Lime rates and methods of application for soybeans grew in a sandy latosol

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Abstract: Soil acidity correction aims to neutralize Al^{3+} and H^+ and supply Ca and Mg for the development of crops, such as soybean. However, there is no consensus on the optimum lime rates and application methods for sandy soils, especially in no-till, given their increased susceptibility to leaching of water and nutrients as well as the reduced capacity of soil colloids. Thus, the aim of this study was to compare the efficiency of lime rates and application methods and establish liming criteria for soybean production in a sandy Latosol in Northwestern Paraná. The experimental soil was a typical dystrophic Red Latosol of sandy texture. Treatments consisted of surface and incorporated application of lime to achieve 50%, 60%, 70%, and 80% base saturation and an untreated control (without lime). Soybean was grown in undeformed soil columns. After 114 days, plants were evaluated for height, stem diameter, shoot fresh weight, and shoot dry weight. The soil was analyzed for pH H_2O, pH $CaCl_2$, Al^{3+}, exchangeable calcium, exchangeable magnesium, available phosphorus and potassium. The liming criteria that resulted in the maximum development of soybean crops in sandy soil were base saturation of 60%, pH H_2O of 6.1, 3.20 $cmol_c\ kg^{-1}$ calcium, and 1.89 $cmol_c\ kg^{-1}$ magnesium.

Keywords: surface and incorporated liming, liming criteria, base saturation, grain yield.

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1 Introduction

Soybean crops are sensitive to soil acidity; high Al^{3+} levels (>0.5 $cmol_c\ kg^{-1}$) and low base saturation (<50%) are known to impair plant development and productive potential (Fontoura et al., 2019). However, Brazilian soils are naturally low in nutrients (<1.5 $cmol_c\ kg^{-1}$ Ca and <0.5 $cmol_c\ kg^{-1}$ Mg) and have low pH (<5.5), low base saturation (<50%), and high aluminum saturation (>20%) (CQFS, 2016; Crespo-Mendes et al., 2019; Ribeiro et al., 1999; Cantarella et al., 2022), demanding correctives for improved yields.

Lime is the most used agricultural input for neutralization of soil acidity. Adequate correction of soil acidity involves two important considerations, the first being the type of corrective agent and the second being the application rate (Fontoura et al., 2019). Different soil parameters can be used to justify the need for liming, such as pH H_2O below 5.5, base saturation below 50%, aluminum levels greater than 0.5 $cmol_c\ kg^{-1}$, calcium levels below 1.5 $cmol_c\ kg^{-1}$, and magnesium levels below 0.5 $cmol_c\ kg^{-1}$ (Nolla and Anghinoni, 2006).

It should be noted that liming not only decreases soil acidity and neutralizes phytotoxic Al^{3+} and H^+ but also fertilizes the soil with calcium and magnesium (Souza et al., 2014). Lime application to sandy soils (<15% clay) is mostly performed for fertilization purposes, as these soils tend to contain

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very low (<0.5 $\mathrm{cmol_c\ kg^{-1}}$) levels of aluminum (Nolla and Anghinoni, 2004). Such a practice indicates that sandy soils may require specific liming criteria that take into account their overall chemical properties, which commonly include low cation-exchange capacity (CEC, <5.0 $\mathrm{cmol_c\ kg^{-1}}$), low aluminum content (<0.3 $\mathrm{cmol_c\ kg^{-1}}$), and low base saturation (<50%) (Nolla et al., 2014). Thus, lime rate recommendations for sandy soils may be different from those for clay soils (Nolla et al., 2014). It is crucial to define optimum liming strategies for adequate crop development.

In conventional cropping systems, soil additives are incorporated by agricultural machinery. Their effects reach a depth of 20 cm and last for 3 to 5 years (Nolla et al., 2014). With the widespread adoption of no-till practices in Brazil, most cropping systems use soil conservation techniques, whereby lime is most commonly applied to the soil surface, producing effects up to a depth of 10 cm for 3 to 5 years (Caires et al., 2015). Therefore, when surface application is used, it is recommended to apply a lower rate of lime, as the effects of the product will be limited to more superficial layers. Another factor to bear in mind regarding no-till systems is that the maintenance of crop residues on the soil surface increases the supply of ligands capable of complexing with Al^{3+}, reducing the toxic effects of this anion on plant crops (Miotto et al., 2020).

One of the recommendations for surface liming in consolidated no-till systems (>5 years of implementation) is to apply half of the rates used in conventional systems CQFS, 2016. However, these guidelines were developed for cold climate soils that are not exposed to frequent droughts, contain more than 3.5% organic matter, and have medium/clay texture (Kaminski et al., 2005; Vezzani and Mielniczuk, 2011). For sandy soils with organic matter contents below 13 $\mathrm{g\ kg^{-1}}$, it is still necessary to assess the suitability of this practice (Fageria, 2001; Zhao et al., 2015).

This study aimed to compare the efficiency of different lime rates and methods of application to establish liming criteria for optimum soybean development in a sandy Latosol.

2 Material and methods

The experiment was installed in early July 2014 at Northwest Paraná state, Brazil. The climate is classified as mesothermal humid subtropical, with an annual average temperature of 22.1 ℃. The soil is a typical dystrophic Red Latosol (EMBRAPA, 2018). Soil chemical properties in the 0–20 cm layer are described in Table 1.

