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CROP PRODUCTION

Application of lime, phosphogypsum and fertilization rates affect soil fertility and common bean development in no-tillage system in a Cerrado Oxisol

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ABSTRACT. There is a lack of information about the effects of interactions among lime, phosphogypsum (PG) and fertilization on soil fertility and their effects on common bean yields in the tropics. This study aimed to determine the effects of annual application of PG and limestone and rates of fertilization on the chemical attributes of soil, fertilization efficiency, yield components and the grain yield of the common bean. The study was performed for three growing seasons in an acidic Oxisol. The experimental design was randomized blocks in a 4x4 factorial scheme. The treatments consisted of lime, lime + PG, PG, and control (without corrective application) with four fertilization rates. In an acidic and low-fertility Cerrado soil, limestone or limestone + PG applied annually at 1/3 of the total rate in a no tillage system increased the common bean yield and the efficiency of the fertilization, although the improvement of the soil acidity indicators did not reach the desired levels. The application of soluble fertilizers to provide adequate and balanced amounts of nutrients provided greater yield gains and improved soil fertility compared to surface liming without fertilization, but the combination of the two practices resulted in the greatest benefits to both plant and soil fertility.

Keywords: *Phaseolus vulgaris*; soil acidity; calcium carbonate; liming; phosphogypsum.

Calcário, fosfogesso e doses de fertilizantes afetando a fertilidade do solo e o desenvolvimento do feijoeiro-comum em sistema de plantio direto em um Latossolo do Cerrado

RESUMO. Existe carência de informação na região tropical sobre a interação entre calcário, fosfogesso (FG) e adubação na fertilidade do solo e seu efeito na produção do feijão-comum. O estudo objetivou determinar o efeito da aplicação anual de PG e calcário e níveis de adubação nos atributos químicos do solo, eficiência de fertilização, componentes de produção e rendimento de grãos do feijão-comum. A pesquisa foi realizada em três safras agrícolas em Latossolo vermelho ácrico. O delineamento experimental foi blocos casualizados em esquema fatorial 4x4. Os tratamentos consistiram na combinação de calcário, calcário + FG, FG e controle (sem corretivo) com quatro níveis de adubação. Em solo argiloso ácido e de baixa fertilidade do Cerrado, o parcelamento da dose de calcário ou calcário + FG com aplicação de 1/3 anualmente em SPD aumenta a produtividade do feijoeiro e a eficiência da adubação, embora a melhoria dos indicadores de acidez do solo não alcance os níveis desejados. A aplicação de fertilizantes solúveis para fornecer quantidades adequadas e equilibradas de nutrientes proporciona ganhos mais expressivos de produtividade e melhoria da fertilidade do solo, em comparação com a calagem superficial, mas a combinação das duas práticas resulta nos maiores benefícios para ambos, planta e solo.

Palavras-chave: *Phaseolus vulgaris*; acidez do solo; carbonato de cálcio; calagem; fosfogesso.

Introduction

The common bean (*Phaseolus vulgaris* L.) has great social and economic importance in several countries as an important source of protein. Despite its importance, technology is not frequently used by dry bean farmers, resulting in a global average grain yield of only 866 kg ha^{-1} (FAO, 2014). However, there are reports of yield ranging from 3,023 to 3,500 kg ha^{-1} (Nascente, Kluthcouski, Crusciol, Cobucci, & Oliveira, 2012). The common bean is a crop considered highly demanding of soil fertility due to the short life cycle and the superficial, underdeveloped root system. Thus, correction of soil acidity and a balanced supply of nutrients are key factors in achieving significant increases in grain yield (Fageria, Baligar, & Jones, 2011).

In a no-tillage system (NTS), soil acidity has been corrected by lime application on the surface without incorporation (Conyers, Heenan, McGhie, & Poile, 2003; Caires, Garbuio, Churka, Barth, & Corrêa, 2008; Churka Blum, Caires, & Alleoni, 2013). However, the limestone reaction is usually limited to the site of its application, since it has low soil mobility, which leads to questions about the viability of this practice to correct soil acidity in deeper layers (Caires et al., 1998; Soratto & Crusciol, 2008a). Previous studies conducted in Cerrado soil showed that the common bean crop responds strongly to improvement in soil acidity indexes (Fageria, 2008). Optimum values for maximum common bean grain yield in the 0 - 0.20 m soil layer were pH (in water) 6.5 and base saturation of 67% (Fageria, 2008). However, in the Cerrado region, it is common to find cropping areas with 30 - 35% base saturation in the 0 - 0.20 m layer, since other crops rotated with common beans, such as soybean and corn, are less sensitive to soil acidity indexes. In those cases, the required amounts of limestone to raise base saturation to 65 - 70% may be greater than 3 t ha^{-1}, and a single application without incorporation may cause nutritional imbalances due to a possible super-liming effect on the topsoil (Padua, Silva, & Melo, 2006). An alternative is to split the calculated dose into two or three applications, but there is a lack of information about the efficiency of this practice for the common bean crop in the short and medium term.

It is also known that liming is one of the most important practices employed to increase the efficiency of fertilizer use, since the availability of most nutrients in the soil is optimal with pH (in water) between 6.0 and 7.0, except for cationic micronutrients, whose availability decreases with increasing pH (Fageria & Nascente, 2014). In addition, the neutralization of exchangeable Al and the supply of Ca favor the growth and distribution of roots in the soil profile, facilitating the uptake of nutrients applied through fertilizers. However, the application of high doses of fertilizers, mainly nitrogen fertilizers, causes soil acidification (Barbosa Filho, Fageria, & Silva, 2004). In recent years, it has been observed that the rates of fertilizer application to crops cultivated in Cerrado soils have been increasing, while liming has often been neglected. This behavior in tropical regions can be explained in part by the insufficiency of research results showing the interaction between these factors on soil fertility, plant nutrition and crop productivity in the different production systems.

For soils from the Cerrado region, the application of phosphogypsum (PG) as a subsoil improver is recommended when, in the 0.20 - 0.40 m and 0.40 - 0.60 m soil layers, the aluminum saturation is higher than 20% or the Ca content is lower than 5.0 $mmol_c$ dm^{-3} (Sousa & Lobato, 2004). However, there is a lack of information on the response of the common bean to the application of PG alone or in combination with dolomitic limestone and their interactions with the application of increasing rates of fertilization in Cerrado soils in common bean crops. It is important to understand these interactions in order to establish management strategies that improve nutrient-use efficiency in long-term crop production, focusing on sustainable intensification.

