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Agronomic Efficiency of Two Types of Lime and Phosphate Fertilizer Sources in Brazilian Cerrado Soils Cultivated with Soybean

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With the increase in phosphate fertilizer prices, there is a need to find lower-cost alternatives that are as efficient as soluble sources such as single (SSP) and triple superphosphate (TSP). In Brazil's northern and northeastern regions, there are reserves of igneous rocks with low solubility containing high concentrations of total phosphorus (P) that can be used to produce fertilizers, such as thermalphosphates. To assess the efficiency of sources of P and two types of lime on soybean yield, a field experiment was carried out in an area with dystrophic Red Latosol (Oxisol) in a Cerrado region in the southern part of Maranhão State. The experimental design was randomized blocks in a 2 × 3 × 4 factorial scheme, with four replicates. The treatments were two types of lime [calcitic (CL) (<5 dag kg^{-1} of MgO) and dolomitic (DL) (>13 dag kg^{-1} of MgO)], three phosphate fertilizer sources [triple superphosphate (TSP), "Yoorin" thermalphosphate (YT), and experimental thermalphosphate (ET)], and four rates of phosphorus pentoxide (P_2O_5; 0, 100, 200, and 300 kg ha^{-1}). After 2 years of cultivation, the application of DL resulted in greater soybean yields than the application of CL. The two lime types influenced the pH, carbon (C), calcium (Ca), and magnesium (Mg) concentrations as well as the Ca/Mg, Ca/K, and Mg/K ratios in the soil. With respect to sources of P, the YT applied in the soil with DL produced an agronomic efficiency index (AEI) similar to that of TSP, whereas in the soil with CL, the TSP, YT, and ET were similar, with maximum technical efficiency (MTE) under both conditions starting at 230 kg ha^{-1} of P_2O_5. The critical concentration of available phosphorus (P) in the soil (Mehlich-1 extractant) for cultivation of soybean under the climate and soil conditions studied was between 5.0 and 6.0 mg kg^{-1}.

Keywords Cerrado, critical P concentration, *Glycine max*, low latitudes, soybean yield

Introduction

In recent years, cultivation of soybean [*Glycine max* (L.) Merr] has been expanding rapidly in areas at low latitudes in Brazil, in contrast to what happened in the 1980s, when attempts to grow this crop in such areas proved to be economically unfeasible due to the lack of cultivars adapted to shorter photoperiods (Vasconcelos et al. 2006). This requires research

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to establish the long-term economic sustainability of growing this crop in such areas (Sfredo, Paludziyzyn Filho, and Gomes 1994; Oliveira, Prochnow, and Klepker 2008), particularly in the states of Maranhão and Piauí, where the areas planted with soybean have risen from 382.5 and 232.0 thousand ha to 527.2 and 377.1 thousand ha from the 2006–2007 to the 2010–2011 growing seasons, respectively, increases of 37.8% and 62.5% (CONAB 2011). Besides the development of new cultivars, such expansion has required the increased use of fertilizers and acidity correctives, which nowadays account for 25% of the total production costs in these regions (Freitas 2011).

Because of the high acidity of the soils in these regions (Sfredo et al. 1996; Oliveira, Prochnow, and Klepker 2008), liming is necessary to increase the nutrient uptake efficiency (Havlin et al. 2005), raising the pH and substituting acidic cations with exchangeable calcium (Ca) and magnesium (Mg). Besides acidity, the most limiting feature under the edaphoclimatic conditions in these regions is lack of P (Sfredo et al. 1996; Oliveira, Prochnow, and Klepker 2008). One of the alternatives to increase the efficiency of the use of this nutrient is to reduce the cost of producing alternative sources of phosphorus (P), as reported by Castro (1993) with different thermalphosphates made from igneous rocks quarried from the Maicuru Range in Pará State.

Depending on the origin and type of phosphate-bearing rock, thermalphosphate can present different degrees of efficiency and P concentrations (Borkert et al. 1979; Moreira et al. 1997; Palhano et al. 1982; Moreira, Malavolta, and Moraes 2002). Fageria, Moreira, and Castro (2011) verified the equivalence of Yoorin thermalphosphate (YT) and single superphosphate (SSP), while Braga et al. (1980), studying the thermalphosphate made by the Institute for Technological Research (Instituto de Pesquisa Tecnológicas; IPT), obtained low efficiency in relation to triple superphosphate (TSP).