Undeformed columns (30 cm diameter × 60 cm height) were taken from the soil that presented typical dystrophic Red Latosol (clay content = 156.5 $\mathrm{g\ kg^{-1}}$). Treatments consisted of the application of dolomitic limestone (relative power of total neutralization = 75.2%) to the soil surface or with incorporation (to a depth of 0−10 cm) at rates calculated to raise base saturation to 50% (1.4 $\mathrm{t\ ha^{-1}}$), 60% (2.4 $\mathrm{t\ ha^{-1}}$), 70% (3.4 $\mathrm{t\ ha^{-1}}$), and 80% (4.4 $\mathrm{t\ ha^{-1}}$). An untreated control was included for both application methods. The experimental design was a randomized block with 10 treatments and 3 replications, totaling 30 plots in a 5 × 2 factorial arrangement.

Table 1 Chemical properties in the 0–20 cm layer of a typical dystrophic Red Latosol of sandy texture under native forest

	OM	Clay	P	K	Al	Ca	Mg	H + Al	CEC	BS
pH (H_2O)	-----g $\mathrm{kg^{-1}}$-----		--mg $\mathrm{dm^{-3}}$--		------------$\mathrm{cmol_c\ dm^{-3}}$------------					%
5.2	5.38	156.5	7.00	31.28	0.0	1.63	1.13	4.96	7.81	36.51

Note: pH was measured in H_2O using a soil/solution ratio of 1:2.5. Ca, Mg, and Al were extracted with 1 mol L^{-1} KCl. P and K were extracted with Mehlich-1 solution (0.05 mol L^{-1} HCl + 0.025 mol L^{-1} H_2SO_4). OM, organic matter (Walkley–Black method); H + Al, potential acidity (SMP method); CEC, cation-exchange capacity at pH 7; BS, base saturation.

At 90 days after lime application, seeds of soybean 5909 RR Nidera were sown in the soil columns. Seeds were previously treated with fungicide (fludioxonil + metalaxyl-M), insecticide (imidacloprid), and biological agent (*Bradyrhizobium* bacteria). At the time of sowing, the soil was fertilized with 40 $\mathrm{kg\ ha^{-1}}$ P_2O_5 and 60 $\mathrm{kg\ ha^{-1}}$ K_2O, in agreement with recommendations for soybean crops (Pavinato et al., 2019). During plant development, soil moisture was kept close to field capacity by irrigation in dry periods. Control of diseases and pests was carried out by spraying plants with 0.3 L ha^{-1} methomyl and 0.5 L ha^{-1} epoxiconazole at 60 days after germination. Weed control was performed manually. At 114 days after sowing, plants were harvested and evaluated for height, stem diameter, shoot fresh weight, and shoot dry weight. Dry weight determination was performed by oven-drying samples at 105 ℃.

Soil samples were collected from the 0−10 cm layer and used for determination of pH H_2O, exchangeable calcium (Ca), exchangeable magnesium (Mg), available phosphorus (P), available potassium (K), and potential acidity (H + Al), according to the methods proposed by Tedesco et al. (1995). Base saturation was calculated.

Data were subjected to analysis of variance by the *F*-test using SISVAR software. When the *F*-value was significant at $p < 0.01$, differences between application methods were assessed using Tukey's test at $p < 0.05$ and lime rates were subjected to regression analysis.

3 Results and discussion

The mean squares for lime rates were significant at $p < 0.01$ for all soil chemical properties (Table 2). As for application methods, only P content was found significant at $p < 0.01$ by the *F*-test. The interaction between lime rate and application method was significant for pH, H_2O and P, as illustrated in Table 2.

Both liming methods were equally efficient in raising the soil pH (Figure 1a). This finding indicates that, under the conditions of the current experiment, surface application of lime would be a suitable strategy for correction of soil acidity, providing the added benefit of preserving soil physical and chemical quality. Surface and incorporated application of 2.4 t ha^{-1} lime increased base saturation by 59% and 63%, respectively (Figure 1h), and increased pH H_2O to above 6.0, regardless of the application method. Lime rates of 3.4 and 4.4 t ha^{-1} resulted in pH H_2O values of 7.3 and 7.2, respectively (Figure 1a). Nolla et al. (2014) and Brignoli et al. (2020) stated that the optimum pH H_2O for soybean development is between 5.4 and 6.0. According to Dede et al. (2017), high pH values lead to unavailability of micronutrients.

Table 2 Analysis of variance for chemical properties of a typical dystrophic Red Latosol treated with different lime rates by different methods of application

Source of variation	pH (H_2O)	Al^{3+}	K	P	Ca	Mg	H + Al	BS
Application method (*A*)	0.0^{ns}	0.0^{ns}	8.74^{ns}	17.48**	0.38^{ns}	0.14^{ns}	0.97^{ns}	2.70
Lime rate (*R*)	4.96**	0.05**	89.5**	116.2**	7.86**	3.72**	7.48**	1672.8**
$A \times R$	0.05*	0.0^{ns}	0.78^{ns}	1.52*	0.05^{ns}	0.08^{ns}	0.24^{ns}	14.7^{ns}
CV (%)	2.05	21.91	4.24	3.08	2.69	4.41	1.4	1.2

Note: BS, base saturation; ns, not significant; * significant at $p < 0.05$ by the *F*-test; ** significant at $p < 0.01$ by the *F*-test; CV, coefficient of variation.