This study was conducted to answer the following questions: First, in clay Cerrado soil cultivated in NTS, is the annual application of 1/3 of the total amount of limestone and PG on the soil surface without incorporation an effective practice to improve the soil acidity indicators to the levels required by the common bean crop and to increase the efficiency of fertilizer use? Second, how does the common bean grown with irrigation in a no-tillage system respond to different levels of fertilization in a Cerrado soil, with or without the annual application of limestone and PG. Third, what are the effects on soil fertility up to a depth of 0.40 m? Therefore, the study aimed to determine the effect of annual application of PG and limestone on the soil surface without incorporation and of rates of fertilization on the chemical attributes of the top layer of the soil, as well as on fertilization efficiency, yield components and the grain yield of irrigated common bean crops grown in a no-tillage system in the tropical Cerrado region.

Material and method

Site description

The experiment was conducted over three growing seasons (2011, 2012, and 2013) at the Capivara Farm, located in the city of Santo Antonio de Goiás, Goiás State, Brazil. The geographical coordinates of the site are 16° 28' 00" S, 49° 17' 00" W. The average daily temperature and precipitation during the experiment were monitored (Figure 1).

The experimental area was cultivated for five years under a NTS, with corn (*Zea mays* L.) grown in summer and common bean (*Phaseolus vulgaris* L.) grown with irrigation in winter. The soil was classified as a clay-textured Typic Acric Red-Yellow Latossol (Oliveira & Rodrigues, 2012). Before the experiment began (May 2011), the chemical characteristics of the soil were determined (at depths of 0 - 0.20 m and 0.20 - 0.40 m) to calculate the requirements for liming and the addition of phosphogypsum (Table 1). The soil analyses were performed following the methods described by Donagema, Campos, Calderano, and Teixeira (2011).

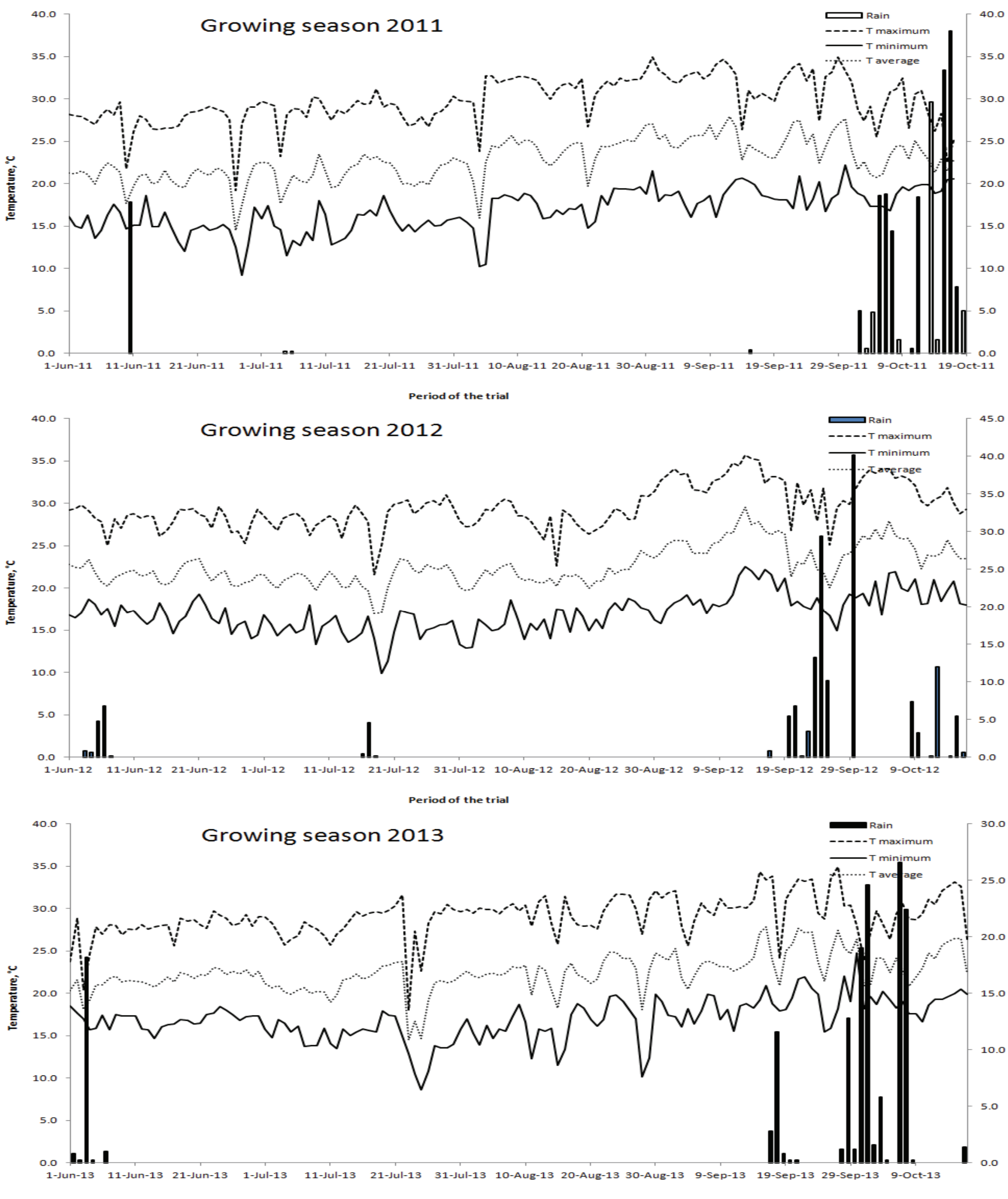

Figure 1. Temperature and rainfall in the experimental area during the experiment (June 2011 to Sept. 2013).

Table 1. Chemical characteristics of the soil before beginning the experiment, May 2011.

