academicJournals

Vol. 9(17), pp. 1366-1383, 24 April, 2014
DOI: 10.5897/AJAR2014. 8626
Article Number: A0DB5BB44144
ISSN 1991-637X
Copyright © 2014
Author(s) retain the copyright of this article
http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Limestone and phosphogypsum effects on soil fertility, soybean leaf nutrition and yield

Maria da Conceição Santana Carvalho and Adriano Stephan Nascente*

Brazilian Agricultural Research Corporation (EMBRAPA), Rice and Beans Research Center, P. O. Box 179
, Zip code 75.375-000, City of Santo Antônio de Goiás, State of Goiás, Brazil.

Received 19 February, 2014; Accepted 7 April, 2014

Quantifying soil and plant response to surface applied limestone and phosphogypsum (PG) will help promote no-tillage soybean production. Our objective was to determine effects of annual surface application of phosphogypsum and limestone on soil profile chemistry, fertilizer use efficiency, soybean leaf nutrient concentrations, seed yield, and yield components under a no-tillage system (NTS). The study was conducted in the Brazilian Cerrado under field conditions during three growing seasons on an acidic clay loam soil. Four soil remediation treatments [(limestone, lime + phosphogypsum, phosphogypsum and control (no soil correction)] with four fertilizer levels (0, 50, 100 and 150% of recommended P and K fertilizer for soybean) were arranged in a randomized design using a 4 × 4 factorial design. Treatments involving lime application improved soil chemical characteristics of the soil, resulted in significant increases in plant nutrient concentrations, and increased soybean grain yield. In contrast, application of phosphogypsum did not improve plant development conditions and resulted in no significant changes in soil properties or soybean grain yield. Using increased fertilizer application rates for 3 years also produced significant increases in soybean grain yield. Our results imply that, for acidic soils liming NTS is the best practice to increase fertilizer use efficiency.

Key words: Calcium carbonate, *Glycine max*, no-tillage system (NTS), mineral nutrition, soil acidity.

INTRODUCTION

Brazil is the second largest producer of soybean in the world, surpassed only by the U.S.A. (FAO, 2013). This crop is widely planted in soils managed under the no-tillage system (NTS) (Embrapa Soja, 2010; Nascente and Crusciol, 2012). Due to the benefits provided (increased levels of soil organic matter (SOM), reduction of soil erosion, increased soil moisture conservation and improvement of soil fertility), NTS use has grown significantly throughout the world, and almost 117 million ha worldwide are cultivated using this system (FAO, 2013). The use of this system has increased in Brazil since 1970s. Currently, an estimated area of more than 25 million ha is cultivated using the NTS (Nascente et al., 2013).

The success and continuity of the NTS over the years is achieved through management planning of the soil fertility over the depth profile, which includes a soil acidity correction. Soil acidity limits crop production in many

*Corresponding author. E-mail: adriano.nascente@embrapa.br, Tel: +55 62 3533 2179.Fax +55 62 35332100.

Author(s) agree that this article remain permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

areas of the world due to the toxicity caused by aluminum, phosphorus deficiency and low base saturation (Caires et al., 2003). Tropical soils such as those of the Brazilian Cerrado or the African savannas are naturally acidic because high levels of rainfall over many years have leached basic ions, resulting in reduced soil fertility (Caires et al., 2008). According to Fageria et al. (2011), tropical soils are highly weathered and are dominated by 1:1 clay minerals such as kaolinite and iron oxides (hematite and goethite) and Al (gibbsite), which have a high P adsorption capacity. In these areas, satisfactory cash crop grain yields are dependent on proper liming and soil fertilization (Caires et al., 2001; Alleoni et al., 2009; Souza et al., 2011).

In Brazil, the most common material used for acidity correction is limestone, which effectively increases soil pH, calcium and magnesium content and base saturation reduces the levels of exchangeable aluminum in the soil (Caires et al., 2004). In most grain-producing areas under the NTS, the soil acidity is corrected by applying limestone to the soil surface without incorporation (Soratto and Crusciol, 2008a; Alleoni et al., 2009). However, the reactions produced by limestone are generally limited to the location at which application/incorporation occurs due to the low mobility of limestone in soil. The results of field studies show that the movement of lime to depth varies according to the timing and rate of liming, the form of lime applied, the soil type, the weather conditions, the addition of acidic fertilizers and the cropping system (Gascho and Parker, 2001; Conyers et al., 2003; Tang et al., 2003; Caires et al., 2008; Soratto and Crusciol, 2008a, b; Churka Blum et al., 2013). According to Caires et al. (2003), liming, whether applied to the surface or incorporated into the soil, provided more intense soil acidity correction in the superficial layer (0 to 0.5 m). On the other hand, a stronger reaction also occurred in the 0.05 to 0.10 m and 0.10 to 0.20 m layers when lime was incorporated into the soil. Caires et al. (2005) added that the effects of surface liming on all three acidity-related variables (pH, Al, and basic cations) were significant at depths of 0 to 0.05 m and 0.05 to 0.10 m from 1 year onward and at a depth of 0.10 to 0.20 m from 2.5 years onward. As a result, the reactions of lime in the soil are subject to further delays, especially at times relatively close to the time of application (Caires et al., 1998; Fageria and Baligar, 2008; Soratto and Crusciol, 2008b).

The application of lime with phosphogypsum (PG) appears to be an excellent alternative for improving the chemical conditions of the soil profile in the Cerrado region because the application of lime alone cannot provide a better environment in the deeper layers of the soil; these conditions may limit the development of the plant root system to the surface layers. As a result, the root systems exploit only a small soil volume, thus limiting crop productivity, especially in locations where periods without rain are frequent (Caires et al., 2005; Soratto and Crusciol, 2008b). Phosphogypsum can be used to improve the environment for root growth in the deep soil layers. This product is a soil conditioner and has high mobility in the soil profile. It can provide Ca^{2+} and SO_4^{2-} in solution in the soil and can be leached, enriching the deep layers with these nutrients and reducing Al^{3+} at depth. Thus, the use of phosphogypsum may allow the development of deep roots, increasing the volume of soil that can be explored and improving the drought tolerance of the plant. The successful use of phosphogypsum to improve the root environment has been far-reaching in the Cerrado region of Brazil (Sousa and Lobato, 2004). Approximately, 80% of the area of this region is subject to problems of soil subsurface acidity and frequent dry spells, especially in the months of January and February, the critical time for the development of summer crops (Ramos et al., 2006; Caires et al., 2008).

The identification of alternatives that allow the correction of soil acidity at depth in the NTS using methods of surface application without incorporation may facilitate the persistence and success of this system. Information is lacking about reactions at depth involving lime and phosphogypsum applied on the soil surface under NTS. Moreover, there is need for additional information about the effect of this approach on soil chemical characteristics, plant mineral nutrition and crop production (Franchini et al., 2003; Caires et al., 2006b; Soratto and Crusciol, 2008b, c). Little is known about the behavior of correctives that can act effectively through the soil profile when they are applied superficially without incorporation. This information is important because the permanence of the system for long periods after the implementation of the NTS may not be feasible in many cases as there are persistent factors contributing to soil acidification, such as rainfall and uptake of nutrients by crops. Accordingly, this study is based on the following hypotheses: a) Due to the higher mobility of phosphogypsum to the deep layers of the soil, the application of this amendment after liming could promote the enrichment of bases in the soil profile more rapidly than that obtained with only limestone; and b) The use of lime and phosphogypsum can significantly increase soybean leaf nutrition and grain yield. The objective of the study was to determine the effect of the annual application of phosphogypsum and lime on the soil surface without incorporation on the correction and the fertilization efficiency through the soil profile as well as its effects on leaf nutrition, yield components and grain yield and on grain nutrient accumulation and content in soybean grown under the NTS.

MATERIALS AND METHODS

Site description

The experiment was conducted for three growing seasons (2010/2011, 2011/2012 and 2012/2013) at Capivara Farm, located in the city of Santo Antonio de Goias, GO, Brazil. The geographical

Table 1. Chemical characteristics of the soil in the experimental area before the beginning of the experiment, November 2010.

Depth (m)	Ca	Mg	Al	H+Al	K	CEC^1	pH (H_2O)
	---------------------------------$cmol_c\ dm^{-3}$-------------------------------						
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
	V^2 (%)	SOM^3 (g dm^{-3})	P (Mehlich)	Zn	Cu	Fe	Mn
			----------------------------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	2.1	1.3	38.6	6.5

[1]Cation exchange capacity; [2]Percent base saturation; [3]Soil organic matter.

coordinates of the site are 16° 28' 00" S, 49° 17' 00" W. The altitude of the site is 823 m. The climate is tropical savanna, considered Aw according to the Köppen classification. There are two well-defined seasons: usually, the dry season extends from May to September (autumn/winter) and the rainy season from October to April (spring/summer). The historic average annual rainfall ranges from 1500 to 1700 mm. The historic average annual temperature is 22.7°C, ranging annually from 14.2 to 34.8°C. Additionally, the daily average temperature and precipitation during the experiment were monitored (Figure 1).

The experimental area was cultivated for 5 years under the NTS, with corn (*Zea mays* L.) grown in summer and common bean (*Phaseolus vulgaris* L.) irrigated in winter. The soil was classified as a clay loam (kaolinitic, thermic Typic Haplorthox). Before the experiment began, the chemical characteristics of the soil were determined (at depths of 0 to 0.20 m and 0.20 to 0.40 m) to characterize the soil in the experimental area to calculate the requirements for liming and phosphogypsum (Table 1). The soil analysis was performed according to Claessen (1997). The soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil/solution). Exchangeable Ca, Mg, and Al were extracted with neutral 1 mol L^{-1} KCl in a 1:10 soil/solution ratio and determined by titration with a 0.025 mol L^{-1} NaOH solution. Phosphorus and exchangeable K were extracted with a Mehlich 1 extracting solution (0.05 M HCl in 0.0125 M H_2SO_4). The extracts were colorimetrically analyzed for P, and flame photometry was used to analyze K. The base saturation values were calculated using the results of exchangeable bases and total acidity at pH 7.0 (H + Al). Micronutrients (Fe, Zn, Cu and Mn) were determined in Mehlich 1 extract by atomic absorption, and organic matter was determined by the method of Walkley and Black (Walkley and Black, 1934).