Al^{3+} contents (Figure 1b) decreased to undetectable levels with all lime rates. This effect is due to the increase in pH H_2O, which corrected the active acidity of soil and increased the contribution of bases to CEC. It is worth noting that, even though the soil was acidic, it did not have problems with high Al^{3+} contribution to CEC, as indicated by analysis of the untreated control, whose Al^{3+} content was found to be lower than 0.5 cmol$_c$ kg^{-1} (Nolla et al., 2014).

Liming increased Ca (Figure 1c) and Mg (Figure 1d) levels, as expected. Lime is recommended as a fertilizer for sandy soils, which are typically classified (Pavinato et al., 2019) as low in both Ca (<1.5 cmol$_c$ kg^{-1}) and Mg (<0.5 cmol$_c$ kg^{-1}) because of their low CEC. The minimum thresholds for Ca and Mg were achieved with the lowest lime rate (1.4 t ha^{-1}). The highest Ca levels (4.4 and 4.9 cmol$_c$ kg^{-1} for incorporated and surface liming, respectively) and the highest Mg levels (2.9 and 2.7 $\text{cmol}_c\ \text{kg}^{-1}$ for incorporated and surface liming, respectively) did not differ between application methods. High lime rates (base saturation above 80%) can lead to nutritional imbalance because, as Ca and Mg increase, some other nutrients may become unavailable to plants. An example of such a nutrient is K, a base cation that competes with Ca and Mg for exchange sites (Mascarenhas et al., 2014).

Surface application and incorporation of lime were equally efficient in increasing available K content (Figure 1e) up to a lime rate of 2.4 t ha^{-1} and a target base saturation of 60%. The highest lime rates (3.4 and 4.4 t ha^{-1}) caused a reduction in K availability compared with intermediate rates (1.4 and 2.4 t ha^{-1}, target base saturations of 50% and 60%). This is because high lime rates increased the levels of Ca and Mg in the exchange complex, favoring K leaching and thereby reducing K availability; ultimately, such effects lead to a reduction in plant development and because of its low adsorption capacity in the exchange complex, K is one of the nutrients with the lowest availability under conditions of excess lime (Prajapati and Modi, 2012).

Lime was efficient in increasing P availability (Figure 1f). Surface application up to a rate of 2.4 t ha^{-1} afforded higher P levels than incorporation (Figure 1f); these methods increased base saturation by 59% and 63%, respectively (Figure 1h). The available P contents in unlimed treatments and treatments receiving the highest rate (4.4 t ha^{-1}) were classified as low (7.1–14 mg kg^{-1}), considering sandy soils with a clay content of less than 20% (Pavinato et al., 2019). In the other treatments, P levels were greater than 17 mg kg^{-1} (intermediate availability), reaching a maximum value (23 mg kg^{-1}, high availability) in incorporated lime treatments. This result can be attributed to pH levels (5.5 to 6.5), which contributed to enhancing P availability, given that P fixation by iron oxides is reduced under conditions of low solubility (Barrow, 2015). High lime rates (3.4 and 4.4 t ha^{-1}) reduced P availability, as the pH was greater than 6.5 (Figure 1f). Thus, high lime rates increased not only OH^- release but also exchangeable Ca levels (Figure 1c). Under these conditions (pH $H_2O > 6.5$), P retrogradation likely occurred via formation of calcium phosphate (insoluble), which precipitates and therefore becomes unavailable to plants (Nolla et al., 2014).

H + Al decreased linearly with increasing lime rates (from 1.4 t ha^{-1} onward). With an increase in pH (Figure 1a), there is a reduction in H^+ availability, as the ion is neutralized by the corrective. Furthermore, we observed an increase in Ca and Mg availability (Figure 1c and 2d). These elements likely displaced Al^{3+} from the exchange complex (Figure 1b), thereby reducing H + Al values.

The corrective was effective in increasing base saturation (Figure 1h). The parameter increased linearly with increasing lime rates (1.4 t ha^{-1} onward), and values were close to target base saturations (50%, 60%, 70%, and 80%). No differences were observed between application methods. This result is attributed to the fact that lime supplied Ca and Mg, which were leached regardless of the mode of application. Soybean has high nutrient requirements (Andric et al., 2012); base saturation must be at least 50% (Pavinato et al., 2019).

In applying lime, it is necessary to determine the rate that provides the best conditions for nutrient availability and utilization by plants. Thus, we derived the regression equations of lime rates (incorporated and surface treatments) to determine the best efficiency rate for P and K availability (Table 3). It was observed that, for both P and K, the optimal lime rate was close to the rate that increased base saturation to 63% by incorporation and 59% by surface application (2.4 t ha^{-1}) (Figure 1). Such base saturation values are higher than that recommended for soybean grown in sandy soils (50%) (Cantarella et al., 2022; Pavinato et al., 2019).