Depth	Ca	Mg	Al	H+Al	K	CEC[1]	pH[4]
(m)	----------------------------cmol$_c$ dm^{-3}----------						
0 - 0.20	0.72	0.37	0.38	6.5	0.16	7.78	5.0
0.20 - 0.40	0.53	0.17	0.42	7.1	0.14	7.94	4.8
Depth	V[2]	SOM[3]	P	Zn	Cu	Fe	Mn
(m)	%	g kg^{-1}	---------------------------mg dm^{-3}-------------				
0 - 0.20	16.0	18.3	6.0	3.1	2.1	58.7	11.7
0.20 - 0.40	10.6	17.0	2.3	3.1	2.1	58.7	11.7

[1]Cation exchange capacity. [2]Percent base saturation. [3]Soil organic matter. [4]pH in water. [5]P Mehlich-1.

Experimental design and treatments

The experimental design was a randomized complete block layout arranged in a 4x4 factorial design with four replications. The treatments consisted of four types of soil amendment [limestone, limestone + phosphogypsum, phosphogypsum, and control (no amendment application)] with four fertilization rates [0, 50, 100, and 150% of the fertilization recommended for common beans with high expected grain yield (Sousa & Lobato, 2004)]. Thus, the following quantities were applied: 0, 60, 120, and 180 kg ha^{-1} N (urea); 0, 60, 120, and 180 kg ha^{-1} P_2O_5 (55% simple superphosphate – 16% P_2O_5, 12% S, 20% Ca and 45% triple superphosphate – 46% P_2O_5, 14% Ca); and 0, 30, 60, and 90 kg ha^{-1} K_2O (potassium chloride – 60% K_2O), respectively, for the four rates of fertilizer. Phosphorus and K were applied on the day of sowing, and the application of N was divided among the day of sowing, five days after emergence and the V4 growth stage (third trifoliate leaf).

The lime application rate (5.0 Mg ha^{-1}) was calculated to increase the base saturation to 70% at a depth of 0 - 0.20 m. The amount of phosphogypsum (PG) used (2.5 Mg ha^{-1}) was determined by the clay content of the soil (500 g kg^{-1}) at a depth of 0.20 - 0.40 m as recommended by Sousa and Lobato (2004). These amendments were broadcasted on the surface of the soil without incorporation. The applications of lime and PG were divided into three applications as follows: on November 11th, 2010 (2 Mg ha^{-1} of lime and 1.0 Mg ha^{-1} PG), on November 11th, 2011 (2 Mg ha^{-1} of lime and 1.0 Mg ha^{-1} of PG) and on October 19th, 2012 (1 Mg ha^{-1} of lime and 0.5 Mg ha^{-1} of PG). The limestone used contained 26% Ca and 7.2% Mg. Its effective neutralizing value was 86.6%. The PG contained 21.8% Ca, 17.4% S, 1% P_2O_5 and traces of Si, Al, Mg, Na, Fe, Ce, Ti, La, K, Sr, Zr, and Pr.

Common bean cultivation (winter 2011, 2012 and 2013)

The sowing of the common bean cultivar 'Perola' was performed mechanically on June 6th, 2011, June 21st, 2012, and June 6th, 2013 using no-till graining with a row spacing of 0.45 m and a density of 12 seeds m^{-1}. Each plot consisted of 10 rows that were each 5 m long. The usable area of each plot consisted of the 8 central rows, with 0.5 m on each side disregarded. Crop management was performed according to the crop recommendations to keep the area free of weeds, diseases and insects. An irrigation sprinkler system was used for water management.

Summer crops

In November 2010, November 2011, and November 2012, soybeans were cultivated in the same area and fertilized with 0, 40, 80, and 120 kg ha^{-1} P_2O_5 (simple superphosphate) and 0, 40, 80, and 120 kg ha^{-1} of K_2O (potassium chloride) in the plots corresponding to common bean fertilization rates of 0, 50, 100, and 150%, respectively (Carvalho & Nascente, 2014).

Soil characterization

A galvanized steel auger 4.5 cm in diameter was used to sample soil at depths of 0 to 0.10 m, 0.10 to 0.20 m, and 0.20 to 0.40 m in November 2013, 36 months after the first liming. For each soil layer, 15 random subsamples were collected from each plot and combined to form a composite sample. These samples were air dried, sieved (2 mm mesh) and analyzed to determine the pH ($CaCl_2$ 0.01 mol L^{-1}), organic matter content, potential acidity (H + Al), Al, Ca, Mg, exchangeable K, and P (Mehlich-1). Percent base saturation (V) was calculated. Soil analyses were performed following the methods described by Donagema et al. (2011).

Yield components, grain yield, and efficiency of fertilizer use

The common bean crop was harvested on September 14th, 2011, October 2nd, 2012, and September 12th, 2013 from the usable area, first by hand and then using the thresher model BC 80 III. The common bean grain was weighed, and the yields were corrected to a moisture content of 130 g kg^{-1} and then converted to kg ha^{-1}. Agronomic characteristics, the number of pods per plant and the number of grains per pod, were evaluated for 10 randomly chosen plants per plot, along with the 100-grain weight (calculated from 20 random samples per plot, adjusted to a moisture content of 130 g kg^{-1}). To calculate the efficiency of fertilizer use, we summed the average yields in each treatment (control, lime, lime + PG, and PG) from the three growing seasons (2011, 2012, and 2013) and divided this sum by the amount of fertilizer used on the common bean crop during the three growing seasons.

Statistical analyses

An analysis of variance was performed for all variables. The soil corrective and level of fertilizer were considered fixed effects. Blocks, years and all interactions were considered random effects. A comparison of means was performed with a Tukey test ($p \leq 0.05$). To analyze the efficiency of fertilizer use, we used an LSD test at $p \leq 0.05$. A regression analysis was used for quantitative data (fertilizer levels). These analyses were performed using SAS statistical software.

Result

Alterations in soil chemical attributes

Thirty-six months after the first soil amendment application, the correctives significantly affected the soil chemical attributes up to 0.40 m depth (Table 2). The largest changes, as expected, occurred in the superficial soil layers (0-0.10 m and 0.10-0.20 m) in which the application of limestone, with or without phosphogypsum (PG), increased the pH, increased the Ca and Mg content, and reduced the Al and H + Al content, thus resulting in an increase in soil base saturation.

