Effects of surface application of dolomitic limestone and calcium-magnesium silicate on soybean and maize in rotation with green manure in a tropical region

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Abstract

Although lime is currently the material most frequently used to ameliorate soil acidity in Brazil, silicate could efficiently replace this source because of its greater solubility and its greater silicon content, which are beneficial for plant development. This study aimed to evaluate the effects of superficial lime and silicate application on soil chemical attributes as well as on soybean and maize nutrition and grain yields when these crops are grown in rotation with green manure. The experimental design was a complete randomized block with sixteen replicates. Plots were treated with one of two materials for acidity correction (dolomitic lime and calcium/magnesium silicate) or with no soil correction, as a control. Silicate corrected soil acidity and increased exchangeable base levels in soil at greater depths faster than does liming. The application of both acidity-correcting materials increased N, Ca and Mg leaf concentrations, and all yield components and grain yield in soybean; but in maize, just silicate also increased N and Si when compared with lime, whereas both acidity-correcting increased just two yield components: grains per ear and mass of 100 grains, resulting in highest grain yield. The application of both acidity-correcting materials increased dry matter production of green manures, but for pigeon pea the silicate provided the best result in this dry-winter region.

Key words: soil acidity correction, crop yield, silicon, mineral nutrition, no tillage.

1. INTRODUCTION

Cropping systems are important tools for minimizing the detrimental effects of agriculture, and green manure cultivated under no-tillage systems may represent the benefits of crop rotation and soil coverage. No-tillage systems are currently used on 55% of the land used for grain production in Brazil, corresponding more than 27 million ha (Caires, 2013). The main principles of this production system include the absence of soil disturbance, permanent soil coverage and crop rotation, all of which contribute to increasing crop residues, reducing pests and diseases and improving fertilizer efficiency (Borghi et al., 2013).

Soil acidity is one of the most yield-limiting factors for crop production. The land area affected by acidity is estimated to be 4 billion ha, which represents 30% of the total ice-free land area of the world (Sumner & Noble, 2003). In Brazil, acid soils represent approximately 70% of all agricultural lands; this acidity may decrease crop yields because of Al and Mn toxicity as well as the low availability of exchangeable cations (Soratto & Crusciol,

2008), as is observed in African savannas. Therefore, soil acidity amelioration is essential to improve crop growth. Fageria & Baligar (2008) reported that soybean, bean, maize and wheat plants require a soil pH of 6.0 for appropriate development; this finding emphasizes the importance of soil acidity correction. A pH of 6.0 is also ideal for precipitating toxic aluminum, which limits agricultural production in tropical soils.

Lime is the most-used material for acidity correction in Brazil because of its price and its capacity to increase the efficiency of fertilizers applied for grain production (Fageria & Baligar, 2008). Nevertheless, lime is not very soluble, and its dissociated components show limited mobility. In addition, liming effects are usually restricted to superficial soil layers when the soil is not tilled (Castro et al., 2011; Soratto & Crusciol, 2008). However, other materials may be applied for acidity correction as long as the product consists of neutralizing components such as calcium and/or magnesium oxides, hydroxides, carbonates and

silicates (Castro & Crusciol, 2013). Calcium and magnesium silicates are similar to carbonates in composition; thus, these materials can potentially substitute for lime more readily than can other materials (Corrêa et al., 2007; Pulz et al., 2008). Recommendations for silicate application can be based on any method for lime application (Korndörfer et al., 2004).

According to Alcarde & Rodella (2003), calcium silicate is 6.78 times more soluble than lime ($CaSiO_3$=0.095 g dm^{-3}; $CaCO_3$=0.014 g dm^{-3}); therefore, this material is a good option for superficial applications such as those made in no-tillage systems (Corrêa et al., 2007). Additionally, silicon is a beneficial element, and it is laid over cell walls of the leaf epidermis in a double layer of silica-cuticle and silica-cellulose (Ma & Yamaji, 2006). Si deposition decreases water losses through evapotranspiration (Crusciol et al., 2009, 2013; Pulz et al., 2008) and increases tolerance to pests, diseases (Fauteux et al., 2005), heavy metals, toxic aluminum (Castro & Crusciol, 2013; Prabagar et al., 2011) and lodging. Plants become more erect and show improved photosynthetic efficiency (Crusciol et al., 2009; Pulz et al., 2008).