In the case of critical P concentrations, various studies have tried to establish adequate ranges for the different edaphoclimatic conditions in Brazil. Sfredo et al. (1980) found that in southern Paraná State, the critical P concentration for Ultisols (>350 g kg^{-1} of clay) is 6.0 mg kg^{-1}, whereas in the two other southernmost states, Rio Grande do Sul and Santa Catarina, Siqueira et al. (1987) found critical concentrations of 24.0 and 6.0 mg kg^{-1} in soils with different texture classes (<100 g kg^{-1} and >550 g kg^{-1} of clay, respectively). In a Cerrado region, Sousa, Miranda, and Lobato (1987) established P concentrations of 18 mg kg^{-1} in soil with less than 200 g kg^{-1} of clay and 3.0 mg kg^{-1} in soils with 610 to 800 g kg^{-1} of clay. All these critical concentrations were defined with the Mehlich-1 extractant [hydrochloric acid (HCl) 0.05 mol L^{-1} + sulfuric acid (H_2SO_4) 0.0125 mol L^{-1}).

Because of the increased cultivation of grain crops in regions near the equator, the aim of this study was to verify the efficiency of dolomitic (DL) and calcitic lime (CL) and three P sources [triple superphosphate (TSP), "Yoorin" thermalphosphate (YT), and experimental thermalphosphate (ET)] on the productivity of soybean grown in a dystrophic Red Latosol (Oxisol) in the Cerrado region of Balsas, Maranhão State, Brazil.

Material and Methods

The experiment was carried out during two growing seasons in a dystrophic Red Latosol–Brazilian classification (Oxisol), with clayey texture, located in the municipality of Balsas (7° 31′ 58″ S, 46° 2′ 9″ W), Maranhão State, Brazil. The soil chemical attributes at depths of 0–20 cm and 21–40 cm were measured before the application of the treatments and after each harvest, as reported in Table 1.

Table 1

Soil chemical attributes before planting and after first and second harvests of soybean with dolomitic or calcitic lime and without P_2O_5 application in a dystrophic Red Latosol (Oxisol) of Cerrado

Type of lime	Depth (cm)	pH ($CaCl_2$)	C (g kg^{-1})	P (mg kg^{-1})	K ($cmol_c$ kg^{-1})	Ca ($cmol_c$ kg^{-1})	Mg ($cmol_c$ kg^{-1})	Al ($cmol_c$ kg^{-1})	H+Al ($cmol_c$ kg^{-1})	CEC ($cmol_c$ kg^{-1})	V (%)	K sat. (%)	Ca sat. (%)	Mg sat. (%)
Before planting														
Dolomitic	0–20	3.8	10.9	1.2	0.03	0.01	0.03	1.2	7.2	7.3	1.0	0.4	0.1	0.4
Dolomitic	21–40	3.8	16.3	0.7	0.07	0.04	0.12	1.8	9.2	9.4	2.4	0.7	0.4	1.3
Calcitic	0–20	3.9	19.6	1.6	0.03	0.01	0.09	1.6	9.1	9.3	1.4	0.3	0.1	1.0
Calcitic	21–40	3.8	11.0	0.5	0.05	0.02	0.04	1.3	7.0	7.2	1.5	0.7	0.3	0.6
After first harvest														
Dolomitic	0–20	4.5	17.7	2.0	0.14	1.80	1.32	0.5	5.5	8.7	37.6	1.6	20.7	15.2
Dolomitic	21–40	4.2	12.5	0.9	0.08	0.65	0.52	0.7	5.0	6.2	20.0	1.3	10.5	8.4
Calcitic	0–20	4.6	17.7	1.0	0.11	2.69	0.19	0.2	3.6	6.6	45.3	1.7	40.7	2.9
Calcitic	21–40	4.2	13.1	0.7	0.04	0.62	0.07	0.9	5.0	5.8	12.7	0.7	10.7	1.2
After second harvest														
Dolomitic	0–20	5.2	24.4	2.6	0.13	2.80	1.92	0.0	4.3	9.1	53.1	1.4	30.8	21.1
Dolomitic	21–40	4.3	19.7	0.8	0.07	0.74	0.53	0.1	5.9	7.2	18.5	1.0	10.3	7.4
Calcitic	0–20	5.1	25.3	2.1	0.09	4.39	0.25	0.0	5.2	9.9	47.5	0.9	44.3	2.5
Calcitic	21–40	4.3	20.9	0.6	0.06	1.07	0.07	0.1	6.5	7.7	15.5	0.8	13.9	0.9
Means														
Dolomitic	0–20	4.5	17.7	1.9	0.10	1.57	1.09	0.6	5.7	8.4	30.7	1.1	17.2	12.2
Dolomitic	21–40	4.1	16.2	0.8	0.07	0.48	0.39	0.9	6.7	7.6	13.6	1.0	7.1	5.7
Calcitic	0–20	4.5	20.9	1.6	0.08	2.36	0.18	0.6	6.0	8.6	31.4	1.0	28.4	2.1
Calcitic	21–40	4.1	15.0	0.6	0.05	0.57	0.06	0.8	6.2	6.9	9.9	0.7	8.3	0.9