Experimental design and treatments

The experimental design was a randomized complete block layout arranged in a 4 × 4 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 fertilizer recommended for soybean (Sousa and Lobato, 2004)]. The recommended fertilization corresponded to the application of 80 kg ha^{-1} of P_2O_5 (55% of superphosphate and 45% of triple superphosphate) and 80 kg ha^{-1} of K_2O (potassium chloride). The lime application rate (5.0 Mg ha^{-1}) was calculated to increase the base saturation to 70% at a depth of 0 to 0.20 m. The amount of phosphogypsum (gypsum) 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 to 0.40 m, as recommended by Sousa and Lobato (2004). These amendments were applied by scattering on the surface of the soil without incorporation. The treatments were divided into three applications and used as follows: on 13/11/2010 (2 Mg ha^{-1} of lime and 1.0 Mg ha^{-1} phosphogypsum), on 11/11/2011 (2 Mg ha^{-1} of lime and 1.0 Mg ha^{-1} of phosphogypsum) and on 19/10/2012 (1 Mg ha^{-1} of lime and 0.5 Mg ha^{-1} of phosphogypsum). The limestone used contained 26% Ca and 7.2% Mg. Its effective neutralizing value was 86.56%. The phosphogypsum contained 21.8% Ca and 17.4% S.

Soybean cultivation (Summer 2010/11, 2011/12 and 2012/13)

The sowing of soybean cultivar BRS 7860 RR was performed mechanically on 19/11/2010, 10/11/2011 and 01/11/2012 using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil) with a row spacing of 0.45 m and a density of 20 pure live seeds m^{-1}. Each plot consisted of 10 rows, each 5 m long. The usable area consisted of the 8 central rows, with 0.5 m on each side disregarded. A corridor 2 m in width was left between the plots. The soybean seeds were inoculated with *Bradyrhizobium japonicum*. Seedling emergence occurred at 8, 9 and 5 days after sowing in 2010, 2011 and 2012, respectively. Crop management was performed according to the crop recommendations (Embrapa, 2010).

Offseason crops

In May, 2011 and May, 2012, common bean was cultivated in the same area and fertilized with 0, 60, 122 and 183 kg ha^{-1} of N (ammonium sulfate and urea), 0, 100, 200 and 300 kg ha^{-1} P_2O_5 (simple superphosphate) and 0, 70, 140 and 210 kg ha^{-1} of K_2O (potassium chloride) in the plots corresponding to soybean fertilization rates of 0, 50, 100 and 150%, respectively.

Soil characterization

A galvanized steel auger 4.5 cm in diameter was used for sampling at depths of 0 to 0.20 m and 0.20 to 0.40 m in November 2012, 24 months after the first liming. For each soil horizon, 15 random subsamples were collected from underneath the soybean plant rows (5 subsamples) and from the middle of the inter-row spaces (0.225 m from the plant row, 10 subsamples) from each plot. For each location (in-row and between rows), the 15 subsamples were combined to form a composite sample.

The composite samples were air-dried and sieved (2 mm mesh) and later analyzed to determine the pH ($CaCl_2$ 0.01 mol L^{-1}),

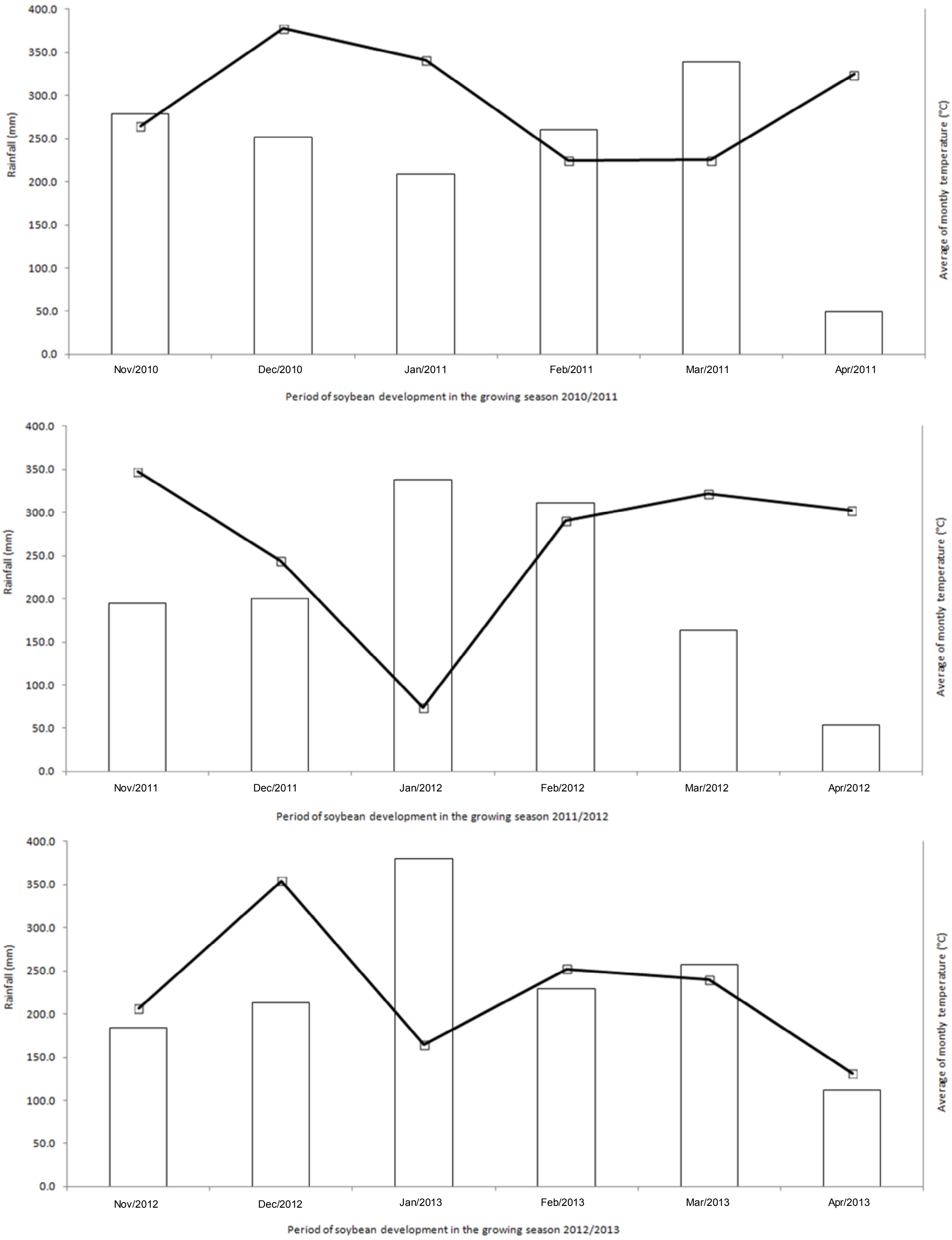

Figure 1. Temperature and rainfall in the experimental area during the trial (November, 2010 to March, 2013).

organic matter content, potential acidity (H + Al), Al, Ca, Mg and exchangeable K, and percent base saturation (V) was calculated. The content of Fe, Zn, Mn and Cu was also analyzed. Soil analyses were performed following the methods described above.

Soybean leaf diagnosis

Soybean leaf samples were collected from the upper third trifoliate at the R_2 growth stage (Fehr and Caviness, 1977). Petioles from 30 plants per plot were collected, washed and then dried under forced-air circulation at 65°C for 72 h before grinding and analyzing the samples for chemical composition. The concentrations of N, P, K, Ca, Mg and S were determined using methods described by Malavolta et al. (1997). Nitrogen was extracted with H_2SO_4, and the other nutrients were extracted with a nitro-perchloric solution. The N concentration in the digested solution was determined by Kjeldahl analysis. The P, K, Ca, Mg and S concentrations were determined by atomic absorption spectrophotometry.

Yield components and grain yield

Soybeans were harvested on 02/04/2011, 22/03/2012 and 12/03/2013 from the usable area (8 central rows, with 0.5 m on each side disregarded) using a mechanical harvester. The soybean seed was weighed, and the yields were corrected to a moisture content of 130 g kg^{-1} and converted to kg ha^{-1}. Agronomic characteristics, including the final plant population (calculated per ha from the number of plants in the two 4 m rows in the center of each plot), plant height (in cm), number of pods per plant and number of seeds per pod, were evaluated for 10 randomly chosen plants per plot, along with the 100-seed weight (calculated from 8 random samples per plot, adjusted to a moisture content of 130 g kg^{-1}).

Efficiency of fertilizer use

To calculate the efficiency of fertilizer use, we summed the average soybean seed yields in each corrective treatment (control, lime, lime + phosphogypsum, phosphogypsum) from the three growing seasons (2010/2011, 2011/2012, 2012/2013) and divided this sum by the amount of fertilizer used on the soybean crop during the three growing seasons.

Statistical analyses

An analysis of variance and F-test were 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 Turkey test ($p \leq 0.05$). To analyze the efficiency of fertilizer use, we used least significant difference (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 (SAS Institute, 1999).

RESULTS

Soil attributes

Twenty-four months after the first application, liming significantly affected the following soil attributes at a depth of 0 to 0.10 m: pH, Ca, Mg, Al, H + Al, CEC, V and Mn (Tables 2 and 3). pH, Ca and base saturation were greater in the treatments with lime (with or without phosphogypsum), and Mg was highest in the treatment with lime alone. Aluminum and H + Al were lowest in the treatments with lime. The highest value of cation exchange capacity (CEC) was achieved by the treatment with phosphogypsum alone. Treatment effects at a depth of 0.10 to 0.20 m were observed only for the levels of Mg, Al and Fe. The highest values of Mg and the lowest values of Al were obtained in the treatments with lime. The highest values of Fe were obtained in the treatments with phosphogypsum, which differed from the control. At a depth of 0.20 to 0.40 m, there was no effect of lime or phosphogypsum on soil attributes.