Hence, calcium and magnesium silicate application may be more efficient than liming and may improve acidity correction in deeper soil layers in a shorter period of time because of their greater solubilities (Castro et al., 2011; Corrêa et al., 2007). Furthermore, supplying Si to plants may improve yield stability as a consequence of improved water-stress tolerance because almost all grain-producing regions are liable to drought, especially those in the Brazilian Cerrado, a biome similar to the African savanna. Most studies only emphasize the effects of acidity correction materials on crop nutrition and final yield. Considering that yields can be influenced by climate conditions, soil fertility and agricultural management, it is equally important to evaluate these factors individually.

This study aimed to evaluate the effects of superficial liming and silicate application on soil chemical attributes, plant nutrition, yield components and the final yields of soybean and maize under a no-tillage system in a dry-winter region, as well as on the dry-matter production of millet and pigeon pea cropped in rotation.

2. MATERIALS AND METHODS

The experiment was conducted in Botucatu, São Paulo State, Brazil (at 48°23'W,22°51'S and 765 m asl) during two consecutive growing seasons, 2006/2007 and 2007/2008. Soil in the area is a deep, acid, clayey Rhodic Hapludox (FAO, 2006). According to Köppen's classification, the climate is Cwa, which corresponds to a tropical latitude with dry winters and hot, wet summers. Figure 1 shows the rainfall and monthly average temperatures during the experiment.

Before carrying out the experiment, the chemical characteristics of the soil (at 0-0.2 m) were determined according to the methods of van Raij et al. (2001). The results were the following: organic matter: 18.25 g dm^{-3}; pH (CaCl$_2$): 4.2; P (resin): 3.62 mg dm^{-3}; K, Ca, Mg, and CEC: 0.76, 11.62, 5.75, and 74.98 mmol dm^{-3}, respectively; and base saturation: 24.2%. The soil pH was determined in a 0.01 mol L^{-1} CaCl$_2$ suspension (1:2.5 soil:solution). P and exchangeable Ca, Mg, and K were extracted using an ion-exchange resin and determined via atomic absorption spectrophotometry.
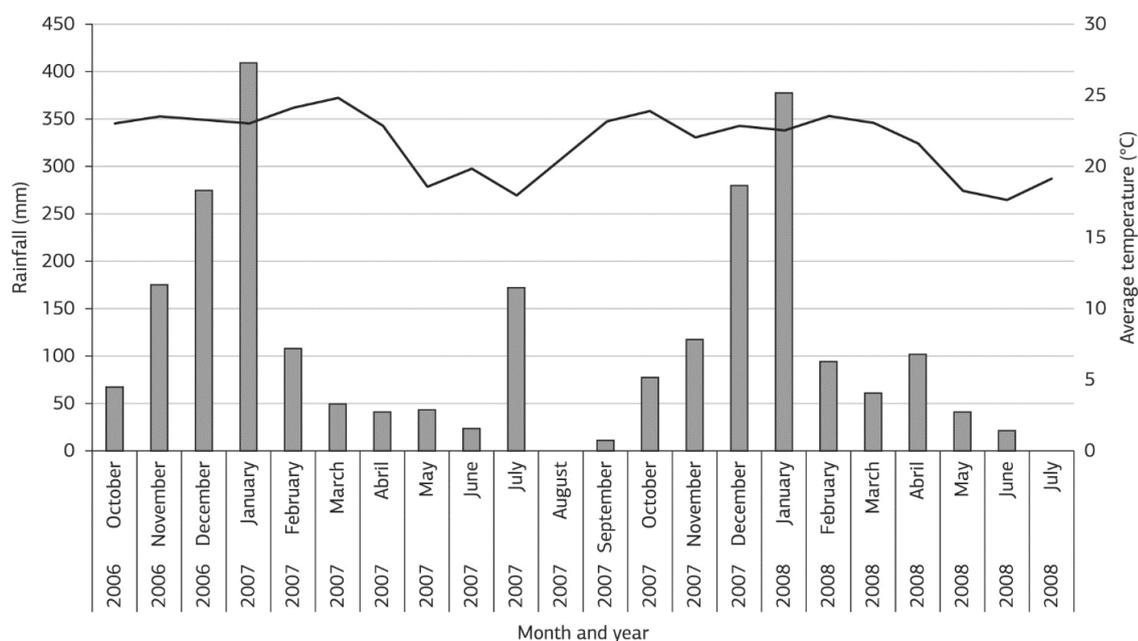

Figure 1. Rainfall and monthly average temperature during the experiment. Botucatu, State of Sao Paulo, Brazil, 2006-2008.

The base saturation values were calculated using the results of exchangeable bases and total acidity at pH 7.0 (H+Al). The organic matter content of the soil was determined by the colorimetric method.