Notes. 0- to 20-cm depth: 510 g kg^{-1} of clay, 80 g kg^{-1} of lime, and 41 g kg^{-1} of sand; 21- to 40-cm depth: 54 g kg^{-1} of clay, 8 g kg^{-1} of lime, and 38 g kg^{-1} of sand; CEC, cation exchange capacity (Σ K, Ca, Mg, H+Al); V, base saturation {[(Σ K, Ca, Mg)/CEC] × 100}; K sat., potassium saturation; Ca sat., calcium saturation; Mg sat., magnesium saturation; P and K, extractants Mehlich 1; K, Ca, Mg, and Al, extractants KCl 1.0 mol L^{-1}; and H+Al, buffer SMP.

The experimental design was randomized blocks in a 2 × 3 × 4 factorial scheme, with four replicates. The treatments were composed of two types of lime [calcitic; CL (<5 dag kg^{-1} of magnesium oxide (MgO); and dolomitic; DL (>13 dag kg^{-1} of MgO)], three phosphate fertilizer sources {triple superphosphate, TSP [45.0% of phosphorus pentoxide (P_2O_5), soluble in water, and 19.6% of calcium oxide (CaO); "Yoorin" thermalphosphate, YT (17.4% of P_2O_5, soluble in citric acid, 27.6% of CaO, 14.9 of MgO, 23.9% of silicon dioxide (SiO_2,), 2.3% of aluminum oxide (Al_2O_3) and 8.2% of iron (Fe)]; and experimental thermalphosphate, ET (17.2% of P_2O_5, soluble in citric acid, 26.2% of CaO, 13.3 of MgO, 24.1% of SiO_2, 2.1% of Al_2O_3, and 7.8% of Fe]} and four rates of P_2O_5 (0, 100, 200, and 300 kg ha^{-1}). Each treatment was composed of plots measuring 5.0 m wide and 6.0 m long.

The base fertilization in the treatments was with 150 kg ha^{-1} of potassium chloride (KCl) (60% potassium oxide; K_2O), 800 kg ha^{-1} of gypsum (15% sulfur; S), and 50 kg ha^{-1} of FTE BR-10® [boron (B) = 2.5%, copper (Cu) = 1.0%, Fe = 4.0%, manganese (Mn) = 4.0%, molybdenum (Mo) = 0.1%, and zinc (Zn) = 7.0%]. The lime quantities were calculated to raise the base saturation to 50% (equivalent to 3.6 t ha^{-1} of lime). In the second growing year, only maintenance fertilizer was applied in the furrow with 300 kg ha^{-1} of a 0–20–20 formula (N–P_2O_5–K_2O).