Table 2. Effects of the application of lime (L) and/or phosphogypsum (PG), fertilization rates and soil depth layers on the values of pH in water, Ca, Mg, Al, H+Al, K, cation exchange capacity (CEC) and base saturation (V) in the soil 36 months (November 2013) after the first application of the soil correction. Crop managed under the no-tillage system.

Soil corrective	Depth 0-0.10 m								
	pH	Ca	Mg	Al	H+Al	K	CEC	P	V
		-------------------cmol$_c$ dm^{-3}	-----------	-----------	-----------	-----------	-----------	mg kg^{-1}	%
Control	5.33 b	1.24 c	0.41 c	0.12 a	5.1 a	0.18 a	7.0 b	11.2 a	26.2 b
Limestone	6.14 a	2.38 a	1.08a	0.00 b	3.3 b	0.19 a	6.9 b	12.1 a	52.9 a
L + PG	6.07 a	2.51 a	0.88 b	0.00 b	3.2 b	0.18 a	6.8 b	11.4 a	53.2 a
Phosphogypsum	5.37 b	1.60 b	0.38 c	0.10 a	5.3 a	0.19 a	7.5 a	9.8 a	29.2 b
Source of variation	F probability								
Soil corrective (SC)	<0.001	<0.001	<0.001	<0.001	<0.001	0.0323	0.0013	0.0433	<0.001
Fertilization rate (F)	<0.001	0.0744	0.0143	0.1829	<0.001	<0.001	0.0002	<0.001	0.0041
SC x F	0.7860	0.7820	0.5170	0.7660	0.7604	0.6906	0.5380	0.6763	0.8278
Soil corrective	Depth 0.10-0.20 m								
Control	5.02 b	0.76 c	0.23 b	0.34 a	5.3 ab	0.14 a	6.5 b	29.4 a	17.6 b
Limestone	5.29 a	1.19 ab	0.56 a	0.13 b	4.7 bc	0.13 a	6.6 ab	29.1 a	28.4 a
L + PG	5.27 a	1.41 a	0.47 a	0.13 b	4.4 c	0.14 a	6.4 b	31.6 a	31.5 a
Phosphogypsum	4.95 b	0.98 bc	0.22 b	0.34 a	6.0 a	0.14 a	7.3 a	29.5 a	18.6 b
Source of variation	F probability								
Soil corrective (SC)	<0.001	<0.001	<0.001	<0.001	<0.001	0.0431	0.0095	0.0341	<0.001
Fertilization rate (F)	0.0142	0.3186	0.4606	0.2002	0.1330	<0.001	0.0347	<0.001	0.7874
SC x F	0.9622	0.8927	0.8197	0.6583	0.4339	0.8532	0.6052	0.6712	0.6071
Soil corrective	Depth 0.20-0.40 m								
Control	5.02 b	0.66 b	0.18 b	0.35 a	5.2 a	0.11 a	6.2 a	4.0 a	15.2 b
Limestone	5.03 ab	0.79 ab	0.32 a	0.29 ab	5.1 a	0.09 b	6.3 a	4.0 a	19.2 ab
L + PG	5.08 a	0.91 a	0.30 a	0.23 b	4.9 a	0.09 b	6.2 a	3.4 a	20.8 a
Phosphogypsum	5.04 ab	0.86 ab	0.21 b	0.30 ab	5.4 a	0.10 ab	6.5 a	3.5 a	17.9 ab
Source of variation	F probability								
Soil corrective (SC)	0.0451	0.0177	<0.001	0.0306	0.2368	0.0120	0.0343	0.6067	0.0057
Fertilization rate (F)	0.0213	0.1298	0.2771	0.4925	0.8743	0.0949	0.9958	<0.001	0.2640
SC x F	0.7598	0.6557	0.4041	0.8844	0.8056	0.7886	0.8328	0.7286	0.5581

[1]Means followed by the same letter in a column within each depth do not differ by the Tukey test at $p < 0.05$.

In the 0.20 - 0.40 m layer, the treatment with limestone + PG was the most effective at reducing soil acidity, resulting in the highest values of pH, Ca content and base saturation as well as the lowest value of exchangeable Al content. These results differed from the control, but were similar to limestone alone and PG alone (Table 2). The application of PG caused an increase in Ca content in the 0 - 0.10 m layer that differed from the control, increases of CEC in the 0 - 0.10 m soil layer that differed from all other treatments, and increases of CEC in the 0.10 - 0.20 m soil layer that differed from both the lime + PG treatment and the control. The available K content in the soil surface layers was not altered by the application of the correctives, but decreased significantly in the 0.20 - 0.40 m layer in limestone treatments (with or without PG) compared to the control. Fertilization rates affected pH, H + Al, base saturation, CEC, and Mg, K, and P contents available in the 0 - 0.10 m layer (Table 2). The pH, CEC, and Mg were adjusted to the linear regression model, and the other attributes were adjusted to the quadratic polynomial regression model (Figure 2). In the 0.10 - 0.20 m layer, significant effects were observed for pH, CEC, P, and K (Table 2), in which pH and CEC were adjusted to the linear regression model and P and K were fitted to a quadratic regression model (Figure 3). In the 0.20 - 0.40 m layer, fertilization rates affected only the pH and available P content; pH was adjusted to the linear regression model, and the available P was adjusted to a quadratic regression model (Figure 4).

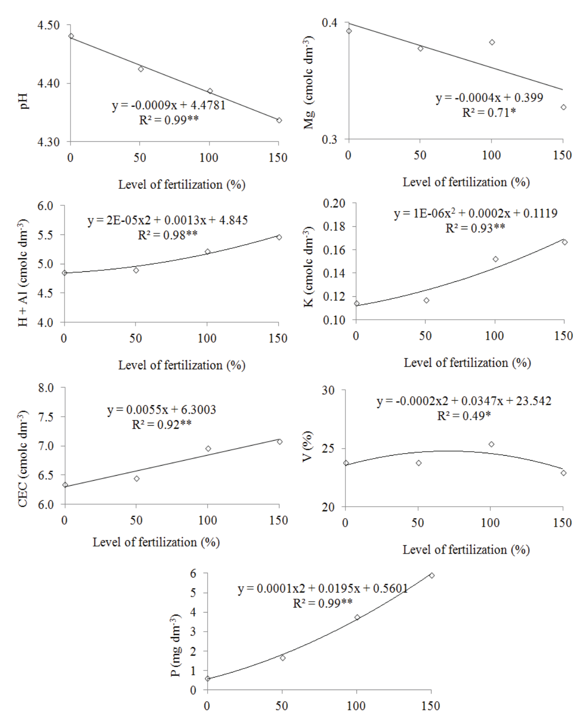

Figure 2. Chemical attributes of the soil (pH in water, Ca, Mg, Al, H+Al, CEC, V, K, and P) in the 0 - 0.10 m soil layer was a function of fertilization rates. Soil was measured 36 months after the first application of lime and phosphogypsum under the no-tillage system.