The experimental design was a completely randomized block with sixteen replications. Treatments (5.4×10-m plots) consisted of two forms of soil-acidity correction (dolomitic lime: ECC=90%, CaO=36% and MgO=12%; calcium/magnesium silicate: ECC=80%, CaO=34%, MgO=10% and SiO_2=22%) and no soil correction, as a control.

The application rates were calculated to increase the soil base saturation to 70%. In October 2006, 3.8 Mg ha^{-1} of dolomitic lime and 4.1 Mg ha^{-1} of calcium/magnesium silicate were applied on the surface without incorporation over previously desiccated (1,800 g ha^{-1} of glyphosate) millet (*Pennisetum americanum* (L.) Leek) residues (4 Mg ha^{-1}).

Soybean (*Glycine max* (L.) Merrill) cultivar Embrapa 48 was sown on November 29, 2006 at 0.45-m row spacing and at a rate of 22 seeds-m^{-1}. This genotype, which has an intermediate maturation cycle, requires high soil fertility. Seeds were treated with fungicide (50 g of Vitavax + 50 g of Thiram for every 100 kg of seeds) and inoculant (*Bradyrhizobium japonicum*). Base fertilization consisted of 250 kg ha^{-1} of 04-20-20 NPK formula, in accordance with the results of soil chemical analyses and recommendations for the soybean crop (van Raij et al., 1997).

Soybean plants were in full flower 45 days after seedling emergence. At that stage, 10 plants were sampled to evaluate shoot dry-matter production. Additionally, the 3rd leaf and its petiole were sampled from 30 plants per plot, using the methods of van Raij et al. (1997), for macronutrient and silicon concentration analysis. Subsequently, the leaf samples were washed, dried in forced-air circulation at 65 °C for 72 h and ground up. Then, concentrations of N, P, K, Ca, Mg, and S in the leaves were determined according to the methods of Malavolta et al. (1997), and concentrations of Si in the leaves were determined according to the methods of Korndörfer et al. (2004).

N was extracted with H_2SO_4, and the other nutrients were extracted in a nitro-perchloric solution. Using the extracted solution, the N concentration was determined using the Kjeldahl distillation method, and the P, K, Ca, Mg, and S concentrations were determined by atomic absorption spectrophotometry. Silicon concentrations in the leaves were assayed according to the methods of Korndörfer et al. (2004). Plant tissue samples weighing 0.1 g were wetted with 2 mL of 50% H_2O_2 in polyethylene tubes. Three mL of 50% NaOH at room temperature was added to each tube. The tubes were placed in a double boiler for 1 h and then in an autoclave at 138 kPa for 1 h. After atmospheric pressure was reached, the tubes were removed, and 45 mL of water was added. The tubes were allowed to rest for 12 h. Afterwards, a 1-mL aliquot of each supernatant was set aside, and 15 mL of water, 1 mL of HCl (500 g L^{-1}), and 2 mL

of ammonium molybdate were added. After 5 to 10 min, 2 mL of oxalic acid (500 g L^{-1}) were added. The silicon concentration was determined with a spectrophotometer at a wavelength of 410 nm.

Soybean was harvested on April 3, 2007, and samples were taken to evaluate yield components (plant population, number of pods per plant, number of grains per pod and mass of 100 grains, in four linear meters) and grain yields (in 48 m^{-2}, transformed to 13% moisture content).

Soon after soybean harvest, on April 10, 2007, millet was sown at 0.45-m row spacing. Cultivar BRS 1501 was cropped, aiming to establish 300,000 plants ha^{-1} (25 kg of seeds ha^{-1}). Plants were in full flower 50 days after sowing. At that stage, 50 flag leaves per plant were sampled for macronutrient (N, P, K, Ca, Mg, and S) and Si concentration analysis, according to the methods of Korndörfer et al. (2004) and Malavolta et al. (1997). On the same day, millet plants were cut 15 cm above the soil surface to stimulate regrowth and, consequently, to increase biomass production. Millet plants reached full flowering again 35 days after this treatment, and the plants were then cut along the soil surface. The shoot dry-matter production was measured for both cuts.

Maize (*Zea mays* L.) was sown on December 2, 2007 at 0.45-m row spacing and at a rate of 3 seeds-m^{-1}. The hybrid chosen was 2B570, which has an intermediate maturation cycle. Seeds were treated with fungicide (50 g of Vitavax + 50 g of Thiram for every 100 kg of seeds). Base fertilization consisted of 300 kg ha^{-1} of the 08-28-16 NPK formula, in accordance with the results of soil chemical analyses and recommendations for the maize crop (van Raij et al., 1997). Side dressing fertilization took place on January 10, 2008 and consisted of 90 kg ha^{-1} of N applied mechanically between rows as urea.