Two soybean cultivars were planted, BRS Cristalina (first crop) and BRS Rio Balsas (second crop), at a density of 15 seeds per linear meter and row spacing of 0.45 m. To determine the soybean yield, the plants along 4 m of the four central rows of each plot were harvested at the end of the cycle. The soil samples were obtained from depths of 0–20 cm and 21–40 cm, before the application of the treatments and after each harvest, by taking five subsamples to compose a single compound one.

These were air dried and taken to the laboratory for measurement of pH in $CaCl_2$, carbon (C), available P, potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), and potential acidity [exchangeable hydrogen (H)+Al] in the soil, after which the cation exchange capacity (CEC) (Σ K, Ca, Mg, H+Al) and base saturation V% {[(Σ K, Ca, Mg)/CEC] × 100} were calculated. The soil analysis methods used were those described in the soil analysis manual published by EMBRAPA (1997). From the concentrations of exchangeable K, Ca, and Mg, the saturations were determined of K [(K/CEC) × 100], Ca [(Ca/CEC) × 100], and Mg [(Mg/CEC) × 100] along with the Ca/Mg, Ca/K, and Mg/K ratios.

The maximum technical efficiency (MTE) was calculated by the derivative of the equation between rates and yield, whereas the responses of the crops to the phosphate fertilization were evaluated by the agronomic efficiency index (AEI) described by Chien and Hammond (1978) and Moreira, Malavolta, and Moraes (2002):

$$\text{AEI}\,(\%) = 100 \times [(\text{Pn} - \text{P}_0)/(\text{P}_{\text{TSP}} - \text{P}_0)]$$

where Pn is the yield obtained with the source at dose n; P_0 is the control yield (0 mg kg^{-1} of P); and P_{TSP} is the yield obtained with the soluble source at dose n.

The data were submitted to analysis of variance (ANOVA), the F-test, and regression at 5% probability. Correlation analysis was also performed to assess the interactions of the available P, yield of grains, and P_2O_5 rates with the available concentration in the soil.

Results and Discussion

Chemical Attributes of the Soil

The effects of the different types of lime [dolomitic (DL) and calcitic (CL)] on the soil chemical attributes at the depths of 0–20 cm and 21–40 cm before planting and after each harvest, regardless of the phosphate source, are shown in Table 1. The average pH increased at the 0- to 20-cm depth from 3.8 to 4.5 and 4.6 after the first harvest and to 5.2 and 5.1 after the second harvest for the dolomitic and calcitic lime, respectively. At the 21- to 40-cm depth, irrespective of the low mobility of the corrective in the soil, there was an average increase of 8.0%, demonstrating the presence of a small acidity neutralization front in the soil profile. This has been attributed to the downward movement of the fine lime particles, or to the movement by flow of the mass of hydroxide (OH^-) and bicarbonate ($HCO_3{}^-$) anions resulting from the dissolution of the lime (Amaral and Anghinoni 2001). The mean pH values reached at the 0- to 20-cm depth after application of the two types of lime were near those obtained by Sfredo et al. (1996), who reported that a pH range of 4.6 to 5.2 is most suitable for soybean in the edaphoclimatic conditions studied here.

Likewise, the exchangeable Ca and Mg in the soil increased in both depths (0–20 cm and 21–40 cm) with application of the two lime types. With respect to the balance of ions in the CEC, only the Mg in the treatment with dolomitic lime at the two depths was within or near the CEC range of 6.0 to 12.0% indicated as adequate by Eckert (1987), but the percentages of K and Ca saturations in the soil, even with the increase observed before planting and after the second harvest (Table 1), remained below the concentrations of 2.0 to 5.0% and 65.0 to 86.0% presented as ideal by Eckert (1987) and Fageria, Santos, and Moreira (2010). The Ca/Mg, Ca/K, and Mg/K ratios were influenced by the application of the two types of lime (Table 1). In the 0- to 20-cm depth, the Ca/Mg ratios were 1.5 and 13.1 for the dolomitic and calcitic lime, respectively, whereas the Ca/K ratios were 15.7 and 29.5 and the Mg/K ratios were 10.9 and 2.3. It can thus be concluded that with the addition of the acidity correctives, these soil properties were improved from the standpoint of soybean yield.