Yield components and grain yield

There was no interaction between soil amendments and fertilization rates for yield components or grain yield, but there were isolated effects of soil amendments and fertilization rates in the three growing seasons (Table 3). In the first growing season (2011), among the soils amendments, treatments with limestone provided the highest number of pods per plant, differing from the control, and grain yield of common bean, differing from both the control and PG alone.

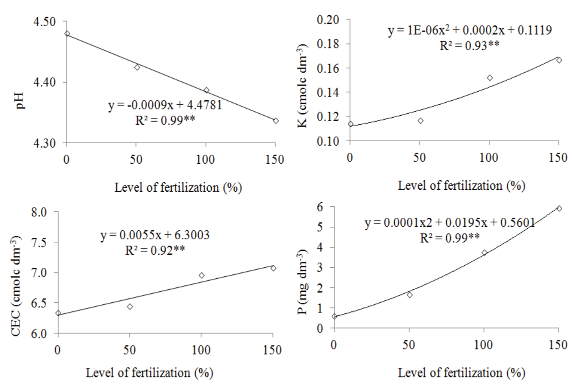

Figure 3. Chemical attributes of the soil (pH in water, CEC, K, and P) in the 0.10 - 0.20 m soil layer as a function of fertilization rates. Soil was measured 36 months after first application of lime and phosphogypsum under the no-tillage system.

The application of PG alone did not affect any of the variables (Table 3). Fertilization rates produced significant effects on the plant population and the number of pods per plant with linear adjustment and on number of grains per pods and grain yield with quadratic adjustment (Figure 6). In 2012, the application of limestone + PG provided the highest grain yield; while the grain yield produced with the application of limestone + PG was not significantly different from the treatment with limestone alone, it did differ from the control and the application of PG alone. Fertilization rates produced significant effects on the plant population with linear adjustment and on the number of pods per plant, the number of grains per plant and the grain yield with quadratic adjustment (Figure 6). In 2013, there was a significant effect of fertilization rates on all variables except plant population (Table 3), with quadratic adjustment for all four variables (Figure 7). The number of grains per pod was higher in the limestone treatment, differing from the control and the application of limestone + PG. Grain yield was higher with the application of limestone and limestone + PG, differing from the control treatment.

Table 3. Effects of application of lime (L) and/or phosphogypsum (PG), fertilization rates and growing season on the plant population (POP), number of pods plant^{-1} (NPP), number of grains pod^{-1} (NGP), 100-grain weight (W100) and grain yield (YIELD) of the common bean crop. Crop cultivated under the no-tillage system.

Soil corrective	POP	NPP	NGP	W100	YIELD
	Growing season 2011				
	n° x 1000	n°	n°	g	kg ha^{-1}
Control	284.4 a	6.67 b	4.10 a	23.5 a	1801 b
Limestone	278.8 a	9.04 a	4.05 a	23.6 a	2176 a
L + PG	272.0 a	8.57 ab	3.65 a	24.3 a	2106 ab
Phosphogypsum	278.8 a	8.58 ab	3.85 a	24.9 a	1826 b
Source of variation	F probability				
Soil corrective (SC)	0.4300	0.0224	0.1781	0.3414	0.0076
Fertilization (F)	<0.001	<0.001	<0.001	0.2508	<0.001
SC x F	0.1405	0.7899	0.6554	0.7405	0.7424
Correctives	Growing season 2012				
Control	251.5 a	11.07 a	4.27 a	27.3 a	2772 b
Limestone	245.6 a	12.03 a	4.30 a	28.1 a	2942 ab
L + PG	249.2 a	11.83 a	4.07 a	28.3 a	3015 a
Phosphogypsum	246.8 a	10.62 a	4.20 a	27.1 a	2783 b
Source of variation	F probability				
Soil corrective (SC)	0.7530	0.1763	0.2313	0.0242	0.0054
Fertilization (F)	<0.001	<0.001	<0.001	0.1376	<0.001
SC x F	0.3528	0.5394	0.5722	0.7534	0.0558
Correctives	Growing season 2013				
Control	230.1 a	11.52 a	2.78 b	27.47 a	2079 b
Limestone	225.0 a	12.39 a	3.09 a	27.93 a	2236 a
L + PG	236.1 a	11.93 a	2.78 b	27.26 a	2246 a
Phosphogypsum	236.1 a	11.25 a	2.90 ab	28.47 a	2148 ab
Source of variation	F probability				
Soil corrective (SC)	0.6608	0.6220	0.0880	0.3261	0.0456
Fertilization (F)	0.3064	<0.001	0.0075	<0.001	<0.001
SC x F	0.0592	0.5454	0.8949	0.3832	0.0923

[1]Means followed by the same letter in a column do not differ by the Tukey test at $p < 0.05$.

The increases in grain yield resulting from the application of fertilizer were much higher than the increases due to the application of limestone alone or limestone + PG (Figure 8). In the absence of fertilization, the application of limestone and limestone + PG provided an increase of 72 and 49%, respectively, in the accumulated grain yield, while in the absence of correctives, the application of 50 and 100% of the recommended fertilization provided an increase of 232 and 375%, respectively (Figure 8A). The greatest increases in accumulated grain yield occurred with the combination of limestone application with or without PG and fertilizer, clearly indicating an additive effect among these factors (Figure 8A). Considering the average of all levels of fertilization, the increase in accumulated grain yield due to the application of limestone or lime + PG was 11%, while increases due to application of fertilizer, regardless of the correctives, were 165, 249, and 250% for the 50, 100, and 150% of recommended fertilizer levels, respectively (Figure 8B). Figure 9 shows a clear relationship between soil P availability and common bean grain yield, in which a variation of the soil P levels from 5 to 30 mg dm^{-3} was associated with a variation from 13 to 100% in the relative yield of common bean.

