compared to the best performance observed in this work (3000 kg ha^{-1}), especially with the highest dose 5320 kg ha^{-1} of agricultural gypsum (Figure 1). This must have occurred because the application of excessive doses of agricultural gypsum can promote an imbalance between nutrient elements in the soil (Ramos *et al.*, 2019) caused by the transport of nutrients such as Mg^{+2} (Caires *et al.*, 2004, Pauletti *et al.*, 2014), harming the development of cultivated plants.

By deriving the formulas obtained through regression analysis, the Maximum Technical Efficiency (MTE) doses for the application of agricultural gypsum in common bean cultivation were obtained (Table 3). The MTE doses were 3291 and 2911 kg ha^{-1} of gypsum for treatments with and without limestone application, respectively, obtaining an average of 3100 kg ha^{-1}. The MTE for treatments with liming may have been higher than those that did not receive it, since the acidity corrective allows the rise of the soil base saturation, facilitating the absorption of nutrient elements



* = significant at 5% probability.

Figure 1: Aerial part height (A), stem diameter (B), fresh mass of the aerial part (C), dry mass of the aerial part (D), 1,000 grain mass (E), and grain yield (F) of *Phaseolus vulgaris* subjected to different doses of agricultural gypsum, with and without the application of limestone in a typical Dystrophic Red Argisol.

by the plants, which allows the crop to reach higher levels of grain yeld (Ramos *et al.*, 2019). The doses of 420, 670, 950, 1140, and 1430 kg ha^{-1} of agricultural gypsum were much lower than the MTE doses, while the dose of 5320 kg ha^{-1} was very high for the common bean development observed in this work.

Therefore, the criterion for the application of agricultural gypsum proposed by Caires & Guimarães (2018) resulted in the dose closest to the maximum technical efficiency for the application of agricultural gypsum observed in this work, which is 3000 kg ha^{-1}. This corroborates the research carried out by Ascari & Mendes (2017) with soybean, also a legume, in which the MTE dose close to 3000 kg ha^{-1} of agricultural gypsum was estimated. However, this dose is higher than the current dose recommended by Pauletti & Motta (2019) for the State of Paraná, which is 700 kg ha^{-1} of gypsum for soils with clay concentrations up to 200 g kg^{-1}. The MTE doses of agricultural gypsum were higher for the height and grain yeld parameters in the treatments combined with liming (3850 and 3443 kg ha^{-1}) and without liming (3167 and 3525 kg ha^{-1}). This can happen due to the demand for Ca^{+2} by the bean plant, especially during the period of pod formation, reducing its abortion (Cardenas *et al.*, 2019), in addition to the benefit of making SO_4^{-2} available by gypsum, to increase plant height as a function of the increase in the root system (Nascente *et al.*, 2017).

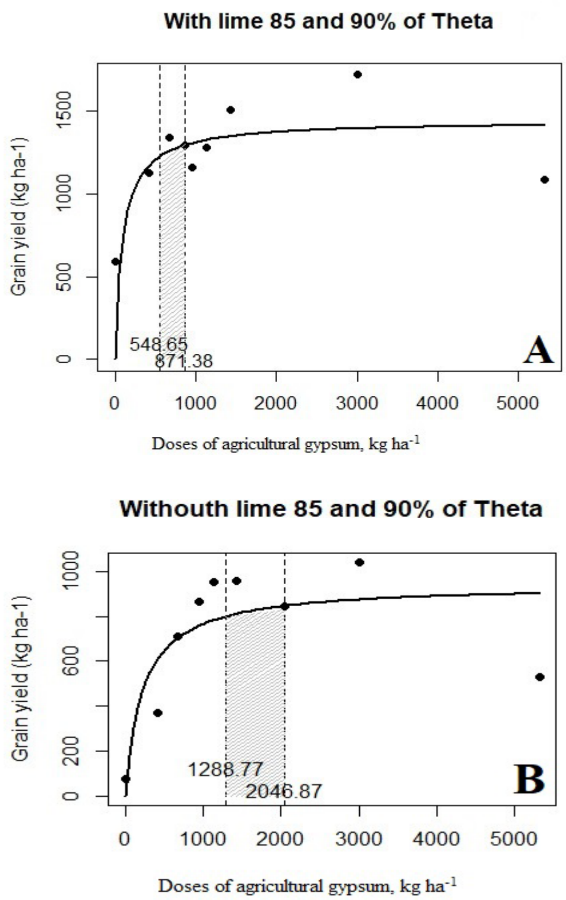
By using the model proposed by Michaelis-Menten, the economic efficiency dose for agricultural gypsum was obtained at 548.7 and 871.4 kg with the application of limestone, and at 1288.8 and 2046.9 kg without the use of