The increase in the C concentrations in the soil at the depth of 0–20 cm observed after the cultivation of soybean (Table 1), even though the application of lime accelerates the mineralization of organic matter (Amaral and Anghinoni 2001), possibly occurred because of the remaining plant material in the arable layer, since during harvest only the soybeans are removed from the field. In the case of the 21- to 40-cm depth, the increased level of C was likely due to the increased volume of roots that are mineralized after the plants' senescence. We also observed that application of the two types of lime diminished the exchangeable Al in the soil, an effect that was practically neutralized after the second harvest (Table 1), corroborating the results obtained by Fageria and Morais (1987) studying rice (*Oryza sativa*) in an Oxisol of Cerrado.

The increase in the P_2O_5 rates linearly increased the available P content in the soil, regardless of the source and type of lime, with an interaction of the P_2O_5 rates with the soil correctives (Table 2). This effect on the concentrations of available P in function of soluble phosphate (TSP) and thermalphosphate sources and of rates of phosphate fertilizer was also reported by Moreira et al. (1997), Moreira and Malavolta (2001), and Fageria, Moreira, and Castro (2011). Both experiments also found similarities between these phosphate sources and the increase of available P in the soil in function of P_2O_5 rates. The critical concentration found ranged from 5.2 to 6.0 mg dm^{-3} (Table 3), values considered

Table 2
Concentrations (mg kg^{-1}) of available P in soil at 0–20 cm deep as function of sources of P and rates of P_2O_5 with dolomitic (DC) or calcitic (CC) lime application in a dystrophic Red Latosol (Oxisol) of Cerrado cultivated with soybean in two growing seasons

Rate of P_2O_5 (kg ha^{-1})	Triple superphosphate (TSP)		"Yoorin" thermalphosphate – (TY)		Experimental thermalphosphate (TE)		Means	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
				Dolomitic lime				
0	1.6	3.2	2.9	2.6	1.7	2.1	2.0	2.6
100	3.4	3.4	3.6	3.2	3.0	3.4	3.5	3.3
200	4.6	4.5	4.5	4.2	8.4	4.7	5.8	4.5
300	10.0	6.9	8.8	4.8	9.7	6.7	9.5	6.1
Mean	4.9	4.5	5.0	3.7	5.7	4.2	5.2	4.1
				Calcitic lime				
0	1.3	1.8	1.1	1.7	0.6	2.7	1.0	2.1
100	5.8	3.4	6.0	3.0	6.3	2.8	6.0	3.1
200	9.0	4.7	6.3	3.4	10.0	4.0	8.4	4.0
300	14.2	4.9	17.7	7.7	9.9	5.2	13.9	5.9
Mean	7.6	3.7	7.8	4.0	6.7	3.7	7.3	3.8
F-test								
Lime (a)	*	*	*	*	*	*	*	*
P_2O_5 (b)	*	*	*	*	*	*	*	*
a × b	*	*	*	*	*	*	*	*
CV (%)	16.48							

*Significant at 5% of probability.
Notes. Extractant Mehlich 1. CV (%), coefficient of variation.

medium according to the recommendation of Sousa, Miranda, and Lobato (1987), demonstrating only the need for maintenance phosphate fertilization applied in the furrow, using as a criterion the uptake of P by the soybean, that is, 20 kg of P_2O_5 for yield of 1000 kg ha^{-1} of grain.

Soybean Yield

Among the rates and sources of P, the application of 3.6 t ha^{-1} of DL caused the greatest soybean yields on average in the two years of evaluation, with the greatest estimated rates (MTE) of TSP, YT, and ET being 18.4, 9.8, and 18.6%, respectively, greater than in the treatments with CL (Figure 1). Soybean is a demanding plant in terms of Mg (Webb, Ohlrogge, and Barber 1954; Rosolem et al. 1992) and the lower yield with CL can be attributed to the low concentrations of the element in the soil (Table 1), because in these treatments, the concentrations of exchangeable Mg in the 0- to 20-cm and 21- to 40-cm depths were well below the 0.8 cmol$_c$ kg^{-1} indicated as adequate for soybean in the Cerrado region (Alvarez Venegas et al. 1999; TPS 2011).