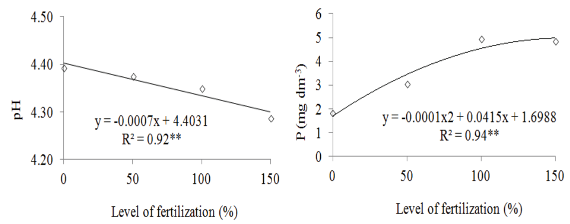

Figure 4. Chemical attributes of the soil (pH in water and P) in soil depths of 0.20 - 0.40 m as a function of fertilization rates. Soil measured 36 months after the first application of lime and phosphogypsum under the no-tillage system.

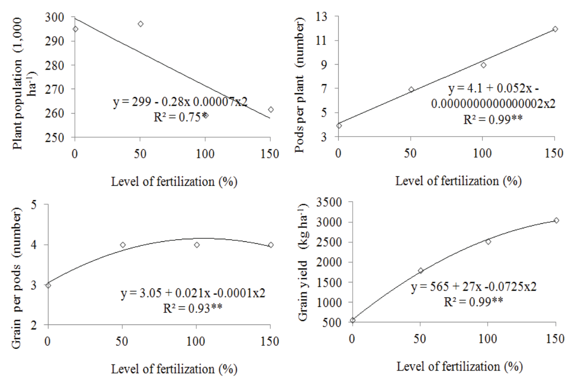

Figure 5. Plant population, grain yield, pods per plant and grains per pods of the common bean crop as a function of the level of fertilization. Growing season 2011.

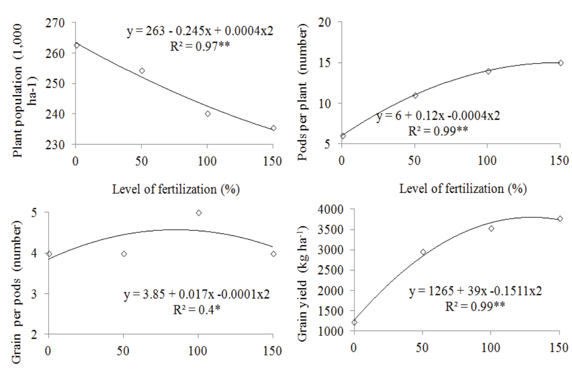

Figure 6. Plant population, grain yield and yield components of the common bean crop as a function of the rates of fertilization. Growing season 2012.

Efficiency of fertilizer use

The treatments with lime, regardless of the addition of PG, increased the efficiency of fertilizer use (Table 4). For every kilogram of fertilizer applied, 11.53 kg of common bean grains were obtained after lime application and 11.56 kg after application of lime with PG. These values differed from the control (10.56 kg of common bean grains) and from the application of PG alone (10.87 kg of common bean grains).

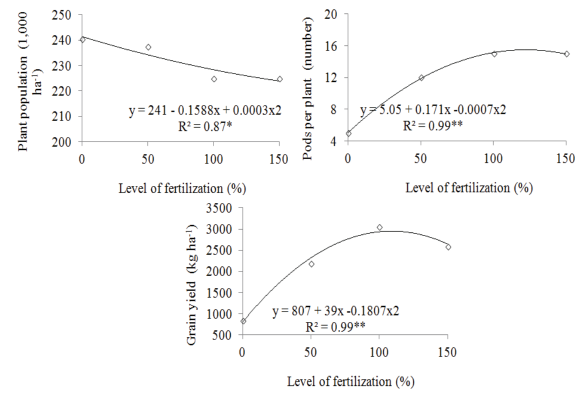

Figure 7. Plant population, grain yield and yield components of the common bean crop as a function of the rates of fertilization. Growing season 2013.

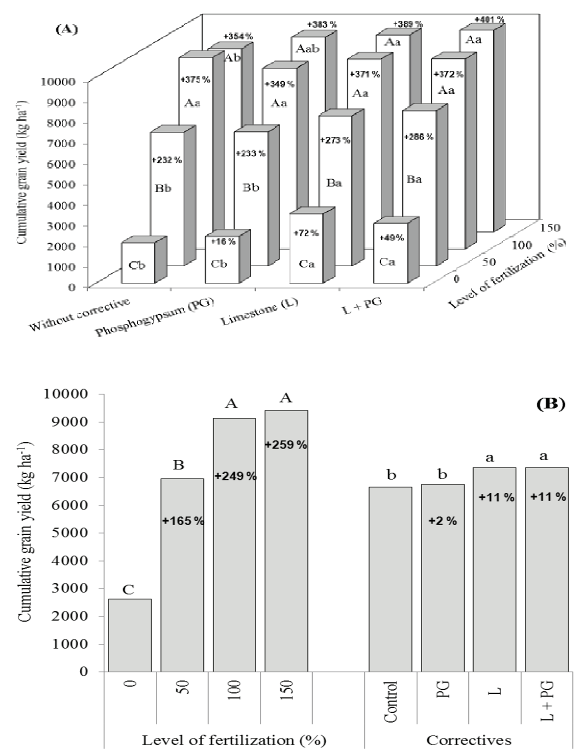

Figure 8. Cumulative common bean grain yield in 2011, 2012, and 2013 growing seasons as a function of the combination between correctives and rates of fertilization (A) and of each isolated factor (correctives or fertilization) (B). The values inside or above the bars correspond to the percent of increase compared to the control (without corrective and/or fertilization). Means followed by the same capital letter among levels of fertilization or the same small letter among correctives do not differ by the Tukey test at $p < 0.05$.