The levels of fertilizer affected pH, Ca, Mg, K, P, Cu, Fe, Mn and Zn at a depth of 0 to 0.10 m (Figures 2 and 3). The pH data fitted with a linear regression, and all nutrients with quadratic regressions. At a depth of 0.10 to 0.20 m, significant effects were observed only for the levels of P, Zn and Cu (Figure 3), which fitted with quadratic regressions. At a depth of 0.20 to 0.40 m, effects were observed on Ca, Mg, Al, K, V, P, Zn and Mn (Figure 4). With the exception of Zn, which fitted a linear equation, all the effects fitted with quadratic regressions.

Nutrient content in soybean leaves

During the first growing season (2010/2011), lime showed a significant effect on the leaf content of Ca, Mg and S (Table 4), with the lowest values occurring in the treatment with lime alone. The rates of fertilizer application affected the levels of P, Ca and Mg (Figure 5). Phosphorus and Ca fit quadratic adjustments, and Mg fit a linear equation. During the second growing season (2011/2012), the amendments affected the leaf content of N, K, Ca and S. N and K were highest in the treatment with lime alone. In contrast, the values of Ca and S were lowest in this treatment. The fertilization rates did not produce changes in the nutrient content. During the third growing season (2012/2013), the amendment did not alter the leaf content of nutrients. The fertilization rates affected the levels of N, P, Ca and S. N and S fit quadratic adjustments, and Ca and P fit linear adjustments.

Yield components and seed yield

The liming and phosphogypsum application produced significant changes in the 100-seed weight and seed yield of the soybeans evaluated during the first growing season (2010/2011) (Table 5). Liming produced the highest 100-seed weight, which differed from that found in the treatment with phosphogypsum. The seed yield was greater in the treatments with liming with or without

Table 2. Effects of the application of lime (L) and/or phosphogypsum (PG), fertilization rates and soil depth layers on the values of pH, Ca, Mg, Al, H + Al, K, cation exchange capacity (CEC) and base saturation (V) in the soil 24 months (November, 2012) after the first application of the soil correction. Crop managed under the no-tillage system (NTS).

Soil corrective	**Depth 0 - 0.10 m**							
	pH	**Ca**	**Mg**	**Al**	**H + Al**	**K**	**CEC**	**V**
		---------------------------cmol$_c$ dm^{-3}--------------------------						**%**
Control	5.3^{b1}	1.09^{c}	0.48^{c}	0.16^{a}	5.6^{a}	0.26^{a}	7.5^{b}	24.6^{b}
Limestone	5.7^{a}	1.81^{a}	1.14^{a}	0.01^{b}	4.1^{b}	0.27^{a}	7.4^{b}	43.9^{a}
L + PG	5.7^{a}	1.75^{a}	0.86^{b}	0.04^{b}	4.5^{b}	0.24^{a}	7.3^{b}	39.5^{a}
Phosphogypsum	5.3^{b}	1.36^{b}	0.43^{c}	0.18^{a}	5.9^{a}	0.25^{a}	8.0^{a}	25.8^{b}
Fertilization rates								
0	5.7	1.35	0.68	0.10	5.0	0.25	7.3	32.2
0.5	5.5	1.66	0.80	0.09	5.0	0.24	7.7	35.5
1.0	5.5	1.58	0.76	0.09	5.0	0.23	7.5	34.5
1.5	5.4	1.42	0.66	0.11	5.2	0.30	7.6	31.6
Source of variation	**F probability**							
Soil corrective (SC)	<0.001	<0.001	<0.001	<0.001	<0.001	0.3983	0.0300	<0.001
Fertilization (F)	0.0027	0.0021	0.0496	0.8010	0.8889	0.0022	0.3256	0.3263
SC × F	0.7639	0.7241	0.5051	0.8200	0.7520	0.4399	0.8831	0.6169
Soil corrective	**Depth 0.10 - 0.20 m**							
Control	5.1^{a}	0.75^{a}	0.29^{b}	0.29^{a}	6.0^{a}	0.17^{a}	7.2^{a}	16.8^{a}
Limestone	5.2^{a}	0.94^{a}	0.48^{a}	0.18^{b}	5.4^{a}	0.13^{a}	6.9^{a}	22.7^{a}
L + PG	5.3^{a}	1.01^{a}	0.45^{a}	0.17^{b}	5.4^{a}	0.15^{a}	7.0^{a}	22.8^{a}
Phosphogypsum	5.1^{a}	0.95^{a}	0.28^{b}	0.26^{ab}	6.0^{a}	0.16^{a}	7.4^{a}	18.8^{a}
Fertilization rates								
0	5.3	0.77	0.33	0.25	5.9	0.15	7.2	17.5
0.5	5.2	0.97	0.43	0.23	5.6	0.15	7.1	22.2
1.0	5.2	0.98	0.41	0.19	5.5	0.15	7.1	21.9
1.5	5.1	0.92	0.32	0.23	5.8	0.16	7.2	19.4
Source of variation	**F probability**							
Soil corrective (SC)	0.0883	0.0838	<0.001	0.0051	0.0554	0.2544	0.3389	0.0322
Fertilization (F)	0.0638	0.1306	0.0659	0.5168	0.4924	0.8582	0.9446	0.1570
SC × F	0.9237	0.9693	0.9515	0.8905	0.9129	0.7262	0.4727	0.9920
Soil corrective	**Depth 0.20 - 0.40 m**							
Control	5.1^{a}	0.61^{a}	0.17^{a}	0.29^{a}	5.0^{a}	0.11^{a}	5.9^{a}	15.1^{a}
Limestone	5.1^{a}	0.68^{a}	0.23^{a}	0.28^{a}	5.2^{a}	0.09^{a}	6.2^{a}	16.5^{a}
L + PG	5.1^{a}	0.66^{a}	0.22^{a}	0.26^{a}	5.0^{a}	0.10^{a}	5.9^{a}	16.9^{a}
Phosphogypsum	5.2^{a}	0.75^{a}	0.20^{a}	0.26^{a}	4.9^{a}	0.10^{a}	5.9^{a}	18.0^{a}
Fertilization rates								
0	5.1	0.52	0.16	0.33	5.2	0.09	6.0	12.9
0.5	5.2	0.61	0.20	0.27	5.0	0.09	5.9	15.6
1.0	5.1	0.79	0.24	0.23	4.7	0.09	5.8	19.5
1.5	5.1	0.80	0.23	0.26	5.2	0.12	6.3	18.6
Source of variation	**F probability**							
Soil corrective (SC)	0.7121	0.3670	0.1361	0.7395	0.6554	0.2141	0.6843	0.4173
Fertilization (F)	0.5837	0.0015	0.0278	0.0456	0.2413	0.0029	0.3628	0.0017
SC × F	0.9790	0.9718	0.9970	0.6190	0.9018	0.2453	0.9113	0.9210

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

Table 3. Effects of the application of lime (L) and/or phosphogypsum (PG), fertilization rates and soil depth layers on the values of SOM, P, Cu, Zn, Fe and Mn in the soil 24 months (November 2012) after the first application of the soil correction. Crop managed under the no-tillage system (NTS).

Soil corrective	Depth 0 - 0.10 m					
	MO	**P**	**Cu**	**Zn**	**Fe**	**Mn**
	g dm^{-3}	**--------------------------------------mg dm^{-3}-------------------------------**				
Control	29.5^{a}[1]	16.2^{a}	1.34^{a}	5.51^{a}	23.4^{a}	11.2^{c}
Limestone	30.7^{a}	14.1^{a}	1.13^{b}	5.38^{a}	23.4^{a}	15.9^{a}
L + PG	30.0^{a}	14.6^{a}	1.13^{b}	4.66^{a}	23.2^{a}	13.6^{b}
Phosphogypsum	30.0^{a}	17.0^{a}	1.28^{a}	4.84^{a}	25.8^{a}	14.0^{ab}
Fertilization rates						
0	29.9	5.9	1.18	2.71	24.0	11.6
0.5	31.5	14.0	1.15	4.89	24.4	15.3
1.0	29.8	13.5	1.19	5.89	21.4	14.7
1.5	28.9	28.4	1.36	6.89	25.9	13.1
Source of variation	**F probability**					
Soil corrective (SC)	0.6312	0.8023	<0.001	0.5060	0.2154	<0.001
Fertilization (F)	0.0561	<0.001	0.0013	<0.001	0.0235	<0.001
SC × F	0.0521	0.9999	0.9615	0.7805	0.7864	0.7299
Soil corrective	**Depth 0.10 - 0.20 m**					
Control	28.6^{a}	12.2^{a}	1.43^{a}	5.41^{a}	21.2^{b}	8.1^{a}
Limestone	27.4^{a}	18.0^{a}	1.51^{a}	6.94^{a}	23.5^{ab}	9.8^{a}
L + PG	27.3^{a}	16.3^{a}	1.49^{a}	6.21^{a}	22.7^{ab}	8.6^{a}
Phosphogypsum	29.2^{a}	16.5^{a}	1.53^{a}	6.67^{a}	24.2^{a}	10.3^{a}
Fertilization rates						
0	29.5	5.7	1.38	2.01	22.8	8.0
0.5	28.8	12.7	1.47	5.98	23.3	10.4
1.0	27.9	18.2	1.48	7.73	21.8	9.9
1.5	26.4	29.5	1.63	9.51	23.7	8.6
Source of variation	**F probability**					
Soil corrective (SC)	0.0999	0.5553	0.6705	0.8779	0.0100	0.1517
Fertilization (F)	0.0680	<0.001	0.0420	0.0036	0.1773	0.0936
SC × F	0.3586	0.9299	0.5098	0.6456	0.6842	0.9795
Soil corrective	**Depth 0.20 - 0.40 m**					
Control	24.2^{a}	2.1^{a}	1.40^{a}	2.47^{a}	20.1^{a}	6.3^{a}
Limestone	25.0^{a}	2.4^{a}	1.41^{a}	2.86^{a}	21.3^{a}	8.4^{a}
L + PG	23.9^{a}	2.7^{a}	1.46^{a}	2.69^{a}	21.5^{a}	6.4^{a}
Phosphogypsum	26.0^{a}	2.4^{a}	1.46^{a}	2.60^{a}	21.9^{a}	7.8^{a}
Fertilization rates						
0	25.4	1.3	1.38	1.58	21.7	5.8
0.5	24.8	2.1	1.46	2.17	20.6	6.5
1.0	23.9	3.1	1.40	3.32	20.7	8.1
1.5	24.9	3.2	1.51	3.56	21.8	8.4
Source of variation	**F probability**					
Soil corrective (SC)	0.0548	0.7126	0.6285	0.8560	0.1745	0.0792
Fertilization (F)	0.3078	0.0004	0.1490	0.0002	0.3058	0.0256
SC × F	0.6677	0.6407	0.9797	0.9698	0.9978	0.8265