Table 3
Correlations between available P in soil [mg kg^{-1} (x)] with yield of grain [kg ha^{-1} (ŷ)] and P_2O_5 rates [kg ha^{-1} (x)] with available P in soil [mg kg^{-1} (ŷ)] with two different limes [dolomitic (DL) or calcitic (CL)] (means of three sources of P and two soybean growing seasons)

Variable	Equation of regression	R
	Dolomitic lime (DL)	
Available P vs. yield of grains	$\hat{y} = -1069.01 + 1256.41x - 104.21x^2$	0.87*
P_2O_5 rates vs. available P	$\hat{y} = 1.92 + 0.018x$	0.63*
	Calcitic lime (CL)	
Available P vs. yield of grains	$\hat{y} = 921.52 + 1240.80x - 118.18x^2$	0.76*
P_2O_5 rates vs. available P	$\hat{y} = 1.48 + 0.024x$	0.49*
	Means	
Available P vs. yield of grains	$\hat{y} = 902.20 + 303.00x - 16.99x^2$	0.79*
P_2O_5 rates vs. available P	$\hat{y} = 1.70 + 0.021x$	0.51*

*Significant at 5% (F test). Extractant Mehlich 1.

The soybean yield in relation to the rates and sources of P increased significantly, independent of the type of lime utilized, but there were no differences between the sources of P (Figure 1). When opening a new field in the Cerrado, as occurred in this study, a large part of the P is temporarily fixed, and later becomes available to the plants. The MTE remained above 230 kg ha^{-1} of P_2O_5 on average for the 2 years of cultivation [TSP: 268 kg ha^{-1} (DL) and 382 kg ha^{-1} (CL), YT: 325 kg ha^{-1} (DL) and 249 kg ha^{-1} (CL), and ET: 232 kg ha^{-1} (DL) and 300 kg ha^{-1} (CL)]. This confirms the recommendations for correction with phosphate fertilizers in Cerrado soils with very low P concentrations ($\leq$4.0 mg kg^{-1}) and clay content between 350 and 600 g kg^{-1} (Sousa, Miranda, and Lobato 1987; Alvarez Venegas et al. 1999), as in the case here, where the 0- to 20-cm depth contained 1.2 mg kg^{-1} of P and 540 g kg^{-1} of clay.

Similar to the observations of Moreira and Malavolta (2001) and Fageria, Santos, and Moreira (2010), the available P in the soil and soybean yield, considering the average of the two growing years, had a significant correlation, regardless of the type of lime (Table 3). This result is due to the many functions of P in the plant, where it acts in the transfer of energy in the plants' metabolism [ATP (adenosine triphosphate)], in cell multiplication, promoting growth or the roots and aerial part, maturation, and better formation and productivity of plants (Malavolta 2006; Fageria 2009).

Agronomic Efficiency

The application of 60 kg ha^{-1} of P_2O_5 in the furrows in all the treatments did not influence the yield, because the agronomic efficiency index (AEI) of the YT and ET at the P_2O_5 rates in the two types of lime (DL and CL) showed that except for the rates of 200 and 300 kg ha^{-1} of P_2O_5 in the treatment with CL in the second growing season, the application of ET was less efficient than that of TSP to obtain better yield (Figure 2). In the case of YT, only the rates of 100 kg ha^{-1} of P_2O_5 with DL and 300 kg ha^{-1} of P_2O_5 with CL in the first crop and 200 kg ha^{-1} of P_2O_5 with DL in the second crop were lower