Maize plants were in full flower 64 days after seedling emergence. At that stage, 10 plants per plot were sampled to evaluate shoot dry-matter production. Additionally, the central third part of 30 leaves was sampled at the ear base (van Raij et al., 1997) for macronutrient (N, P, K, Ca, Mg, and S) and Si concentration analysis according to the methods of Korndörfer et al. (2004) and Malavolta et al. (1997).

The maize crop was harvested on April 1, 2008, and samples were collected to evaluate yield components (plant population, ears per plant, number of grains per ear and mass of 100 grains in four linear meters) and grain yields (in 48 m^{-2}, transformed to 13% moisture content).

Soon after the maize harvest, pigeon pea (*Cajanus cajan* (L.) Millsp) was sown on April 5, 2008. Cultivar IAPAR 43 was cropped at 0.45-m row spacing and a rate of 20 viable seeds m^{-1}. The plants were in full flower on July 1, 2008, by the time 20 plants were sampled to evaluate shoot dry-matter production and macronutrient (N, P, K, Ca, Mg, and S) and Si concentrations; the concentrations were measured according to the methods of Korndörfer et al. (2004) and Malavolta et al. (1997).

Soil chemical characteristics (pH, organic matter and concentrations of H and Al, P, K, Ca, Mg, Al^{+3} and Si) were evaluated after 6 (April 2007), 12 (October 2007) and 18 months (April 2008) after the application of the correction materials at 0.00-0.05-, 0.05-0.10-, 0.10-0.20-, 0.20-0.40- and 0.40-0.60-m depths. Six simple samples were taken at random from the useful area of each plot and between rows of the previous crop to form a compound sample. The samples were dried, sieved (using 2-mm sieves) and analyzed according to van Raij et al. (2001). Using a 0.01-mol L^{-1} $CaCl_2$ solution, the soluble Si content in the soil was determined by beta-molybdosilicic complex formation using a spectrophotometer at 660 nm according to the methods of Korndörfer et al. (2004).

The data for all variables were analyzed by one-way analysis of variance (ANOVA) using the SISVAR statistical software package. The blocks and all block interactions were considered as random effects. The treatments were considered as fixed effect. One error term was considered in the analysis of the data; this one term was associated with the treatments. Mean separations were conducted using the LSD test. The effects were considered to be statistically significant at $p \leq 0.05$.

3. RESULTS AND DISCUSSION

Figure 2 shows the pH, organic matter and H+Al, Al^{3+} and Si levels after acidity correction. Liming and silicate application increased the soil pH down to depths of 0.10 and 0.20 m, respectively, 6 months after application. Soil correction by silicate and lime was also observed 12 months after treatments were applied in even deeper layers, down to 0.40 and 0.20 m, respectively. By the 18th month, both materials had equally corrected the soil pH down to 0.40 m. The results show that silicate is dissociated faster than lime; thus, silicate establishes an alkalinization front and increases the soil pH in deeper layers over a shorter period of time than does lime. Similarly, Corrêa et al. (2007) studied the effects of superficial liming and of the application of Ca/Mg silicate as slag. The authors found that slag corrected the soil pH down to a depth of 0.40 m, whereas lime effects were observed only down to 0.10 m after 15 months.

The hydroxyl concentration is increased, and the H^+ concentration in the soil solution is decreased by the application of materials to correct acidity; consequently, the soil pH is increased (Castro & Crusciol, 2013; Oliveira & Pavan, 1996). It has been believed that acidity correction materials had to be fully incorporated to maximize their benefits. Nevertheless, many studies about no-tillage systems have demonstrated that the effects of superficial liming on the correction of subsuperficial soil layers depend on the product dose and particle size, application method, soil, climate (especially rainfall), crop system and amount of

time that has elapsed since the application (Castro et al., 2015; Crusciol et al., 2011; Oliveira & Pavan, 1996; Soratto & Crusciol, 2008). These influences render this form of management controversial, particularly when it is applied for subsuperficial correction.