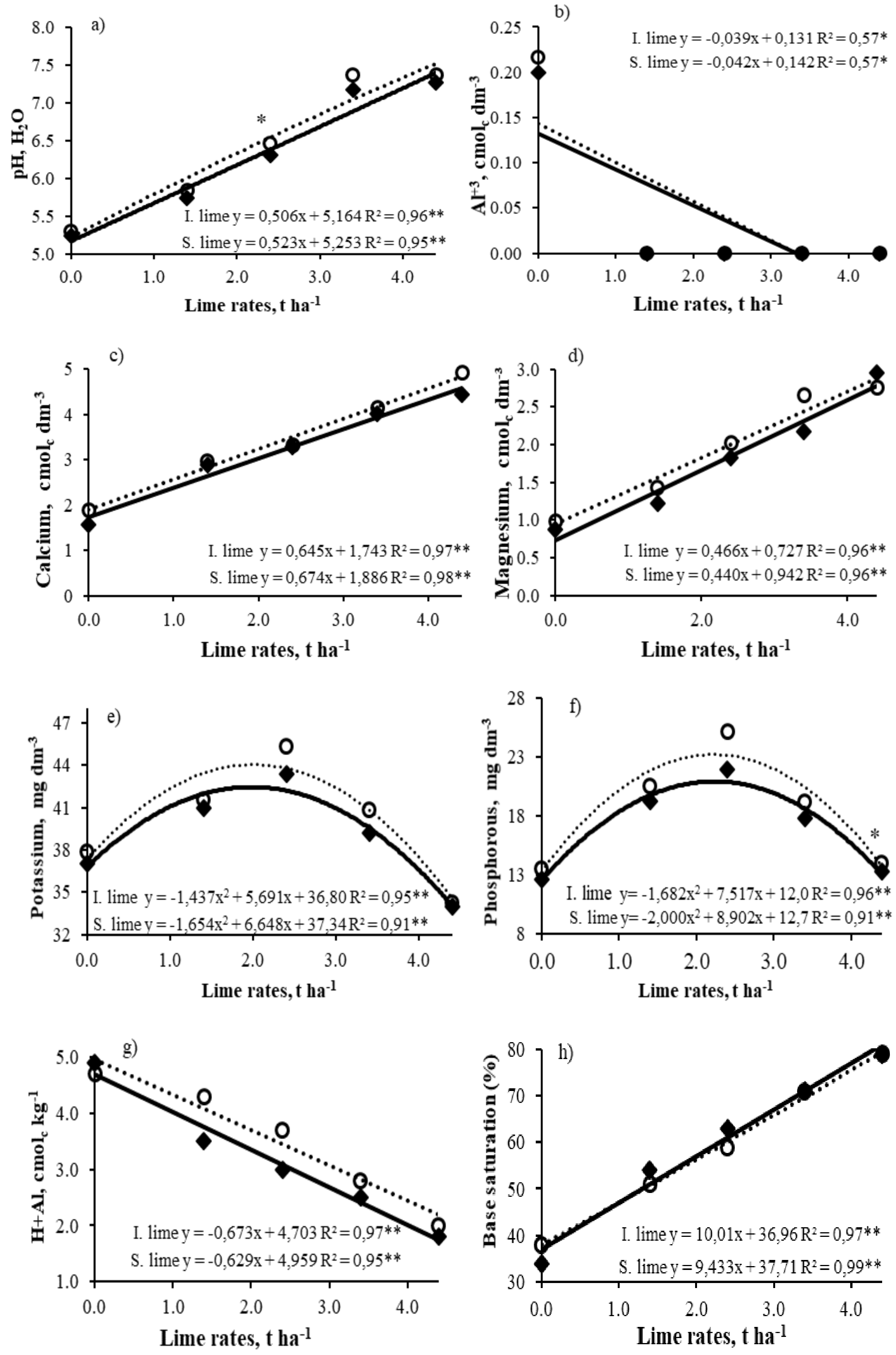


Figure 1 – pH H_2O, Al, Ca, Mg, K, P, H + Al, and base saturation of a typical dystrophic Red Latosol treated with different lime rates by different methods of application.

* indicate significant differences between methods of application ($p < 0.05$, Tukey's test)

Table 3 Reference rates for meeting lime requirements in a typical dystrophic Red Latosol under soybean based on maximum contents of available phosphorus and potassium

Liming method	Phosphorus method	Potassium method
	Lime rate (t ha^{-1})	
Surface application	2.2	2.0
Incorporated application	2.2	1.9
Mean	2.2	2.0

Such a difference between optimal (59% and 63%) and recommended (50%) base saturations may be explained by the fact that, in addition to correcting soil acidity, liming should be used to optimize P and K use, given that crop profitability depends on optimizing input costs. Thus, lime rates of 3.4 and 4.4 t ha^{-1} are not recommended for the tested sandy soil, as they decrease P and K availability, reducing the efficiency of fertilizers (Nolla et al., 2014).

For all agronomic variables, the mean squares of lime rate were significant at p <0.01 by the F-test (Table 4). Method of application only exerted significant effects (p < 0.01, F-test) on stem diameter and plant height. Significant interaction effects were observed on shoot fresh and dry weights.