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

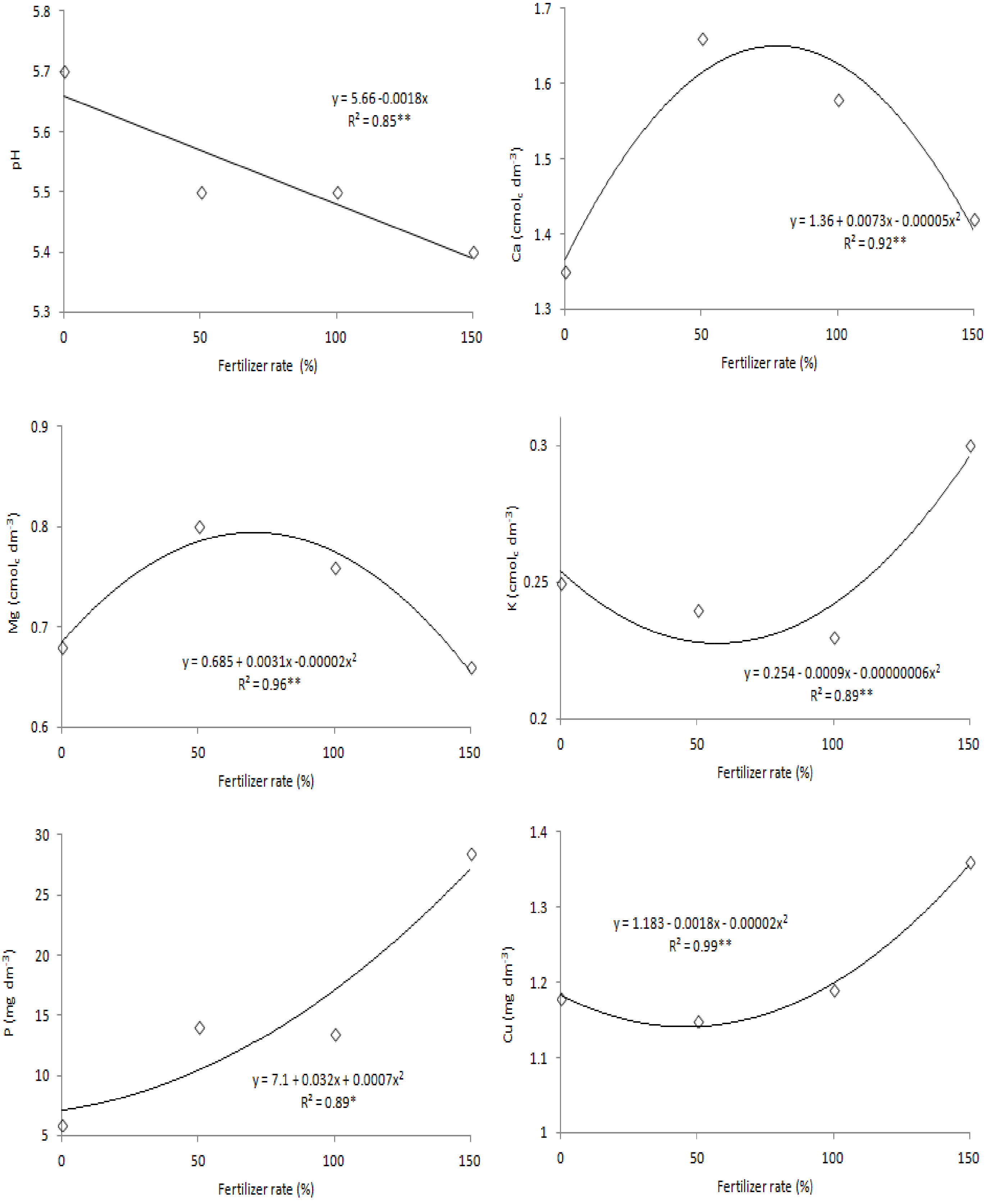

Figure 2. Chemical attributes of the soil (pH, Ca, Mg, K, P and Cu) in the depth 0 - 10 cm as a function of fertilization rates. Soil measured 24 months after first application of lime and phosphogypsum under the no-tillage system.

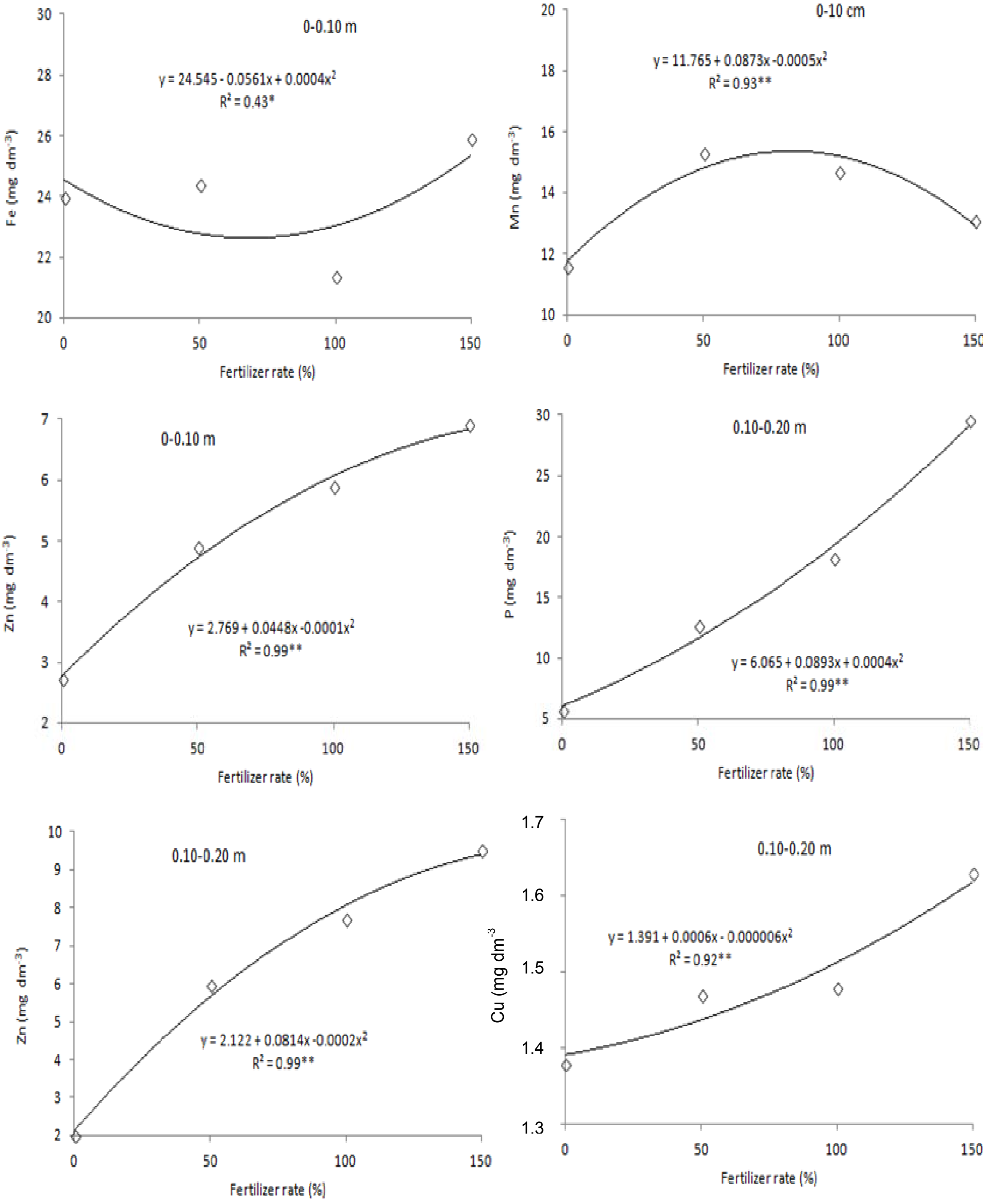

Figure 3. Chemical attributes of the soil (Fe, Mn and Zn in the depth 0 - 10 cm and P, Zn and Cu in the depth 10 - 20 cm) as a function of fertilization rates. Soil measured 24 months after first application of lime and phosphogypsum under the no-tillage system.