In all periods of analysis, organic matter levels were affected by product application, with decreasing values down to 0.05-m and 0.20-m depths in the first and last evaluations, respectively. It is possible that increasing pH may have improved microbial activity and organic matter mineralization (Castro et al., 2015; Fuentes et al., 2006). Even so, corrected soils may increase biomass production and increase organic matter content in the medium term. It is probable that the elapsed time after soil correction was sufficient only to increase the mineralization of organic matter and that it was not possible to observe the effects of higher biomass production on terms of organic carbon inputs into the soil. H+Al levels decreased whenever soil pH was increased by the application of acidity-correction materials, which confirms that silicate affects deeper soil layers faster than does liming. At first, the hydroxyl concentration is increased; subsequently, the silicate or lime begins to react with excess H^+ found in the soil solution. When the remainder of the applied substance reacts with the soil solution, aluminum is precipitated as non-toxic $Al(OH)_3$ (Castro & Crusciol, 2013; Corrêa et al., 2007; Oliveira & Pavan, 1996). Soratto & Crusciol (2008) also noticed the progression of a front for potential acidity correction. Those authors observed that superficial liming decreased H+Al levels at depths of 0.05-0.10 m and 0.10-0.20 m 6 and 12 months after application, respectively.

Al^{3+} levels were efficiently decreased 18 months after the application of either material. In the first analysis period, both materials inactivated Al^{3+} down to 0.05 m, but only silicate decreased levels at depths of 0.10-0.20 m, as well. Twelve months after application, both products reduced Al^{3+} levels at a depth of 0.05-0.10 m, but only silicate decreased toxicity down to 0.20 m. Upon comparing these values with Si levels in soil, it was found that Si levels were greater at those depths where the levels of toxic Al^{3+} had been reduced by silicate application. Thus, in addition to increasing pH, silicate treatment also results in the reduction of Al^{3+} levels by Si in soil, through chemical reactions initially and later by precipitation as hydroxy-aluminosilicate (HAS) (Exley, 1998). Si levels were increased by liming down to 0.05 m 6, 12 and 18 months after application. Similarly, Pulz et al. (2008) applied lime superficially and observed increasing Si content that could be extracted by 0.5 mol-L^{-1} acetic acid. Silicate application increased Si levels at all soil depths after 18 months, in agreement with previous findings (Corrêa et al., 2007).

As shown in figure 3, both materials for acidity correction had efficiently improved P availability in the first two soil layers by the 6 months after application. However, P levels
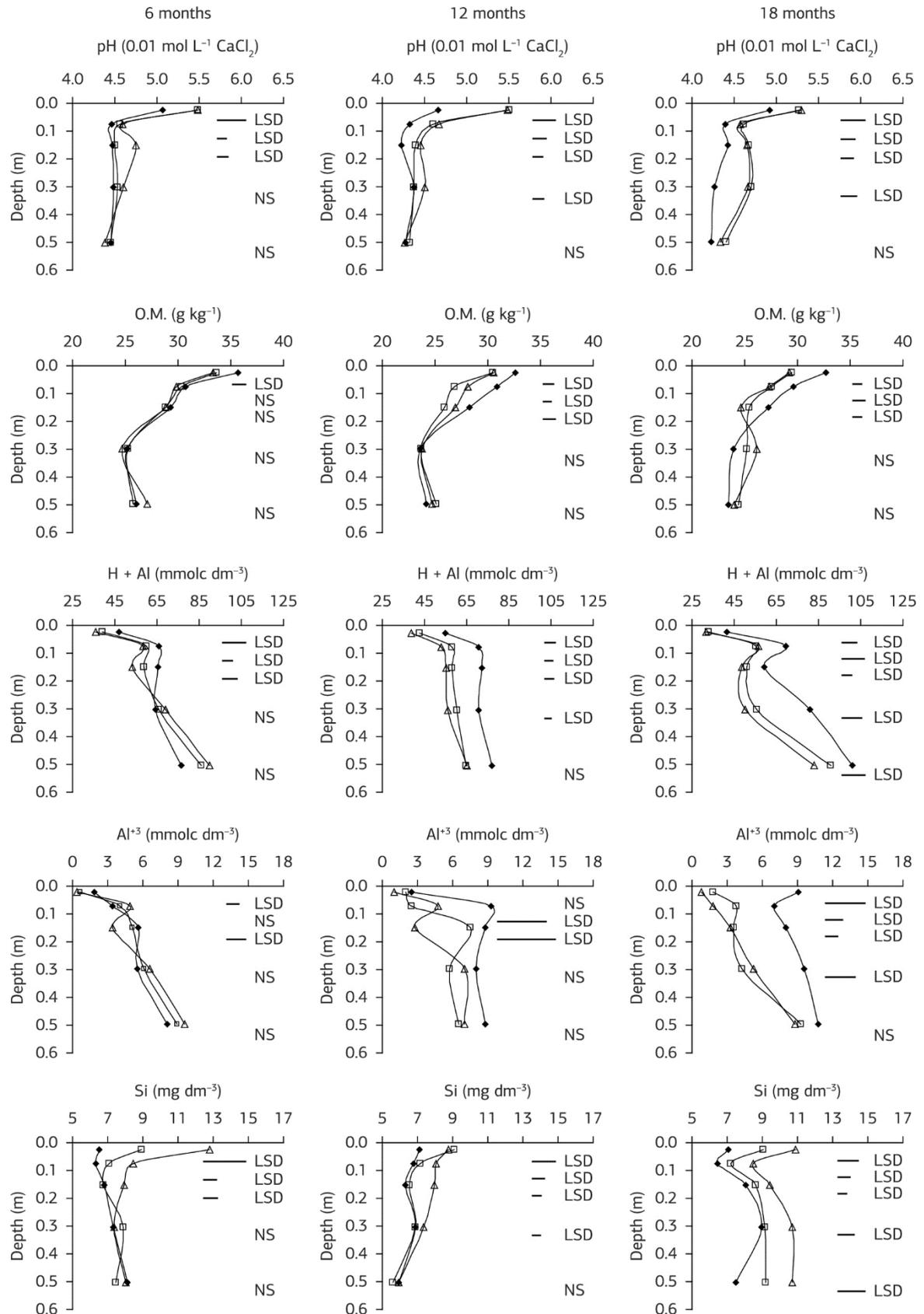
Figure 2. pH, organic matter (O.M.), H+Al, Al^{+3}, and Si after six, 12 and 18 months from the application of lime (□), silicate (Δ) and the control (♦). Vertical bars indicate the Least Significant Difference (pd0.05). Botucatu, State of Sao Paulo, Brazil, 2006-2008.