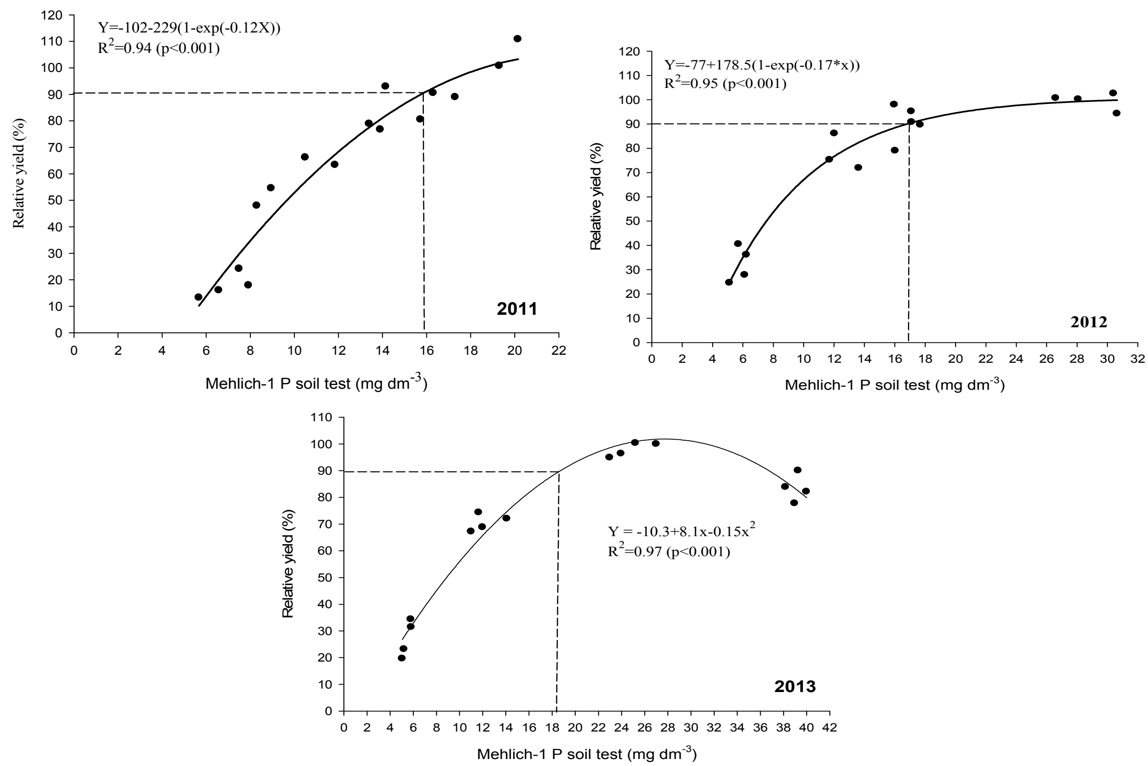

Figure 9. Relationship between the relative yield (RY) and soil Mehlich-extractable P at 0 - 0.20 m soil depth in 2011, 2012, and 2013 growing season. The data points represent the means of each rate of fertilization in each corrective treatment. Dashed lines represent the equivalent soil P level for 90% of the RY.

Table 4. Efficiency of NPK fertilizer use in the common bean crop cultivated under the no-tillage system as a function of lime (L) and phosphogypsum (PG) application.

	No corrective	Limestone	L + PG	PG
SSASY – A[1]	6653	7354	7367	6756
N - K_2O-P_2O_5 applied by fertilizer - B[2]	630	630	630	630
Fertilizer efficiency use - A/B	10.56 B[3]	11.67 A	11.69 A	10.72 B

[1]SSASY - Sum of average of the common bean grain yield from application of rates 0, 50, 100, and 150% of the recommended fertilization in three growing seasons (2011, 2012, and 2013). [2]Average of the amount of N, P_2O_5, and K_2O applied via fertilizer at doses 0, 50, 100 and 150% of the recommended fertilization in three growing seasons (2011, 2012 and 2013). Thus, it was applied 0, 60, 120 and 180 kg ha^{-1} for N, totaling 360 kg ha^{-1} of N; 0, 40, 80, and 120 kg ha^{-1}, for P_2O_5 and K_2O totaling 240 kg ha^{-1} of each nutrient, i.e., applied 840 kg N + K_2O + P_2O_5. The average was 210 kg ha^{-1} (840/ 4 fertilizer rates) for each year time 3 (growing season) = 630. [3]Means followed by the same letter in the row do not differ by LSD test at $p < 0.05$..

Discussion

Alterations in soil chemical attributes

The limestone treatment, with or without PG, produced the greatest changes in soil acidity indexes 36 months after the first application (Table 2). When the research was planned, we intended to reach the base saturation of 70% in the 0 - 0.20 m layer, but the highest value we achieved was 53% in the 0 - 0.10 m layer. Considering the average between 0 - 0.10 m and 0.10 - 0.20 m, the highest base saturation achieved was only 41 - 42%. Thus, splitting the rate of liming to apply 1/3 of the total annually was not a fully effective practice for correcting the soil acidity, considering the conditions of this experiment. However, our data do not allow us to determine whether the application of the same 5 Mg ha^{-1} of limestone all in the first year would be enough to reach the aimed base saturation. This could be a question investigated in future research.

Results from the field in subtropical regions have shown that the movement of the limestone when applied on the soil surface is very low (Conyers et al., 2003; Caires et al., 2008; Soratto & Crusciol, 2008a; 2008b; Churka Blum et al., 2013). However, after some time, the limestone can reach deep layers. According to Caires, Alleoni, Cambri, and Barth (2005), the effects of surface liming on all three acidity-related variables (pH, Al, and basic cations) were significant at depths of 0 - 0.05 m and 0.05 - 0.10 m from 1 yr after the first application onward and at a depth of 0.10 - 0.20 m from 2.5 yr after the first application onward. Our results showed that in a tropical region after 36 months it is likely that movement of the lime to deep layers (0.10 – 0.20 m and 0.20 – 0.40 m) occurred that produced changes in the chemical attributes, although not at the magnitude that we expected. In the evaluation done 24 months after lime application, there were only effects in the 0 - 0.10 m layer (Carvalho & Nascente, 2014).

The application of PG, which is not a soil acidity corrective, did not result in significant alterations of the pH of the soil or on other chemical attributes (Table 2). If applied in large quantities, this soil conditioner can cause leaching of bases (Ca, Mg, and K), especially Mg, to deeper layers (Ramos, Korndorfer, Pereira, & Camargo, 2006; Caires et al., 2008). In our experiment, we found higher amounts of Ca in the 0.10 - 0.40 m layer only when PG was applied with limestone, probably because Ca from PG moved to layers below 0.40 m. This could be an important strategy in tropical soil to enrich deeper layers with Ca and to stimulate root development. The greater root development could contribute to the plants reaching water in deep layers and could reduce problems caused by a period with no rain (Crusciol et al., 2016).