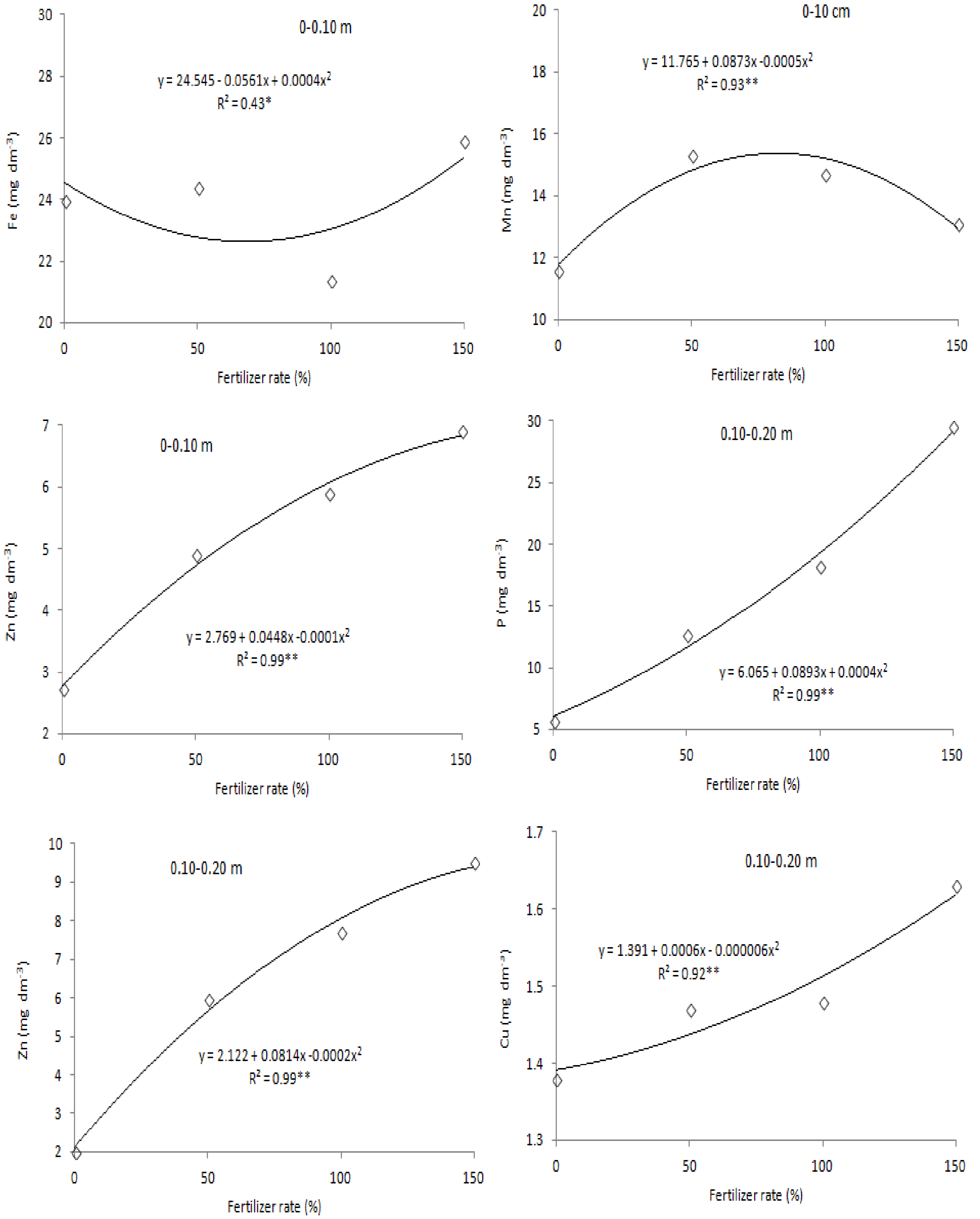

Figure 4. Chemical attributes of the soil (Ca, Mg, Al, K, V, P, Mn and Zn) in the depth 20 - 40 cm as a function of fertilization rates. Soil measured 24 months after first application of lime and phosphogypsum under the no-tillage system.

Table 4. Effects of the application of limestone (L) and/or phosphogypsum (PG), fertilization rates and growing season on the values of N, P, K, Ca, Mg and S in leaves sampled at the full flowering state (R2) in the soybean crop. Crop managed under the no-tillage system (NTS).

Soil corrective	Growing season 2010/2011					
	N	**P**	**K**	**Ca**	**Mg**	**S**
	g kg^{-1}					
Control	39.8^{a}[1]	2.42^{a}	15.97^{a}	12.88^{ab}	3.18^{a}	1.53^{a}
Limestone	37.1^{a}	2.45^{a}	16.01^{a}	12.38^{b}	2.56^{b}	1.30^{b}
L + PG	37.5^{a}	2.46^{a}	15.63^{a}	13.38^{ab}	2.97^{ab}	1.59^{a}
Phosphogypsum	37.3^{a}	2.45^{a}	16.59^{a}	13.72^{a}	3.09^{a}	1.46^{ab}
Fertilization rates						
0	37.5	2.07	15.39	12.95	2.65	1.38
0.5	37.2	2.53	16.11	12.13	2.84	1.43
1.0	38.7	2.57	16.49	13.20	3.08	1.53
1.5	38.2	2.61	16.20	14.08	3.23	1.54
Source of variation	**F probability**					
Soil corrective (SC)	0.5296	0.9732	0.8328	0.0221	0.0036	0.0057
Fertilization (F)	0.8703	<0.001	0.7517	0.0009	0.0075	0.1898
SC × F	0.6877	0.4265	0.9909	0.2578	0.6388	0.9456
Soil corrective	**Growing season 2011/2012**					
Control	30.8^{b}	3.12^{a}	17.16^{b}	10.39^{b}	2.83^{a}	1.64^{b}
Limestone	36.3^{a}	3.18^{a}	19.46^{a}	10.25^{b}	3.06^{a}	1.40^{c}
L + PG	34.8^{ab}	3.01^{a}	16.69^{b}	10.47^{ab}	3.04^{a}	1.61^{bc}
Phosphogypsum	33.2^{ab}	3.21^{a}	16.69^{b}	11.52^{a}	3.15^{a}	1.88^{a}
Fertilization rates						
0	31.5	3.04	18.41	11.03	2.96	1.65
0.5	34.9	3.27	16.93	9.97	2.89	1.67
1.0	34.2	3.21	16.97	10.84	3.31	1.57
1.5	34.7	3.01	17.69	10.80	2.92	1.64
Source of variation	**F probability**					
Soil corrective (SC)	0.0276	0.3699	0.0005	0.0118	0.4854	<0.001
Fertilization (F)	0.2208	0.0751	0.1291	0.0566	0.1694	0.6699
SC × F	0.4622	0.0894	0.0809	0.3045	0.9726	0.4508
Soil corrective	**Growing season 2012/2013**					
Control	44.0^{a}	2.99^{a}	14.68^{a}	9.47^{a}	2.25^{a}	2.33^{a}
Limestone	46.4^{a}	3.06^{a}	13.53^{a}	9.30^{a}	2.18^{a}	2.43^{a}
L + PG	45.6^{a}	3.13^{a}	14.81^{a}	9.96^{a}	2.20^{a}	2.44^{a}
Phosphogypsum	43.8^{a}	3.09^{a}	14.26^{a}	9.90^{a}	2.08^{a}	2.48^{a}
Fertilization rates						
0	41.4	2.60	14.20	8.93	2.01	2.22
0.5	45.6	3.05	14.25	9.25	2.24	2.43
1.0	45.9	3.29	14.38	10.17	2.23	2.50
1.5	46.9	3.35	14.46	10.29	2.23	2.52
Source of variation	**F probability**					
Soil corrective (SC)	0.1572	0.1295	0.0812	0.1192	0.4359	0.3306
Fertilization (F)	0.0005	<0.001	0.9603	0.0001	0.1208	0.0022
SC × F	0.8952	0.3019	0.5854	0.8080	0.2700	0.6687

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

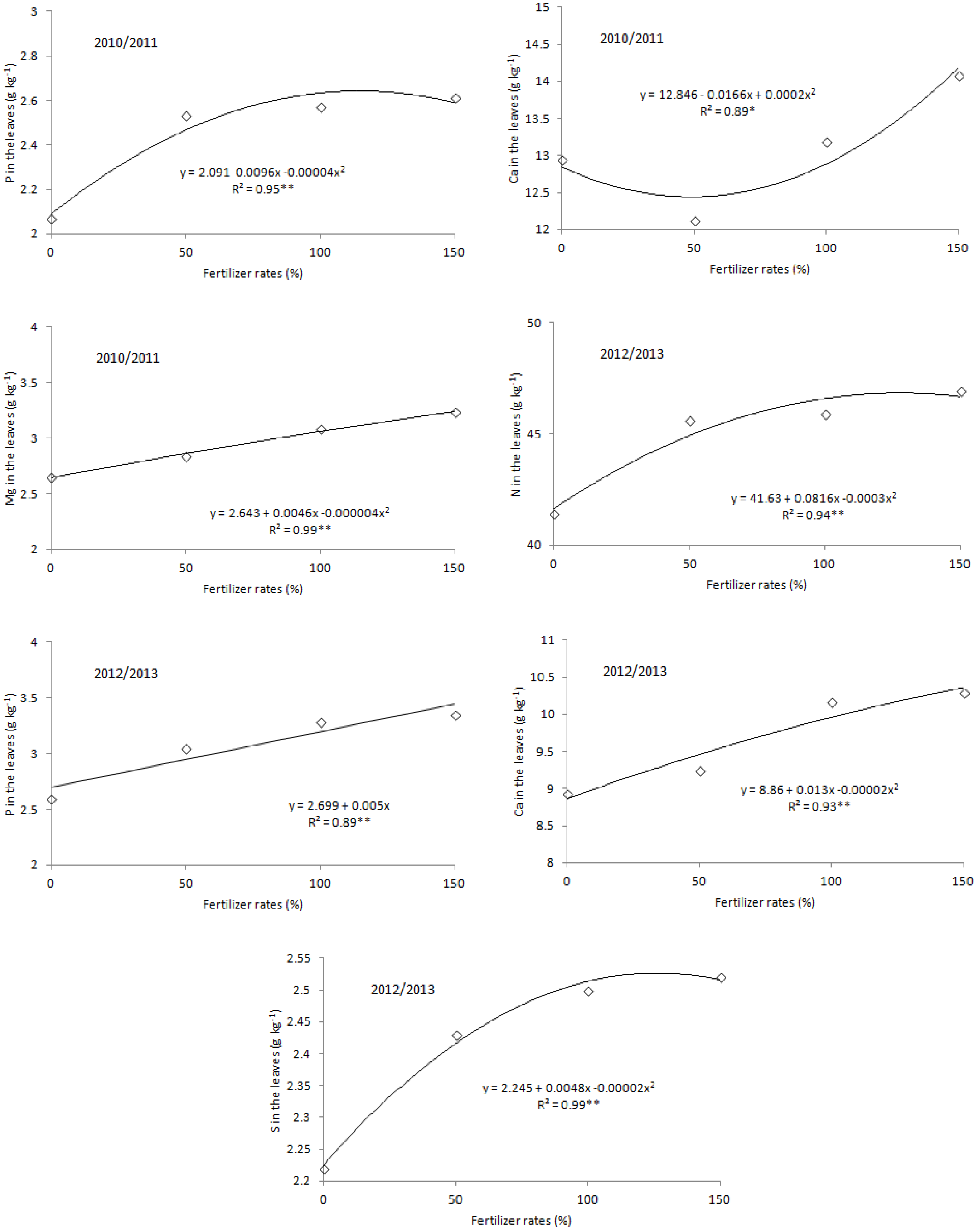

Figure 5. Concentration of nutrients (P, Ca, Mg in the growing season 2010/2011 and N, P, Ca and S in the growing season 2012/2013) in soybean leaves as a function of fertilization rates.