Soybean development was superior with liming, whether superficially applied or incorporated (Figure 2). This finding demonstrated that surface liming, the main technique used in no-till systems, is feasible for the tested soil conditions. Thus, it is feasible to leave crop residues on the soil surface and stir the soil only on the sowing line, practices that protect soil against erosion and promote the use of nutrients (resulting from mineralization of organic matter) by plants throughout the crop cycle (Verdum, 2016).

Plant development was higher at lime rates of 1.4 and 2.4 t ha^{-1}, because, under these conditions, the pH was 5.5–6.5, leading to an increase in P and K availability (Barrow, 2015) and adequate balance of macro- and micronutrients (Mascarenhas et al., 2014). P availability is related to soil pH: when the soil pH is lower than 5.5, P availability decreases. Liming increases P availability because of the increase in pH (reduced acidity) and Mg^{2+} levels in the soil solution. Mg exerts synergistic effects, stimulating plant development (Nolla et al., 2014). High lime rates (3.4 and 4.4 t ha^{-1}), however, promoted a reduction of up to 25% in plant height (10 cm reduction) (Figure 2a). This effect was due to the excessive increase in pH H_2O (>6.5), which reduced the availability of P (retrogradation) and K, nutrients that play a major role in plant metabolism, photosynthesis, respiration, and growth (Viviani et al., 2010).

Lime at a rate of 2.4 t ha^{-1}, whether applied to the soil surface or incorporated, increased stem diameter by up to 21% (Figure 2b). The improvement in nutrient availability with soil treatment likely promoted vegetative development, as reflected on plant height (Figure 2a) and, consequently, stem diameter (Figure 2b). High lime rates (3.4 and 4.4 t ha^{-1}), however, reduced stem diameter, resulting from the decrease in P and K availability and a possible nutritional imbalance, particularly in soils with pH greater than 7.0 (Figure 1e).

Table 4 Analysis of variance for agronomic characteristics of soybean crops grown in a typical dystrophic Red Latosol treated with different lime rates by different methods of application

Source of variation	Shoot fresh weight	Shoot dry weight	Stem diameter	Plant height
Application method (A)	0.00^{ns}	0.00^{ns}	0.45**	14.0**
Lime rate (R)	102.0**	94.67**	1.56**	55.5**
$A \times R$	6.40**	5.69**	0.00^{ns}	0.23^{ns}
CV (%)	4.50	3.87	2.86	5.38

Note: ns, not significant; ** significant at p < 0.01 by the F-test; CV, coefficient of variation.

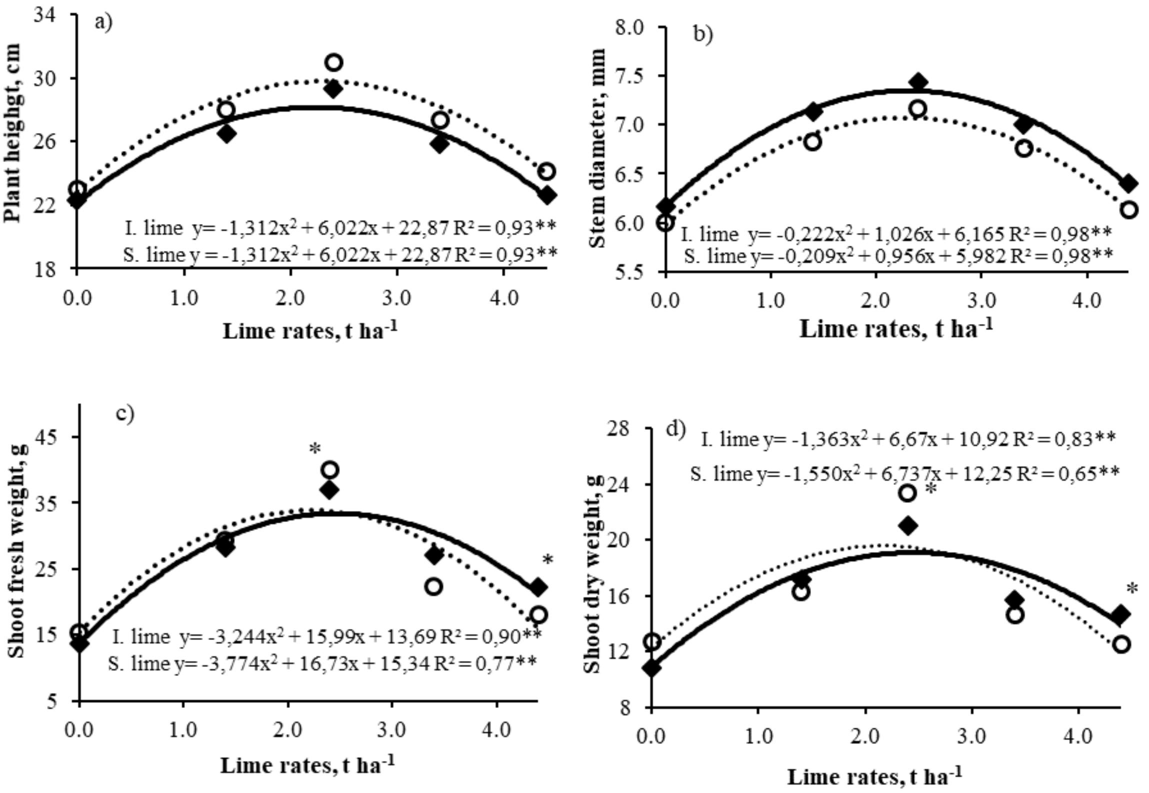


Figure 2 Plant height , stem diameter, shoot fresh weight and shoot dry weight of soybean crops grown in a typical dystrophic Red Latosol treated with different lime rates by different methods of application

Shoot fresh (Figure 2c) and dry (Figure 2d) weights increased with liming. Surface application was more efficient in promoting biomass accumulation, underscoring the efficiency of no-till management practices, which increase the residual effect of nutrients (Caires et al., 2015).