Table 3: Maximum technical efficiency doses of agricultural gypsum for the cultivation of *Phaseolus vulgaris* in a typical Dystrophic Red Argisol in northwestern Paraná

Variable	With liming (kg ha^{-1})	Without liming (kg ha^{-1})
Aerial part height	3850	3167
Stem diameter	2500	3000
Aerial part fresh mass	3450	2583
Aerial part dry mass	3500	2750
Grain yield	3443	3525
1,000 grain mass	2720	2446
Means	3291	2911

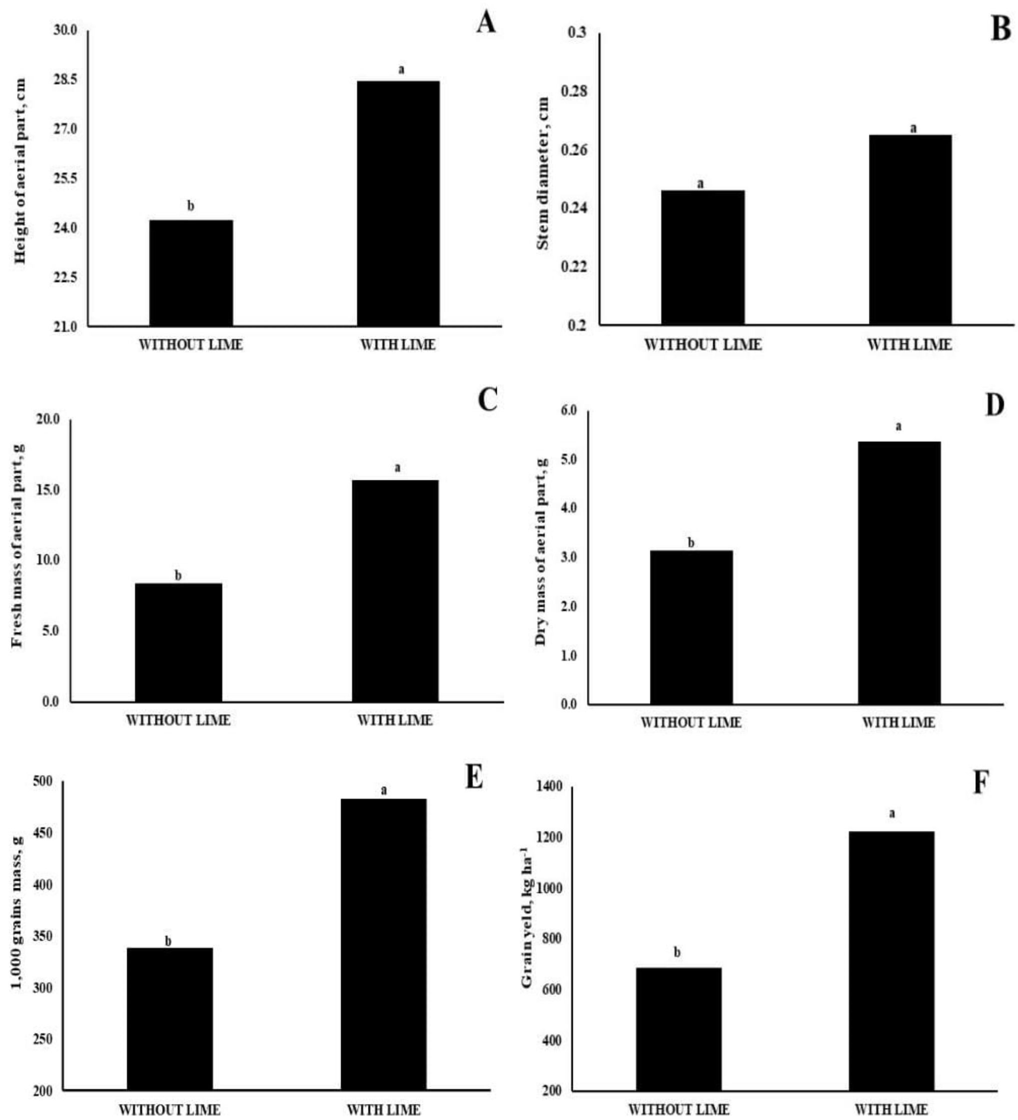
limestone (Figure 2), both compared to 85% and 90% of the maximum grain yeld obtained, respectively, according to the recommendations of Malchow & Ripps (1990).