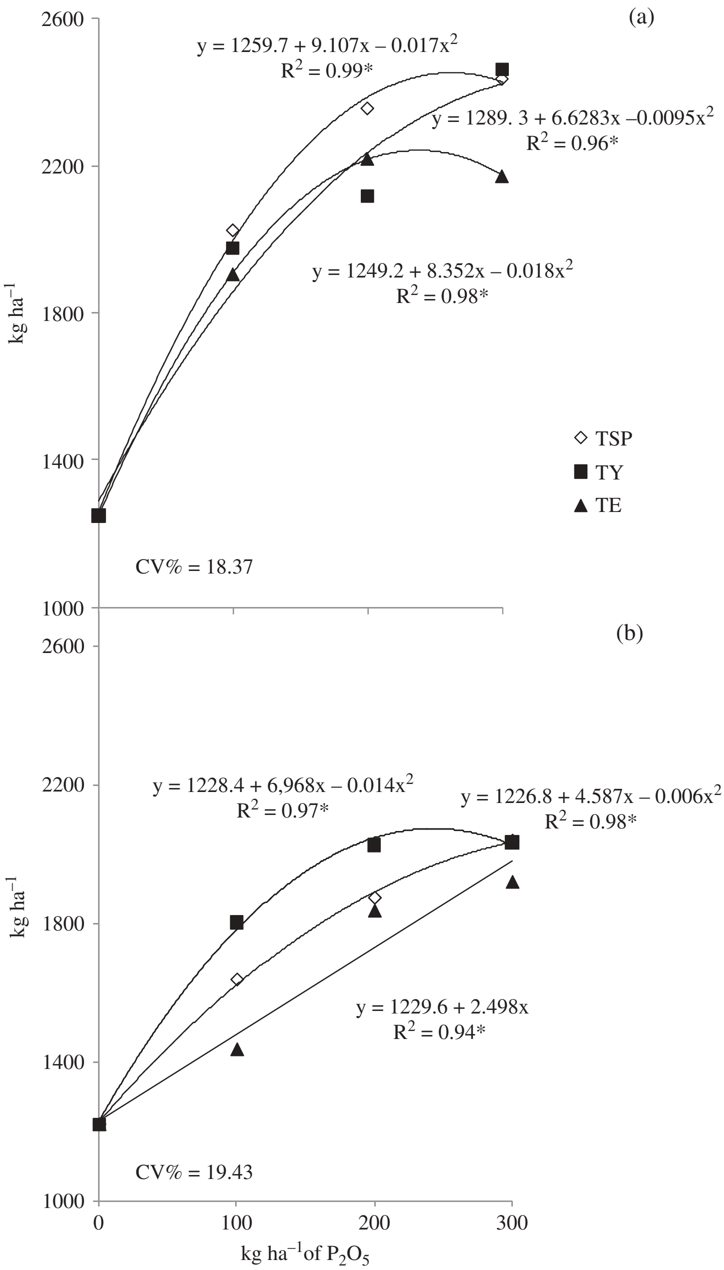

Figure 1. Means of soybean yields of two growing seasons with three sources [triple superphosphate (TSP), "Yoorin" thermalphosphate (TY), and experimental thermalphosphate (TE)] and four rates of P_2O_5 in soils with two different limes [dolomitic (a) or calcitic (b)]. *Significant at 5% of probability with F-test.

than the figures for TSP (Figure 2). Moreira, Malavolta, and Moraes (2002) and Fageria, Moreira, and Castro (2011), studying different sources of P in an Oxisol cultivated with alfalfa (*Medicago sativa*) and common beans (*Phaseolus vulgaris*), respectively, found that