Shoot dry weight increased by up to 2.4-fold in limed treatments compared with unlimed treatments. Adequate correction of soil acidity and the consequent increase in nutrient utilization by plants contribute to plant development, promoting growth and biomass accumulation (Figure 2c and 3d) (Barrow, 2015). As observed previously, the use of the highest lime rates (3.4 and 4.4 t ha^{-1}) decreased dry matter accumulation. A reduction in nutrient availability directly influences plant development (Mascarenhas et al., 2014). In soybean, chlorosis may occur at the leaf edge, reaching the ribs and leading to necrosis of the leaves and stem, thereby affecting plant height and weight.

The maximum efficiency point was determined from the first derivative of equations depicted in Figure 1 (Table 5). Vegetative indices (plant height, stem diameter, and shoot fresh and dry weights) for lime requirements were quite similar, demonstrating the reliability of the proposed criteria.

Table 5 Reference rates for meeting lime requirements through surface and incorporated application in a typical dystrophic Red Latosol based on maximum vegetative parameters of soybean crops

Parameter	Lime rate (t ha^{-1})	
	Surface application	Incorporated application
Plant height	2.3	2.2
Stem diameter	2.4	2.3
Shoot fresh weight	2.3	2.3
Shoot dry weight	2.3	2.4
Mean	2.3	2.3

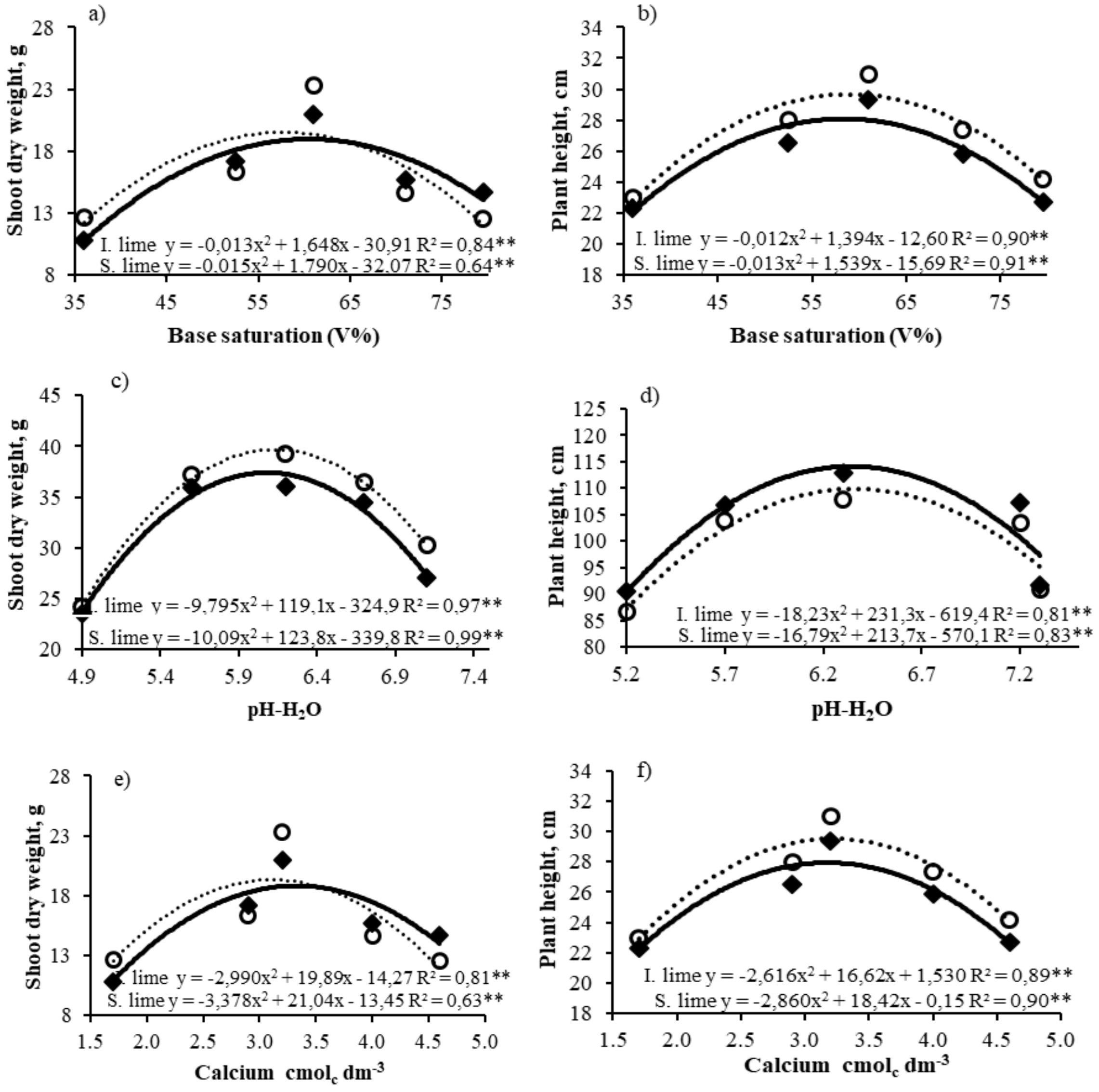
The relationship of plant height and shoot dry weight with soil chemical attributes (base saturation, pH H_2O, Ca, and Mg) was assessed to determine the conditions that provide maximum vegetative development in soybean. Regression equations were derived to estimate maximum values, as described in Table 6.