The pH level in all layers decreased with increases in the amount of fertilizer applied (Figure 2). An explanation of this pH decrease could be because of the use of nitrogen fertilizers that contain or produce $N\text{-}NH_4^+$, such as ammonium sulfate and urea. In the soil, this ion rapidly oxidizes to nitrate, releasing H^+ and producing significant decreases in pH (Fageria et al., 2011; Nascente et al., 2012).

The Mg content decreased with increasing levels of fertilization. This finding can be explained by competition with K for soil adsorption sites. Soil K content increased with increasing levels of fertilization (Figures 2 and 3), probably because the quantities of K-fertilizer applied were higher than the quantities exported in the grains, which is approximately 14 kg ha^{-1} of K_2O in each 1,000 kg of grains. According to Fageria et al. (2011), the application of K to soils directly affects Mg, as it competes for the same adsorption sites in the soil. Thus, it is probable that greater amounts of K caused the release of Mg from soil colloids and, possibly, the leaching of this nutrient to deeper layers. In addition, the reduction of the soil Mg level can be explained by exportation into grains, once the grain yield was increased as the rate of fertilization increased, since the fertilizers applied do not contain Mg.

In the soil layers evaluated, phosphorus also increased significantly with increasing fertilization rates (Figures 2, 3, and 4). This result was expected because at higher rates of fertilization, the amounts of phosphorus applied were higher than the quantities exported in grains. The quantity of P exported is approximately 9 kg ha^{-1} of P_2O_5 in each 1,000 kg of grains produced. This can be used as a strategy for corrective fertilization in areas with low soil P tests, considering the low mobility of P into the soil, especially in tropical soils such as Oxisols, which results in accumulation of this nutrient in the soil.

Yield components, grain yield, and efficiency of fertilizer use

Liming increased the common bean grain yield in all growing seasons (Table 4). This result is a consequence of the changes in soil properties caused by the application of limestone to the soil, such as increased pH, availability of Ca and Mg, base saturation and CEC (Table 2).

Over all growing seasons, application of PG alone did not increase the common bean grain yield. Other researchers have also reported similar results in areas with annual crops when the soil was under a NTS (Caires, Chueiri, Madruga, & Figueiredo, 1998, Caires, Blum, Barth, Garbuio, & Kusman, 2003; Carvalho & Nascente, 2014). The use of PG is more recommended when you have, in soil depths of 0.20 to 0.40 m, aluminum saturation higher than 20% or if the calcium contents are below 5 mmol$_c$ dm^{-3} (Sousa & Lobato, 2004). Under these conditions, the use of PG would stimulate root development in deeper soil layers, facilitating plants reaching water in case of a period of no rain, and allowing plants to obtain more nutrients and develop better (Sousa & Lobato, 2004; Caires, Barth, & Garbuio, 2006). However, in an NTS, the greatest quantity of nutrients remains in the top soil, as observed in our trial (Table 2). Additionally, our trial was irrigated, so it is likely that in our trial, PG did not provide increases in the soil profile that allowed better development of the common bean plants. Moreover, the low Mg content in the soil (Table 1) may have influenced the absence of a response to the application of PG alone, since, as already demonstrated in other works (Oliveira & Pavan, 1996; Michalovicz et al., 2014; Carvalho & Nascente, 2014), the application of PG may result in preferential leaching of Mg and a reduction of the nutrient content in the leaves. Increased fertilization rates produced increases in the yield components and grain yield in all growing seasons. Therefore, this confirms that the common bean is highly responsive to fertilization (Fageria et al., 2011; Nascente et al., 2012). From the equations displayed in Figures 5, 6, and 7, the maximum common bean grain yield was achieved when the rates of fertilization were 206, 129, and 109% in 2011, 2012, and 2013, respectively. This reduction in the rate of fertilizers required by the common bean is a result of the accumulation of nutrients in the soil (Figures 2, 3, 4, and 9) due to the residual effect of previous fertilization. Thus, these results reinforce the importance of monitoring the soil fertility status as a tool to support the planning of fertilization in cropping systems in order to adjust possible nutritional imbalances.

The equations displayed in Figure 9 show that the equivalent soil P (Mehlich-1) level for 90% of the relative P production was 16, 17 and 18 mg dm^{-3} in growing seasons 2011, 2012, and 2013, respectively. These values are higher than the 12 mg dm^{-3} reported by Sousa and Lobato (2004) as the critical level for irrigated cropping systems in clay Oxisols in the Cerrado region at a 0 to 0.20 m depth, indicating that the common bean is a lower P-acquisition efficiency crop compared to soybean or maize. Föhse, Claassen, and Jungk (1988) demonstrated that the common bean is a low P-uptake efficiency species, as determined by both a low root-shoot ratio and a low influx rate. In 2013, the mathematical model that best expressed this relationship was the quadratic model (Figure 9), suggesting a negative interaction effect could be occurring with other nutrients, such as zinc, when the soil P content was higher than 30 mg dm^{-3}.

The effects of fertilization rates were of greater magnitude than the effects of liming. This could be because the changes in soil attributes up to a depth of 0.20 m that were caused by the application of limestone to the soil surface were of low magnitude for a highly demanding crop such as the common bean (Table 2). For example, the optimal pH in the 0 - 0.20 m layer for developing common bean crops ranges from 5.8 to 6.3 (Fageria et al., 2011). Fageria (2008) verified that the maximum common bean yield was achieved with a base saturation of 67% and a pH of 6.5. In our work, these values were not reached. Even so, it was observed that the response to fertilization was increased by surface-applied lime, improving the efficiency of fertilizer use. This indicates that the better strategy for farmers to increase fertilizer use efficiency and, consequently, to increase common bean grain yield in NTS is to avoid the decrease of base saturation to rates lower than 50%, since the effect of surface application of limestone without incorporation is slow.

Conclusion

The annual application of 1/3 of the total rate of limestone or limestone + PG improved the soil acidity indexes up to a depth of 0.20 m 36 months after the first application. The application of PG alone did not result in significant alterations in soil chemical attributes and common bean grain yield.

Increasing levels of NPK and with fertilizers also containing Ca and S provided significant increases in grain yield and alterations in soil fertility. The common bean productivity increases in response to fertilization were even greater when combined with the application of limestone alone or limestone + PG.

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