This indicates that the economic efficiency of agricultural gypsum can be up to 134% higher in soils with corrected acidity as the acidity corrector contributes to soil fertility, not only by neutralizing phytotoxic elements but also through fertilization with Ca^{+2} and Mg^{+2}, which may reduce the demand for agricultural gypsum in corrected soils (Duart *et al.*, 2021; Lange *et al.*, 2021), which meets the results observed by Zandoná *et al.* (2015). This positive effect of limestone is confirmed by the increase in plant height (up to 16.7%), in the accumulation of fresh (up to 86.4%) and dry (up to 70.2%) matter in the aerial part by



Calculated by Michaelis-Menten equation, using R statistical software.

Figure 2: Maximum economic efficiency dose of agricultural gypsum for 85% and 90% of maximum grain yeld of *Phaseolus vulgaris* with (A) and without (B) lime application in a typical Dystrophic Red Argisol.



Equal letters are not different from each other by the T test at a 5% error probability.

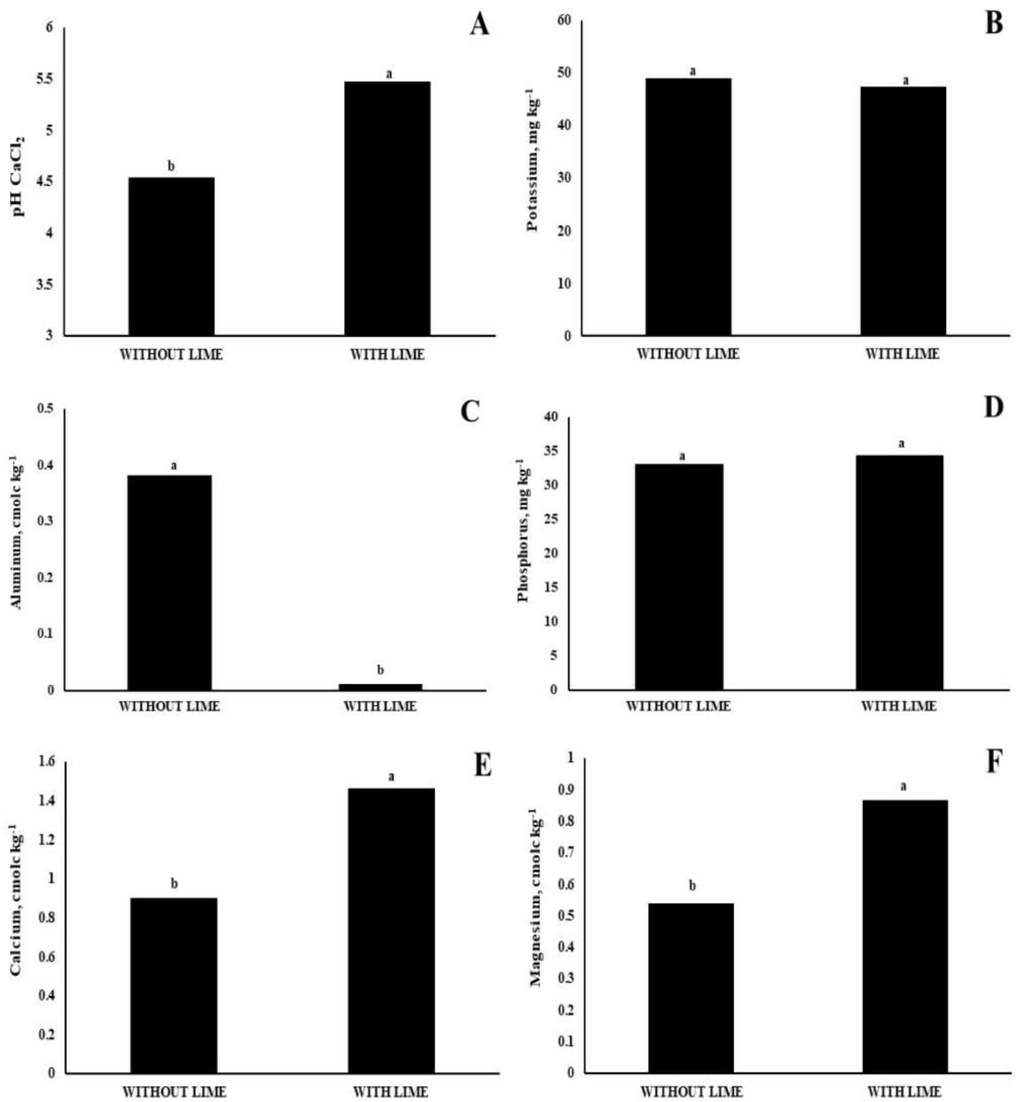
Figure 3: Aerial part height (A), stem diameter (B), fresh matter of the aerial part (C), dry matter of the aerial part (D), 1,000 grain mass (E), and grain yield (F) of *Phaseolus vulgaris* subjected to limestone application in a typical Dystrophic Red Argisol.