Maximum shoot dry weight (Figure 3a) and plant height (Figure 3b) were estimated to be achieved with a base saturation of 60% (Table 5), corresponding to a lime rate of 2.4 t ha^{-1}. Under these conditions, plants showed superior growth and development, corroborating the results of Caires et al. (2015).

Table 6 Liming criteria for optimum development of soybean crops in a typical dystrophic Red Latosol

Plant parameter	Application method	Base saturation	pH (H_2O)	Ca	Mg
		%		$cmol_c\ dm^{-3}$	
Shoot dry weight	Incorporated	59.6	6.1	3.11	1.86
	Surface	63.3	6.0	3.32	1.95
Height	Incorporated	59.1	6.3	3.22	1.88
	Surface	58	6.3	3.17	1.90
Mean		60	6.1	3.20	1.89

H_2O and pH had a quadratic relationship with shoot dry weight (Figure 3c) and plant height (Figure 3d). Vegetative parameters decreased at pH levels below 5.5 and above 6.5, showing that these pH conditions negatively affect plant development. The mean pH that afforded maximum soybean development was 6.1, which is within the ideal pH range for soybean (5.5 to 6.5), according to Brignoli et al. (2020).



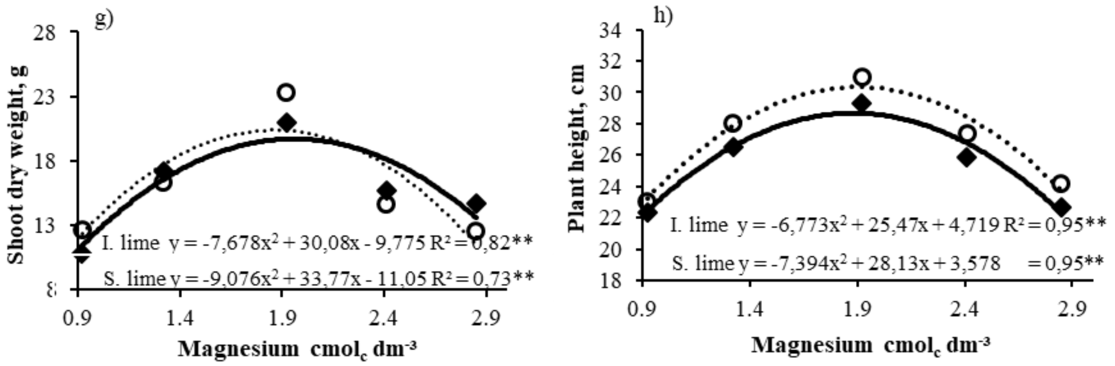


Figure 3 Shoot dry weight (a, c, e, and g) and height of soybean plants (b, d, f, and h) as a function of pH H_2O, calcium, and magnesium in a typical dystrophic Red Latosol treated with different lime rates by different methods of application

Ca (Figure 3e and 3f) and Mg (Figure 3g and 3h) contents were related to shoot dry weight and plant height, respectively. Ca levels below 3.0 cmol$_c$ kg^{-1} and above 3.5 cmol$_c$ kg^{-1} were estimated to reduce shoot dry weight. Similarly, Mg contents below 1.8 cmol$_c$ kg^{-1} and above 2.0 cmol$_c$ kg^{-1} were associated with reduced plant height. Maximum vegetative development was estimated to be achieved with 3.20 cmol$_c$ kg^{-1} Ca and 1.89 cmol$_c$ kg^{-1} Mg. These values are below the critical levels preconized for Rio Grande do Sul and Santa Catarina States (CQFS, 2016) but higher than those determined by Minas Gerais State (Ribeiro et al., 1999) and São Paulo State (Cantarella et al., 2022). Even when Ca and Mg contents were higher than the critical levels (Viviani et al., 2010), there was a reduction in vegetative growth, probably because of the decrease in P and K availability. Differences in critical levels may be explained by the fact that sandy soils generally have low CEC and, thus, fewer binding sites for Ca and Mg, resulting in low base saturation. By contrast, soils of Rio Grande do Sul and Santa Catarina States are generally clayey, with high CEC (15 cmol$_c$ kg^{-1}).