Figure 3. Phosphorus , K, Ca, and Mg levels and base saturation (BS) after six, 12 and 18 months from the application of lime (□), silicate (Δ) and the control (♦). Vertical bars indicate the Least Significant Difference (pd0.05). Botucatu, State of Sao Paulo, Brazil, 2006-2008.
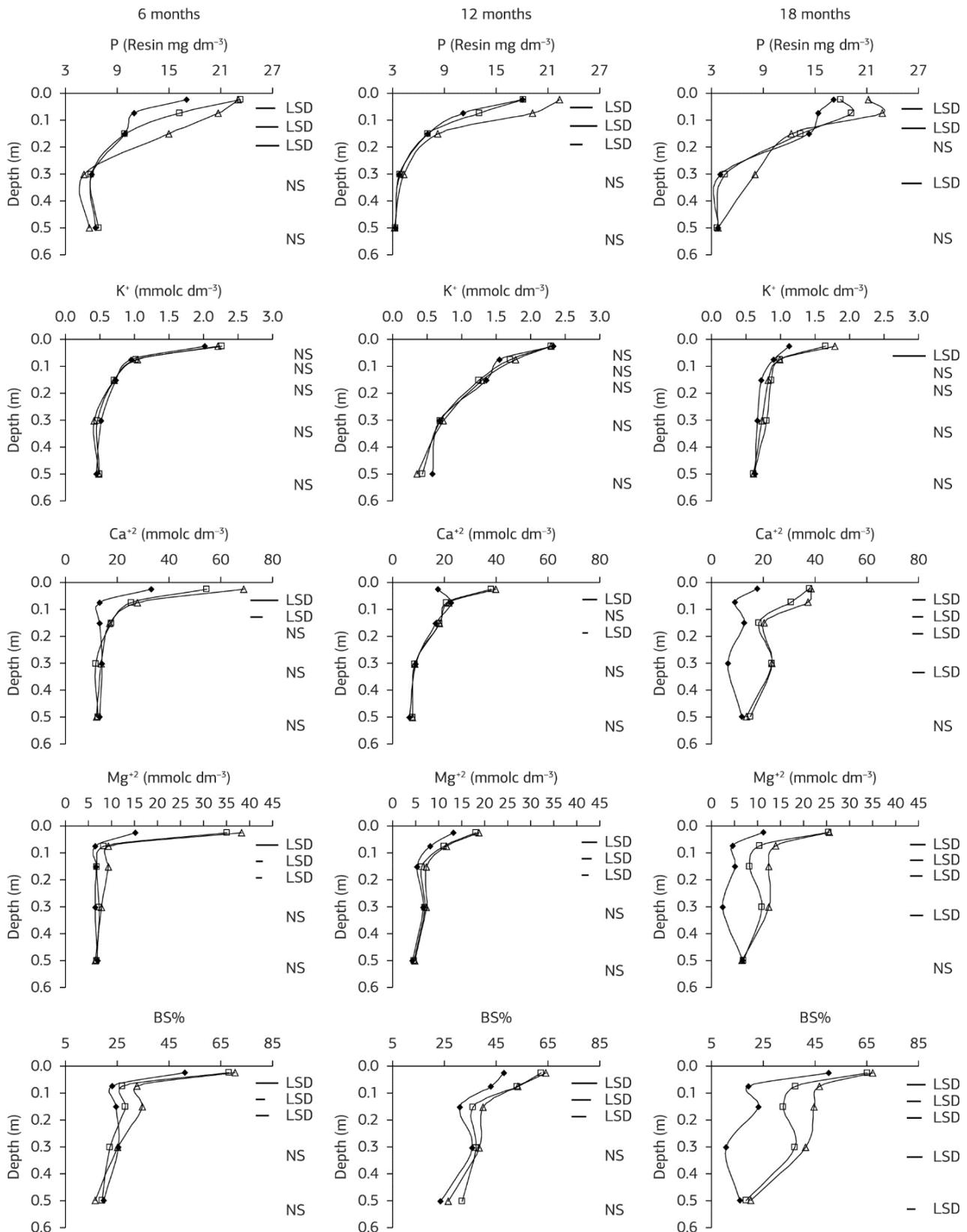
were greater at a depth of 0.05-0.10 m in soil treated with silicate. Only silicate application increased P levels at a depth of 0.10-0.20 m after 6 months and down to 0.10 m 12 months later. Liming effectively increased P levels at a depth of 0.05-0.10 m; in contrast, silicate application increased P availability in superficial layers and at depths of from 0.020 m to 0.40 m after 18 months.