78%, and the increase (up to 78%) in grain yeld and mass (up to 41.3%) of a thousand bean grains when compared to the results obtained without the use of limestone (Figure 3).

In the soil, limestone increased the pH by up to 20.4%, allowing the pH to be raised to the ideal range, between 5.0 and 5.5 (Figure 4 A), which can provide 90 to 100% of the maximum production of culture (Pauletti & Motta, 2019).

Liming increased the Ca^{+2} concentration by 63% and the Mg^{+2} concentration by 59% in the soil (Figure 4 E and F), which proves the calcium and magnesium fertilization capacity of this acidity corrector (Coldebella *et al.,* 2018). The lime application also reduced the concentration of exchangeable aluminum in the soil by more than 97% (Figure 4 C). This occurs due to the acidity correction promoted by liming, through the release of hydroxyls (OH-), which act by insolubilizing toxic aluminum in solution (Al^{+3}) and binding to H^+ ions, causing the removal of these harmful elements from the cation exchange complex and allowing the nutrients responsible for the correct development of the plants to be absorbed by the root system of the crop (Melo *et al.*, 2019). There was no difference in the concentration of available P and K^+ in the soil with the application of limestone (Figure 4 B and D), which may occur due to the limestone composition, which does not allow the availability of these elements in the soil.

No changes were observed in the pH and Al^{+3} concentrations with the application of agricultural gypsum (Figure 5 A and B), which shows that this input does not



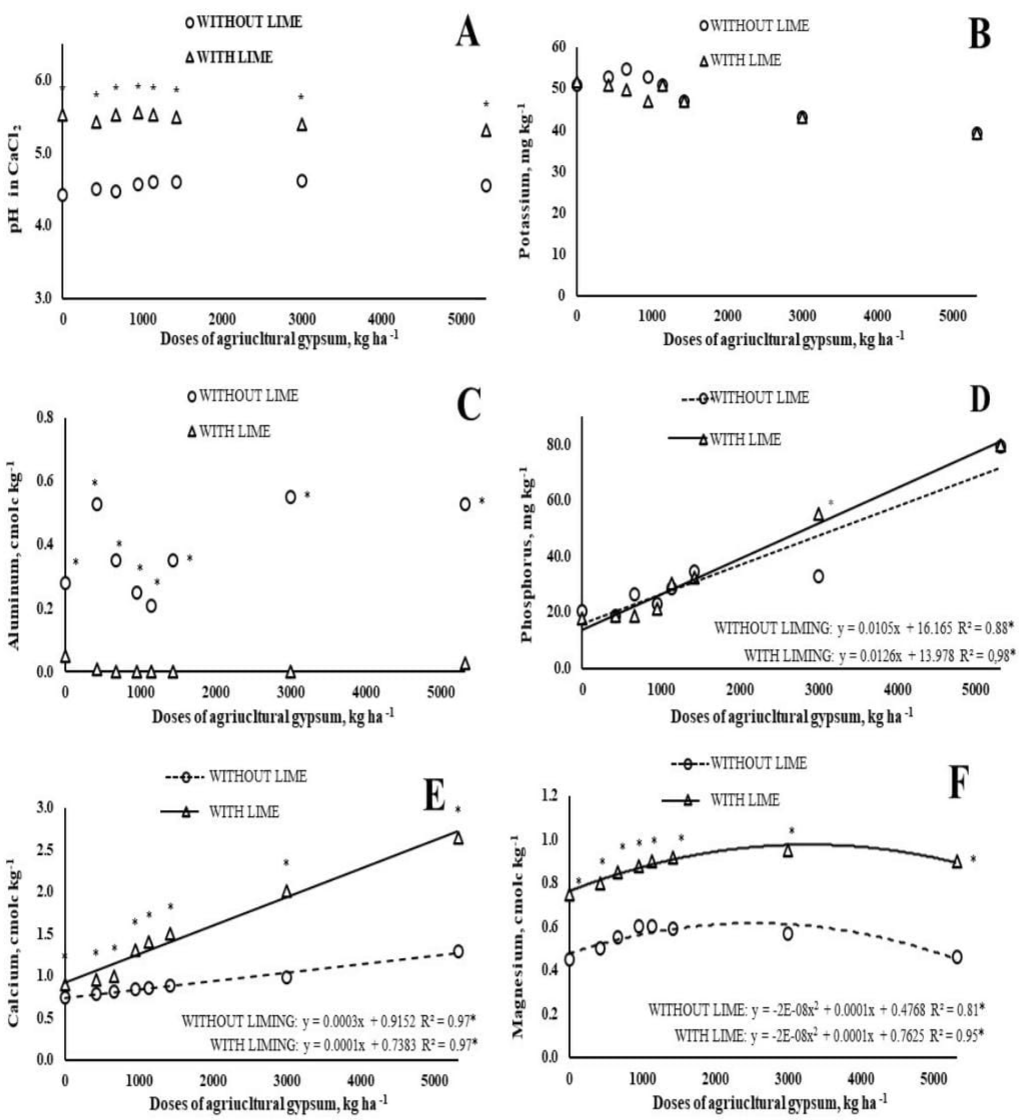
Equal letters do not differ from each other by the T test at a 5% error probability.