Shoot dry weight (Figure 4a and 4c) and plant height (Figure 4b and 4d) increased linearly with K and P levels. These nutrients directly influence soybean growth and development. P and K deficiency is associated with loss of biomass and may even result in leaf necrosis (Bender et al., 2015).

The derivative of the regression equations for shoot dry weight and plant height afforded the values of base saturation, pH H_2O, Ca, and Mg that provide maximum soybean development (Table 6).

The optimum base saturation was found to be 60%, similar to the value recommended for São Paulo State (Cantarella et al., 2022) but different from that recommended for Rio Grande do Sul (65%–70%) (CQFS, 2016) and it is corroborating the results of previous studies (Nolla et al., 2014; Bossolani et al., 2021).

The optimal pH H_2O was 6.1, similar to the recommendation for São Paulo and Minas Gerais (Cantarella et al., 2022) and different from the recommendation for Rio Grande do Sul and Santa Catarina (pH 5.5) (CQFS, 2016).

The Ca and Mg contents that promoted maximum soybean development were 3.20 cmol$_c$ kg^{-1} and 1.89 cmol$_c$ kg^{-1}, respectively. These values were higher than the critical levels for Minas Gerais (1.5 cmol$_c$ kg^{-1} Ca and 0.5 cmol$_c$ kg^{-1} Mg) but lower than the critical levels for Rio Grande do Sul and Santa Catarina (4.0 cmol$_c$ kg^{-1} Ca and 1.0 cmol$_c$ kg^{-1} Mg) (CQFS, 2016).

Overall, using acidity indices and plant parameters as a reference to determine the optimum lime rate, it was found that the rates estimated here (2.27 and 2.30 t ha^{-1} lime, respectively) were similar to the index used to determine lime requirements (pH 5.5) for soybean grown in São Paulo State (Cantarella et al., 2022). Thus, the recommendation to lime to 60% base saturation reflects with good accuracy the real lime requirements of soybean grown in sandy soil.

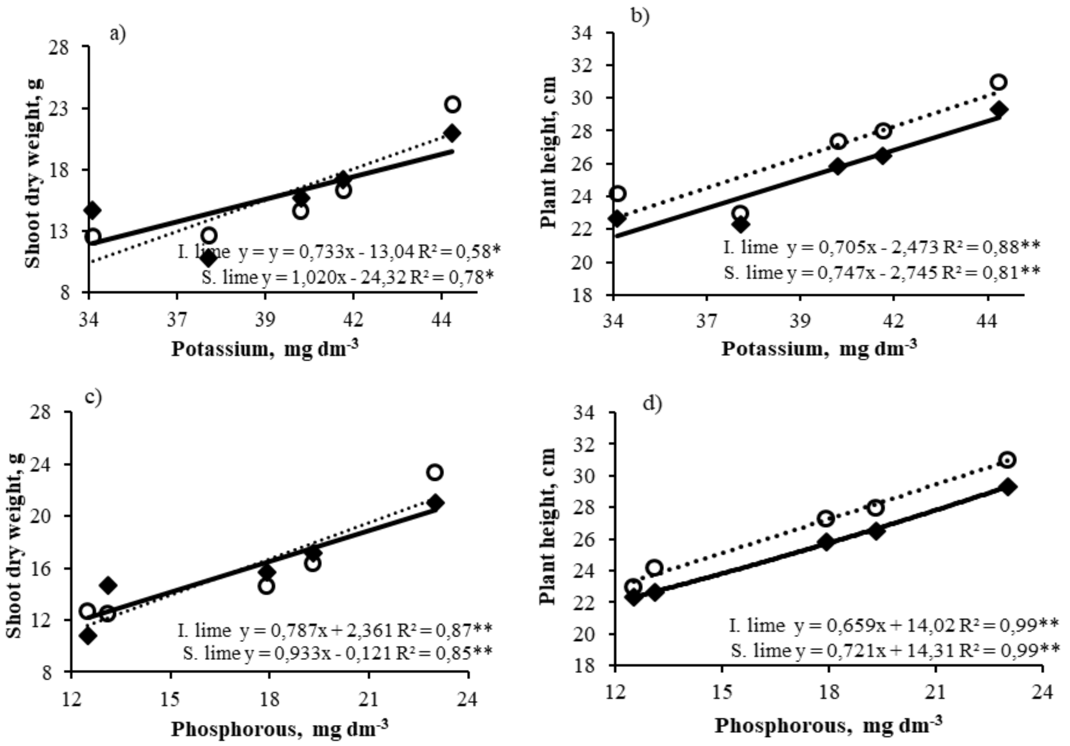


Figure 4 Shoot dry weight (a and c) and height of soybean plants (b and d) as a function of potassium and phosphorus contents in a typical dystrophic Red Latosol treated with different lime rates by different methods of application

4 Conclusions

Liming corrected soil acidity and enhanced soybean growth by both methods of application. Surface application, however, was more efficient in increasing P content and plant height. Maximum soybean development was estimated to be achieved with liming at a rate of 2.3 t ha^{-1} by either application method, which would increase base saturation to 60%. Liming criteria for maximum soybean development in sandy soils are base saturation of 60%, pH H_2O of 6.1, Ca content of 3.20 cmol$_c$ kg^{-1}, and Mg content of 1.89 cmol$_c$ kg^{-1}.

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