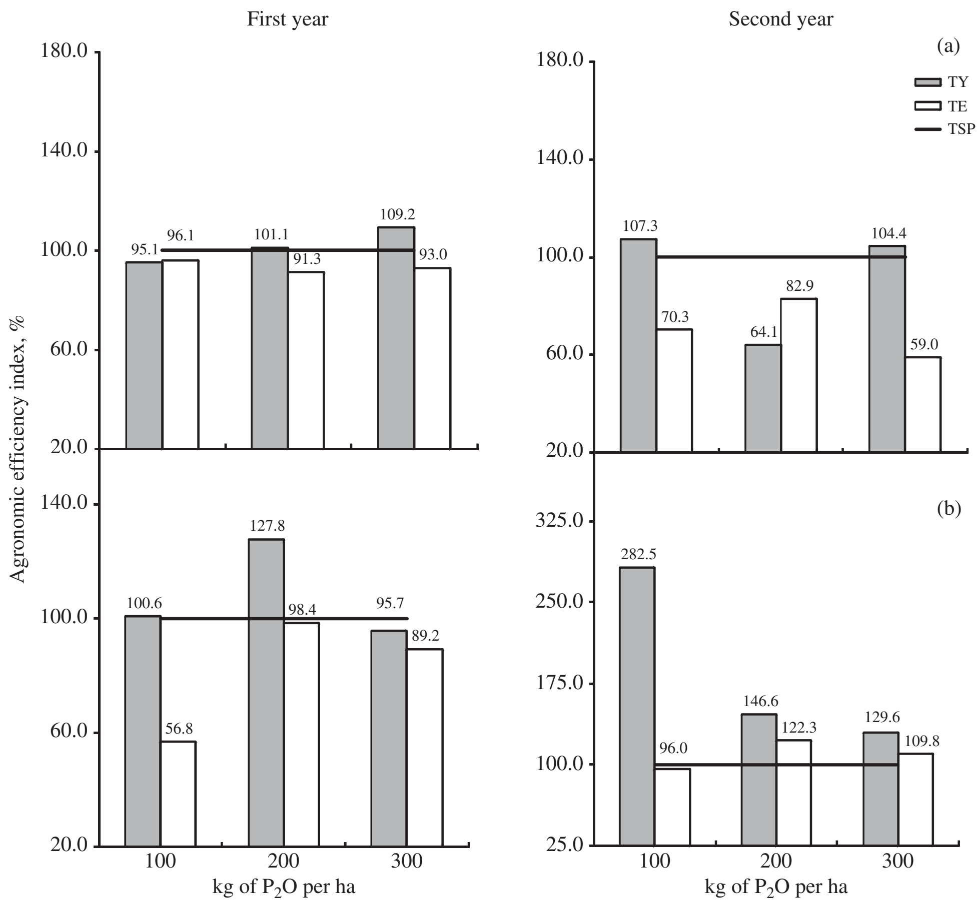

Figure 2. Agronomic efficiency index (AEI) of "Yoorin" (YT) and experimental (TE) thermalphosphates compared with triple superphosphate (TSP) as 100% in two seasons of soybean yields in the treatments with dolomitic (DL) (a) or calcitic (DC) (b) lime.

the thermalphosphates were similar to TSP regarding availability of P to the plants after successive crops.

In the treatments with CL, because of the lower solubility of TSP, at the lowest rate of P_2O_5 (100 kg ha^{-1}) there was a reduction of the AEI, with an increase from the first to the second harvest of 181.9% in the YT and 39.2% in the ET, when compared to the TSP. With application of DL, the effect of the treatments was less pronounced, with an increase of 13.1% in the YT and a reduction of 25.8% in the ET. Based on the findings of Goedert, Rein, and Souza (1990) and Moreira and Malavolta (2001), these results can be attributed to the nutritional enhancement and acidity correction effects of the silicates of Ca and Mg present in these phosphate sources. The good solubility of the thermalphosphate fertilizers also observed in the first soybean crop can be explained by the heating and destruction of the crystalline structure of the apatitic rock used as a source of P_2O_5 in their production and the silicon–phosphate transformation of Ca and Mg, increasing the availability of these nutrients to the plants (Yost et al. 1982; Nakayama et al. 1998).

Conclusions

The sources and rates of P_2O_5 and the two types of lime (dolomitic and calcitic) significantly influenced the soybean yield, with the maximum technical efficiency (MTE) being achieved by applications estimated between 232 and 325 kg ha^{-1} of P_2O_5 in the treatment with dolomitic lime (DL) and of 249 to 382 kg ha^{-1} of P_2O_5 in the soil treated with calcitic lime (CL) depending on the P source used. In the case of the lime types, the lowest productivity was obtained with CL in the average of the three P sources, with this being 19.0% lower than with the use of DL. These results demonstrate that the use of CL is only indicated when there is no DL in the region and when there is a low concentration of exchangeable Mg in the soil. On average for the two lime types, the agronomic efficiency indexes (AEI) were greater with the "Yoorin" thermalphosphate (YT) compared to the experimental thermalphosphate (ET). The applications of triple superphosphate (TSP) and YT in the treatment with DL were similar regarding increase in soybean productivity, so both can be used efficiently to fertilize this crop. In the case of application of CL, the three phosphate sources (TSP, YT, and ET) were similar regarding the availability of P to the plants.

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