Table 5. 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 seeds pod^{-1} (NSP), 100-seed weight (W100) and seed yield (Yield) of the soybean crop. Crop cultivated under the no-tillage system (NTS).

Soil corrective	Growing season 2010/2011				
	POP	NPP	NSP	W100	Yield
	nº × 1000	nº	nº	g	kg ha^{-1}
Control	180.6^{a}[1]	71^{a}	1.66^{a}	14.20^{ab}	2013^{b}
Limestone	191.1^{a}	71^{a}	1.66^{a}	14.49^{a}	2494^{a}
L + PG	203.5^{a}	64^{a}	1.78^{a}	13.68^{ab}	2534^{a}
Phosphogypsum	195.7^{a}	69^{a}	1.61^{a}	13.19^{b}	2063^{b}
Fertilization rates					
0	163.9	62	1.58	13.60	2042
0.5	181.0	67	1.76	13.98	2348
1.0	200.8	68	1.75	13.53	2358
1.5	225.1	77	1.61	13.46	2356
Source of variation			**F probability**		
Soil corrective (SC)	0.1788	0.4581	0.0975	0.0094	0.0009
Fertilization (F)	<0.001	0.0242	0.0277	0.0785	0.0143
SC x F	0.6293	0.8306	0.1929	0.7521	0.1234
Soil corrective			**Growing season 2011/2012**		
Control	278.1^{a}	59^{a}	1.54^{a}	13.09^{a}	1819^{c}
Limestone	282.6^{a}	64^{a}	1.65^{a}	13.16^{a}	2538^{a}
L + PG	282.8^{a}	60^{a}	1.63^{a}	13.28^{a}	2276^{b}
Phosphogypsum	277.4^{a}	57^{a}	1.60^{a}	12.59^{a}	1874^{c}
Fertilization rates					
0	278.3	54	1.46	12.96	1490
0.5	277.9	57	1.61	12.82	1899
1.0	282.5	61	1.66	13.16	2459
1.5	282.3	67	1.69	13.18	2659
Source of variation			**F probability**		
Soil corrective (SC)	0.9122	0.5272	0.4898	0.2131	<0.001
Fertilization (F)	0.9423	0.0358	0.0239	0.6842	<0.001
SC x F	0.8982	0.2657	0.7106	0.2680	0.1293
Soil corrective			**Growing season 2012/2013**		
Control	393.3^{a}	27^{a}	1.90^{a}	17.00^{a}	2820^{b}
Limestone	394.9^{a}	30^{a}	1.99^{a}	17.58^{a}	3151^{a}
L + PG	400.1^{a}	31^{a}	2.01^{a}	17.25^{a}	3248^{a}
Phosphogypsum	408.8^{a}	27^{a}	1.93^{a}	17.29^{a}	3148^{ab}
Fertilization rates					
0	389.0	22	1.90	16.05	2674
0.5	404.0	28	2.00	17.27	3083
1.0	406.6	30	2.00	17.68	3228
1.5	397.5	34	1.93	18.12	3382
Source of variation			**F probability**		
Soil corrective (SC)	0.0842	0.0159	0.4232	0.2216	0.0001
Fertilization (F)	0.1035	<0.001	0.9890	<0.001	<0.001
SC × F	0.2740	0.9129	0.6809	0.1584	0.0907

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

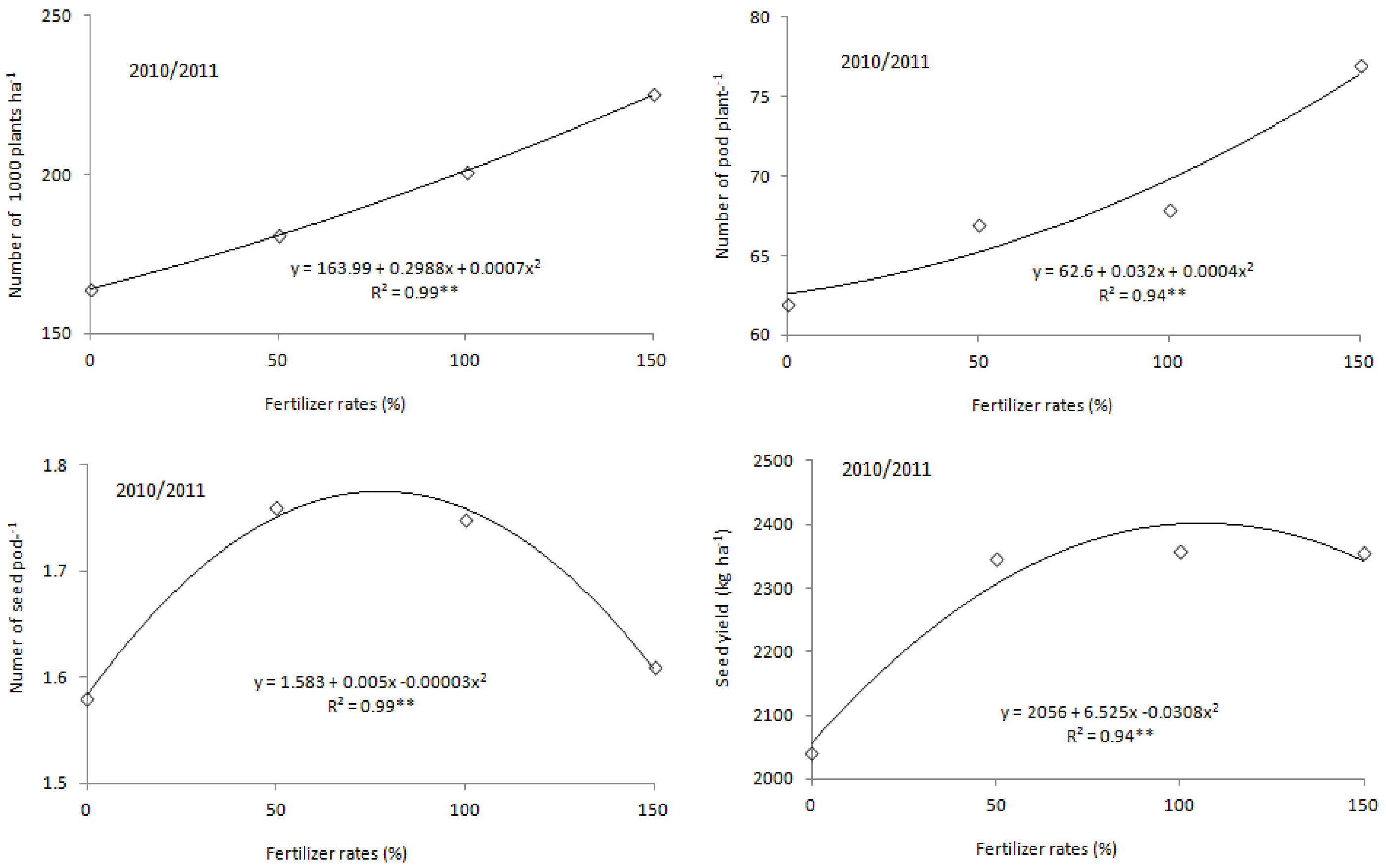

Figure 6. Number of plants ha^{-1}, yield components and seed yield of soybean in the growing season 2010/2011 as a function of fertilization rates.

Table 6. Efficiency of PK fertilizer use in the soybean crop cultivated under the NTS as a function of lime (L) and phosphogypsum (PG) application.

Variable	No corrective	Limestone	L + FG	Phosphogypsum
SSASY - A[1]	6652	8183	8058	7085
K_2O-P_2O_5 applied by fertilizer - B[2]	360	360	360	360
Fertilizer efficiency use - A/B	18.48 B[3]	22.73^{A}	22.38^{A}	19.68^{B}

[1] SSASY - Sum of average of the soybean seed yield from application of rates 0, 50, 100 and 150% of the recommended fertilization in three growing seasons (2010/2011, 2011/2012 and 2012/2013).[2] Average of the amount of P_2O_5 and K_2O applied via fertilizer at doses 0, 50, 100 and 150% of the recommended fertilization in three growing seasons (2010/2011/2011/2012 and 2012/2013). Thus, it was applied for each nutrient 0, 40, 80 and 120 kg ha^{-1}, totaling 240 kg ha^{-1} of each nutrient, that is, applied 480 kg K_2O + P_2O_5. The average was 120 kg ha^{-1} (480/4 fertilizer rates) for each year time 3 (growing season) = 360.
[3] Means followed by the same letter in the row do not differ by LSD test at $p < 0.05$.

phosphogypsum than without liming. The fertilization rates had significant quadratic effects on the plant population, the number of pods plant^{-1}, the number of seeds pod^{-1} and the seed yield (Figure 6).