Figure 4: pH (A), potassium (B), exchangeable aluminum (C), available phosphorus (D), calcium (E) and magnesium (F) of a typical Dystrophic Red Argisol subjected to lime application for *Phaseolus vulgaris* cultivation in northwestern Paraná.

replace liming to correct soil acidity (Costa *et al.*, 2020). Agricultural gypsum is not considered acidity corrective because it does not release OH^- ions in solution, responsible for neutralizing soil acidity, acting only as a source of Ca^{+2} and SO_4^{-2}, conditioning the subsurface layers of the soil (Eckert *et al.*, 2022). The doses of agricultural gypsum increased the availability of available P and Ca^{+2} in the soil, regardless of the liming application (Figure 5 D and E). This may occur because agricultural gypsum is rich in Ca^{+2}, in addition to being a by-product of the fertilizer industry that has igneous phosphate rocks as raw material and may have varying concentrations of P_2O_5 in its composition (Brignoli *et al.,* 2022).

However, the highest dose of gypsum (5320 kg ha^{-1}) reduced the Mg^{+2} concentration of the soil by up to 30% (Figure 5 F). Probably, the use of excessive doses of agricultural gypsum must have generated an imbalance in the ratio (Ca / Mg) between nutrients in the soil due to the saturation of electrical charges due to the high presence of Ca^{+2}, which may cause nutritional disorders in plants (Pauletti *et al.*, 2014; Ascari & Mendes., 2017).

Thus, the dose of 5320 kg ha^{-1} of agricultural gypsum raised the concentration of Ca^{+2} and available P in the soil to a level considered high and very high (Pauletti & Motta, 2019), respectively, for soils in Paraná, as it can provide a decline in grain yeld due to nutritional imbalance or toxicity caused by the excess of nutrients (Ramos *et al.*, 2013). This highlights the importance of



* = significant at 5% probability.

Figure 5: pH (A), potassium (B), exchangeable aluminum (C), available phosphorus (D), calcium (E) and magnesium (F) of a typical Dystrophic Red Argisol subjected to different doses of agricultural gypsum, with and without the application of limestone for cultivation of *Phaseolus vulgaris* in northwestern Paraná.

works on the impact of the criteria for the application of agricultural gypsum on the development of cultivated plants.

CONCLUSION

The doses of agricultural gypsum benefited the development and grain yeld of common beans, especially when associated with the application of limestone to correct soil acidity. The dose of maximum technical efficiency of agricultural gypsum for the cultivation of common bean was 3291 and 2911 kg ha^{-1} with and without the use of limestone, respectively, the criterion being the closest to the appropriate dose: NG = (0.6 x t – Ca concentration, in cmol$_c$ dm^{-3}). Gypsum did not change pH, $K^{+,}$ and Al^{+3} in the soil, only increasing the levels of P, Ca^{+2} and Mg^{+2}.

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