Hydroxyl concentrations and ionic activity in soil solutions may be increased by increasing pH as well as by Fe and Al precipitation. On the other hand, the precipitation of less-soluble P-Fe and P-Al compounds is reduced. Additionally, negative charges are generated by OH⁻ deprotonation and are exposed by clays and organic matter. In this way, phosphate is repelled by the adsorption surface (Haynes, 2014; Pulz et al., 2008), thereby releasing P into the soil solution. Thus, it was expected that both acidity correction materials would similarly increase P availability.

Nevertheless, the benefits of silicate application were also increased by the competition between Si and P for the same sorption sites on soil colloids (Pulz et al., 2008). Those sites are saturated or blocked by silicate anions, thereby increasing the efficiency of P fertilization.

Potassium levels in the soil were not affected by liming or by silicate application six and 12 months after application (Figure 3). However, K levels were increased down to 0.05 m 18 months after application. Flora et al. (2007) reported increased K availability after liming as a result of reduced leaching. Soil correction increases pH and negative charges in superficial soil layers, where K⁺ ions are adsorbed. Increases in K levels may also be related to ions leaching from plant tissues (Calonego & Rosolem, 2013; Zoca et al., 2014), considering that soil correction increased dry matter production and thus resulted in the accumulation of K in plant shoots (Tables 1, 2 and 3).

Table 1. Nitrogen, P, K, Ca, Mg, S, and Si leaf concentrations, shoot dry matter production, yield components (plant population, number of pods per plant, number of grains per pod and mass of 100 grains) and soybean yield affected by superficial liming and silicate application under no tillage system. Botucatu, State of Sao Paulo, Brazil, 2006-2008

Treatments	N	P	K	Ca	Mg	S	Si
				g kg⁻¹			
Control	44.1 b	3.68 a	18.7 a	7.49 b	3.39 b	3.22 a	2.64 b
Lime	45.4 a	3.47 a	18.9 a	8.61 a	3.88 a	2.96 a	2.73 b
Silicate	45.3 a	3.58 a	18.3 a	8.51 a	4.09 a	2.99 a	3.70 a
ANOVA	**	NS	NS	**	**	NS	**
LSD (p≤0.05)	0.79	0.24	0.83	0.36	0.38	0.28	0.33
	Population	Pods plant⁻¹	Grains pod⁻¹	Mass of 100 grains		Dry matter	Grain yield
	plants ha⁻¹	Number			g	kg ha⁻¹	
Control	381,274 b	28.6 b	1.49 b	15.4 b		3,036 c	2,691 b
Lime	403,826 a	33.9 a	1.58 ab	17.8 a		3,328 b	3,395 a
Silicate	404,597 a	32.5 a	1.67 a	17.7 a		3,646 a	3,566 a
ANOVA	**	**	**	**		**	**
LSD (p≤0.05)	1,656	2.93	0.12	0.51		238	240

** and NS: significant at a probability level of 1% and not significant, respectively, by the F test. Means followed by different letters in the column statistically differ from each other by the t test (p≤0.05).