During the second growing season (2011/2012), the lime treatment significantly affected soybean seed yield (Table 5). Lime applied alone provided the highest yield and this value differed from those produced by the other treatments. The fertilization rates had significant quadratic effects on the number of pods plant^{-1}, number of seeds pod^{-1} and seed yield (Figure 7). During the third growing season (2012/2013), significant treatment effects were found only for seed yield. The application of lime with or without phosphogypsum resulted in higher seed yields, which differed from the values found for the control. The fertilization rates had significant quadratic

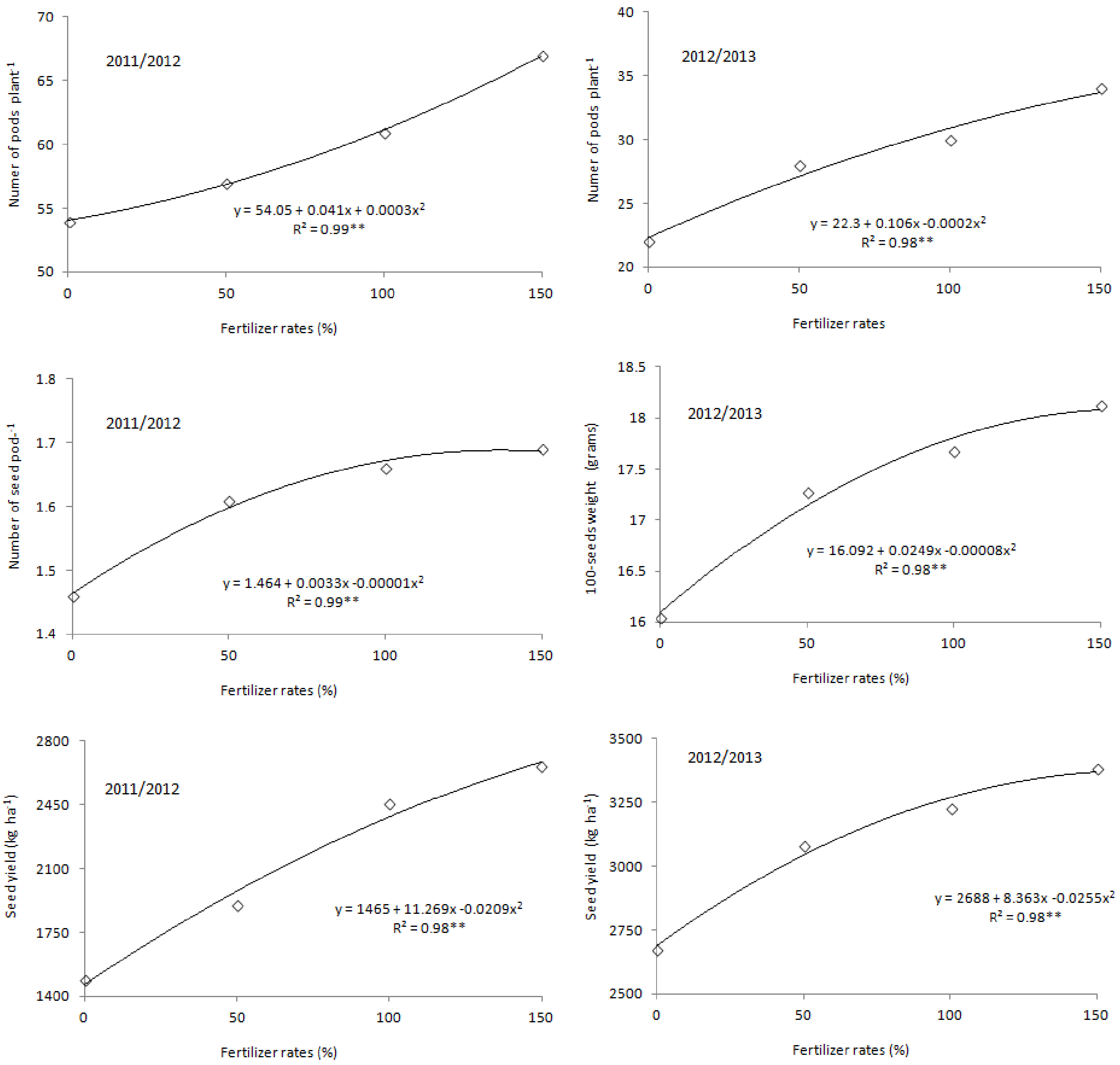

Figure 7. Yield components and seed yield of soybean in the growing season 2011/2012 and 2012/2013 as a function of fertilization rates.

effects on the number of pods plant^{-1}, 100-seed weight and seed yield.

Efficiency of fertilizer use

The treatments with lime, with or without phosphogypsum, allowed a higher efficiency of fertilizer use. This value differed from those found for the control and for phosphogypsum alone (Table 8).

DISCUSSION

Soil attributes

The lime treatment produced the greatest changes in soil properties, resulting in increased pH levels, an increased availability of Ca and Mg and a decreased content of Al and H + Al, with increases in CEC and base saturation at a depth of 0 to 0.10 m 24 months after the first application. However, the effects on soil attributes were more pronounced in the surface layer, with small changes in the 0.10 to 0.20 m layer (only Mg, Al and Fe) and no change in the 0.20 to 0.40 m layer. Results from the field have shown that the movement of the limestone when applied on the soil surface is very low (Gascho and Parker, 2001; Conyers et al., 2003; Tang et al., 2003; Caires et al., 2008; Soratto and Crusciol, 2008a, b; Churka Blum et al., 2013). Our results imply that the reaction of the non-incorporated lime with the soil was delayed; only supplying acidity correction in the first few cm of the soil.

The application of phosphogypsum, which is not a soil corrective, did not result in significant alterations in the pH of the soil or in other attributes. If applied in large quantities, this soil conditioner can cause the leaching of bases (Ca, Mg and K) to deeper layers (Ramos et al., 2006; Caires et al., 2008). In our experiment, however, higher levels of these bases were not observed in the 0.20 to 0.40 m layer.

The pH level decreased linearly with increases in the amount of fertilizer applied. An explanation of this result is that nitrogen fertilizers were applied when common bean was cultivated during the off season between the soybean growing seasons. These fertilizers were applied in the same correspondent plots of soybean. In other words, the common bean plots which received a rate of 150% of fertilizer were the same with the ones which received 150% of fertilizer on soybean. The nitrogenous fertilizers ammonium sulfate and urea contain $N\text{-}NH_4^+$ and $N\text{-}NH_3^-$, respectively. In the soil, these ions rapidly oxidize to nitrate, releasing H^+ and producing significant decreases in pH (Fageria et al., 2011; Nascente et al., 2012).

The content of Ca and Mg increased up to a certain level of fertilization and then began to decrease. This finding can be explained by competition with K for soil adsorption sites. The increased application of KCl increased the amount of K in the soil (Figure 2). According to Liebhardt (1981), the application of K to soils directly affects Ca and Mg, as they compete for the same adsorption sites in the soil. Thus, it is probable that greater amounts of K caused the release of Ca and Mg from soil colloids and possibly the leaching of these nutrients to deeper layers. The observed levels of these nutrients in the 0.20 to 0.40 m layer (Figure 4) are consistent with this suggestion.

Phosphorus increased significantly with increasing fertilization rates. This result can be explained by an increase of P in amounts larger than that exported by the seeds (Figures 9 and 10). Cu, Zn and Mn increased with increasing levels of fertilizer. These findings may reflect the decreased pH in those treatments that increased the availability of cationic micronutrients (Fageria et al., 2011). Micronutrients are influenced strongly by pH, and decreases in pH are accompanied by a greater availability of these nutrients (Fageria et al., 2002). Note that the levels of Fe were affected little by fertilization rates. A possible reason for this outcome is that Oxisols typically contain large amounts of Fe, and agricultural management alters the balance of this nutrient in the soil only in rare cases (Fageria et al., 2002).

At a depth of 0.20 to 0.40 m, due to the probable leaching of Ca and Mg, increased levels of fertilization produced higher levels of these nutrients. Potassium, which is more readily leachable, also showed increases with increasing rates of fertilization. However, these increases were much lower than those obtained for Ca and Mg. These results indicate that the majority of K was absorbed by soil colloids in the superficial layers. Most likely, the addition of phosphate fertilizers at the 0.10 to 0.20 m depth produced increased levels of P at depth as fertilization rates increased. With rising levels of bases at depth (Ca, Mg and K), increases in base saturation were expected, and these expected increases were observed. The micronutrients Zn and Mn also showed significant increases with increasing levels of fertilization. This result may reflect the lower pH normally found in the deeper soil layers (Table 2).

Nutrient content in soybean leaves

The decrease in Ca, Mg and S content in the treatment with lime can be explained by the dilution effect because the Ca and Mg content in the soil increased, resulting in better plant development and higher seed yields (Table 5). Caires et al. (2001) have reported that in soybean crops, liming allowed the absorption of nutrients to increase, resulting in higher seed yield. In contrast, increased levels of N and K, the nutrients accumulated in greater amounts in the plant, should be related to adequate conditions for the development of the root system, with positive effects on biological nitrogen fixation and the absorption of K. According to Rosolem and Marcello (1998), Costa and Rosolem (2007) and Veronese et al. (2012), liming can increase the growth of soybean root in terms of length and surface area. The increase in nutrient content in the soybean leaves with the increasing levels of P and K resulting from fertilization was expected given the original low soil fertility (Table 1). This increase was associated with an increase in the levels of these nutrients in the soil (Figures 3 and 4) and the decrease in soil acidity caused by liming, increasing the availability of the nutrients to the plants (Fageria et al. 2011). According to Gonçalves Junior et al. (2010) as the soil from the Cerrado Region normally has low fertility, P and K application to the soybean crop provided better plant nutrition and resulted in higher grain yield than no fertilization.

Yield components and seed yield

Liming increased soybean seed yield in the three seasons. This result may be a consequence of the changes in the soil properties caused by the application of the limestone to the soil, such as increased pH, increased availability of Ca and Mg, base saturation and CEC. Likewise, Caires et al. (2001) have reported significant increases in the seed yield of soybean due to the use of surface liming without incorporation in the NTS. The authors attributed this result to the greater availability of Mg.

On the other hand, the application of phosphogypsum did not increase the crop seed yield over the 3 years of cultivation. Similar results have been reported in other studies in areas of annual crops when the soil was under the NTS (Caires et al., 1998, 2003). The lack of a response by soybean to the application of phosphogypsum may have occurred because the application of this soil conditioner does not provide acidity correction in the topsoil and because the growth of soybean roots in the absence of soil water deficit is not influenced by decreased Al saturation in the subsoil (Caires et al., 2006a). Indeed, it appears that the values of Al in the deep layers of the soil were low (less than 0.3 $mmol^c\ dm^{-3}$) and were affected little by the application of phosphogypsum, showing no differences from the results of the other treatments.

Increased fertilization rates produced increases in the plant population, yield components and seed yield to a certain point. Thus, it can be inferred that it is likely that other nutrients may have limited the seed yield after fertilization with only P and K.

Efficiency of fertilizer use

For every kilogram of fertilizer applied, 22.73 kg of soybean seeds were obtained from the lime application and 22.38 kg from the application of lime with phosphogypsum. These values differed from the control (18.48 kg of soybean seeds) and from the application of phosphogypsum alone (19.68 kg of soybean seeds). The results show that the lime effectively increased the soybean seed yield and improved the efficiency of fertilizer use. In contrast, the application of phosphogypsum produced no significant increase in seed yield.

Conclusion

The use of lime alone or in combination with phosphogypsum improved soil chemical characteristics, the nutritional status of the soybean plants and yield. In contrast, the application of phosphogypsum alone did not produce significant alterations in the soil or affect soybean seed yield. The use on soybean of increasing application rates of fertilizer containing P and K (simple superphosphate, triple superphosphate and potassium chloride) during three growing seasons produced significant increases in the seed yield of the crop. Accordingly, the application of lime increased fertilization efficiency, enabling a greater production of soybean seeds per kg of fertilizer applied. Based on these results, it is clear that, particularly in areas of the Cerrado, the surface application of lime without incorporation under the NTS is a better practice to increase fertilizer efficiency than phosphogypsum application. The application of phosphogypsum alone was not effective under the conditions tested in the experiment, which included soil acidity in the surface layer.

Conflict of Interests

The authors have not declared any conflict of interests.

REFERENCES

Alleoni LRF, Cambri MA, Caires EF, Garbuio FJ (2009). Acidity and aluminum speciation as affected by surface liming in tropical no-till soils. Soil Sci. Soc. Am. J. 74(3):1010-1017. http://dx.doi.org/10.2136/sssaj2009.0254

Caires EF, Alleoni LRF, Cambri MA, Barth G (2005). Surface application of lime for crop grain production under a no-till system. Agron. J. 97(3):791-798.http://dx.doi.org/10.2134/agronj2004.0207

Caires EF, Barth G, Garbuio FJ (2006a). Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. Soil Till. Res. 89(1):3-12. http://dx.doi.org/10.1016/j.still.2005.06.006

Caires EF, Correa JCL, Churka S, Barth G, Garbuio FJ (2006b). Surface application of lime ameliorates subsoil acidity and improves root growth and yield of wheat in an acid soil under no-till system. Sci. Agric. 63(5):502–509. http://dx.doi.org/10.1590/S0103-90162006000500013

Caires EF, Chueiri WA, Madruga EF, Figueiredo A (1998). Alterações de características químicas do solo e resposta da soja ao calcário e gesso aplicados na superfície em sistema de cultivo sem preparo de solo. Rev. Bras. Cienc. Solo 22(1):27-34.

Caires EF, Blum J, Barth G, Garbuio FJ, Kusman MT (2003). Alterações químicas do solo e resposta da soja ao calcário e gesso aplicados na implantação do sistema de plantio direto. Rev. Bras. Cienc. Solo 27(2):275-286. http://dx.doi.org/10.1590/S0100-06832003000200008

Caires EF, Fonseca AF, Feldhaus IC, Blum J (2001). Root growth and nutrient uptake by soybean as affected by lime and gypsum, under a no-tillage system. Rev. Bras. Cienc. Solo 25(4):1029–1040.

Caires EF, Garbuio FJ, Churka S, Barth G, Corrêa JCL (2008). Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield. Eur. J. Agron. 28(1):57-64. http://dx.doi.org/10.1016/j.eja.2007.05.002

Caires EF, Kusman MT, Barth G, Garbuio FJ, Padilha JM (2004). Alterações químicas do solo e resposta do milho à calagem e aplicação de gesso. Rev. Bras. Cienc. Solo 28(1):125-136.http://dx.doi.org/10.1590/S0100-06832004000100013

Churka Blum S, Caires EF, Alleoni LRF (2013). Lime and phosphogypsum application and sulfate retention in subtropical soils under no-till system. J. Soil Sci. Plant Nutr. 13(2):279-300.

Claessen MEC (1997). Manual de métodos de análise de solo, 2nd ed. Embrapa, Rio de Janeiro, RJ, Brazil. PMCid:PMC2228098

Conyers MK, Heenan DP, McGhie WJ, Poile GP (2003). Amelioration of acidity with time by limestone under contrasting tillage. Soil Till. Res. 72(1):85-94. http://dx.doi.org/10.1016/S0167-1987(03)00064-3

Costa A, Rosolem CA (2007). Liming in the transition to no till under a wheat soybean rotation. Soil Till. Res. 97(2):207 217.

http://dx.doi.org/10.1016/j.still.2007.09.014

Embrapa Soja (2010). Tecnologia de produção de soja- Região Central do Brasil 2011. Embrapa, Londrina, PR, Brazil.

Fageria NK, Baligar VC (2008). Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. Adv. Agron. 99:345–399.http://dx.doi.org/10.1016/S0065-2113(08)00407-0

Fageria NK, Baligar VC, Clark RB (2002). Micronutrients in crop production. Adv. Agron. 77:185-268. http://dx.doi.org/10.1016/S0065-2113(02)77015-6

Fageria NK, Baligar VC, Jones CA (2011). Growth and mineral nutrition of field crops. CRC Press, Boca Raton, FL, USA.

FAO (2013). FAOSTAT – production :crops. Available at: <http://faostat.fao.org>. Acessed on 29 Oct 2013.

Fehr WR, Caviness CE (1977). Stages of soybean development. Ames, Iowa State University, USA.

Franchini JC, Hoffmann-Campo CB, Torres E, Miyazawa M, Pavan MA (2003). Organic composition of green manures during growth and its effect on cation mobilization in an acid Oxisol. Comm. Soil Sci. Plant Anal. 34(13/14):2045-2058. http://dx.doi.org/10.1081/CSS-120023237

Gascho GJ, Parker MB (2001). Long-term liming effects on Coastal Plain soils and crops. Agron. J. 93(6):1305-1315. http://dx.doi.org/10.2134/agronj2001.1305

Gonçalves Junior AC, Nacke H, Marengoni NG, Carvalho EA, Coelho GF (2010). Yield and production components of soybean fertilized with different doses of phosphorus, potassium and zinc. Cienc. Agrotec. 34(3):660-666.

Liebhardt WC (1981). The basic cation saturation ratio concept and lime and potassium recommendations an Delaware's Coastal plain soils. Soil Sci. Soc. Am. J. 45(3):544-549. http://dx.doi.org/10.2136/sssaj1981.03615995004500030022x

Malavolta E, Vitti GC, Oliveira SA (1997). Avaliação do estado nutricional de plantas: princípios e aplicações, 2nd ed. Potafos, Piracicaba, SP, Brazil.

Nascente AS, Crusciol CAC (2012). Cover crops and herbicide timing management on soybean yield under no-tillage system. Pesqui. Agropecu. Bras. 47(2):187-192. http://dx.doi.org/10.1590/S0100-204X2012000200006

Nascente AS, Crusciol CAC, Cobucci T (2012). Ammonium and nitrate in soil and upland rice yield as affected by cover crops and their desiccation time. Pesqui. Agropecu. Bras. 47(12):1699-1706.http://dx.doi.org/10.1590/S0100-204X2012001200004

Nascente AS, Crusciol CAC, Cobucci T (2013). The no-tillage system and cover crops – alternatives to increase upland rice yields. Eur. J. Agric. 45(2):124-131. http://dx.doi.org/10.1016/j.eja.2012.09.004

Ramos LA, Korndorfer GH, Pereira HS, Camargo MS (2006). Reatividade de corretivos da acidez e condicionadores de solo em colunas de lixiviação. Rev. Bras. Cienc. Solo 30(5):849-857. http://dx.doi.org/10.1590/S0100-06832006000500011

Rosolem CA, Marcello CS (1998). Crescimento radicular e nutrição mineral da soja em função da calagem e adubação fosfatada. Sci. Agric. 55(3):448 455. http://dx.doi.org/10.1590/S0103-90161998000300013

SAS Institute (1999). Procedure guide for personal computers. Version 5. Sas Institute, Cary.

Soratto RP, Crusciol CAC (2008a). Atributos químicos do solo decorrentes da aplicação em superfície de calcário e gesso em sistema plantio direto recém-implantado. Rev. Bras. Cienc. Solo 32(2):675-688. http://dx.doi.org/10.1590/S0100-06832008000200022 http://dx.doi.org/10.1590/S0100-06832008000200026

Soratto RP, Crusciol CAC (2008b). Métodos de determinação de cálcio e magnésio trocáveis e estimativa do calcário residual em um latossolo submetido à aplicação de calcário e gesso em superfície. Rev. Bras. Cienc. Solo. 32(2):663-673. http://dx.doi.org/10.1590/S0100-06832008000200021

Soratto RP, Crusciol CAC (2008c). Nutrição e produtividade de grãos da aveia-preta em função da aplicação de calcário e gesso em superfície na implantação do sistema plantio direto. Rev. Bras. Cienc. Solo 32(2):715-725. http://dx.doi.org/10.1590/S0100-06832008000200022 http://dx.doi.org/10.1590/S0100-06832008000200026

Sousa DMG, Lobato E (2004). Cerrado: correção do solo e adubação, 2nd ed. Embrapa, Brasília, DF, Brazil.

Souza HA, Natale W, Rozane DE, Hernandes A, Romualdo LM (2011). Liming and fertilization with boron in production of bean. Rev. Cienc. Agron. 42(2):249-257. http://dx.doi.org/10.1590/S1806-66902011000200001

Tang C, Rengel Z, Diatloff E, Gazey CR (2003). Responses of wheat and barley to liming on a sandy soil with subsoil acidity. Field Crop. Res. 80(3):235-244. http://dx.doi.org/10.1016/S0378-4290(02)00192-2

Veronese M, Francisco EAB, Zancanaro L, Rosolem CA (2012). Cover crops and liming in the implementation of no tillage system. Pesqui. Agropecu. Bras. 47(8):1158-1165. http://dx.doi.org/10.1590/S0100-204X2012000800017

Walkley A, Black IA (1934). An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37(1):29-37. http://dx.doi.org/10.1097/00010694-193401000-00003