Table 2. Nitrogen, P, K, Ca, Mg, S, and Si leaf concentrations and millet shoot dry matter production affected by superficial liming and silicate application under no tillage system. Botucatu, State of Sao Paulo, Brazil, 2006-2008

Treatments	N	P	K	Ca	Mg	S	Si
				g kg⁻¹			
Control	30.0 b	1.96 b	28.0 a	5.16 b	4.35 b	1.71 a	10.8 b
Lime	31.5 ab	2.55 a	28.6 a	7.08 a	6.51 a	1.75 a	11.0 b
Silicate	32.4 a	2.82 a	28.0 a	7.31 a	6.40 a	1.77 a	11.9 a
ANOVA	*	**	NS	**	**	NS	**
LSD (p≤0.05)	2.00	0.41	1.14	0.69	0.69	0.14	0.72
	Shoot dry matter production						
	First cut		Second cut			Total	
	t ha⁻¹						
Control	2.96 b		2.46 b			5.42 b	
Lime	3.92 a		3.26 a			7.18 a	
Silicate	3.84 a		3.20 a			7.04 a	
ANOVA	**		**			**	
LSD (p≤0.05)	0.38		0.32			0.71	

*, ** and NS: significant at a probability level of 5%, 1% and not significant, respectively, by the F test. Means followed by different letters in the column statistically differ from each other by the t test (p≤0.05).

Table 3. Nitrogen, P, K, Ca, Mg, S, and Si leaf concentrations, shoot dry matter production, yield components (plant population, ear per plant, number of grains per ear, and mass of 100 grains), and maize yield affected by superficial liming and silicate application under no tillage system. Botucatu, State of Sao Paulo, Brazil, 2006-2008

Treatments	N	P	K	Ca	Mg	S	Si
				g kg⁻¹			
Control	31.1 b	2.60 a	12.7 a	3.37 b	2.25 b	2.31 a	10.0 c
Lime	31.6 b	2.60 a	12.4 a	4.07 a	3.50 a	2.38 a	10.7 b
Silicate	33.6 a	2.72 a	12.2 a	4.04 a	3.63 a	2.34 a	11.8 a
ANOVA	**	NS	NS	*	**	NS	**
LSD (p≤0.05)	0.83	0.19	0.79	0.42	0.21	0.09	0.07

	Population	Ear per plant index	Grains per ear	Mass of 100 grains	Dry matter	Grain yield
	plants ha⁻¹	number		g	kg ha⁻¹	
Control	60,527 a	1.10 a	416 b	36.5 b	15,631 b	6,140 b
Lime	61,180 a	1.12 a	458 a	39.5 a	18,202 a	8,832 a
Silicate	60,600 a	1.10 a	447 a	39.9 a	18,049 a	8,785 a
ANOVA	NS	NS	**	**	**	**
LSD (p≤0.05)	2,859	0.12	22.43	0.74	1,341	534

*, ** and NS: significant at a probability level of 5%, 1% and not significant, respectively, by the F test. Means followed by different letters in the column statistically differ from each other by the t test (p≤0.05).

As more time passed, the effects of liming and silicate application were noticed in deeper soil layers, most likely due to Ca leaching (Figure 3). Ca levels were increased to depths of 0.10, 0.20 and 0.40 m six, 12 and 18 months after application, respectively. Corrêa et al. (2007) and Soratto & Crusciol (2008) found similar results in the same soil type. Although both materials had similar effects, Ca levels were increased more by silicate down to 0.05 m and 0.10 m after six and 18 months, respectively. Mg levels at a depth of 0.10-0.20 m were significantly increased 6 months after silicate application. However, both materials increased Mg availability after 18 months. Corrêa et al. (2007) observed that Ca and Mg levels were increased down to depths of 0.05 m and 0.20 m after lime and steel slag application, respectively. The authors attributed the latter effects to the greater solubility of slag.

Intense Ca and Mg leaching may be related to the formation of inorganic ionic pairs with NO_3^-, HCO_3^-, OH^-, Cl^- and SO_4^{2-} (Crusciol et al., 2011) from mineral fertilization. Additionally, there may have been Ca and Mg mobility through root canals, biological microcanals (biopores) and weakness planes in low-mobility soils under no tillage (Castro et al., 2011).

The effects of soil correction on H+Al, K, Ca and Mg levels affected base saturation (Figure 3). Significant variations were found down to 0.20 m in the first two evaluation periods and down to 0.40 m after 18 months. The main differences between the effects of lime and silicate application were observed at 0.05-0.10-m and 0.10-0.20-m depths six and 18 months after their application, confirming the greater solubility of silicate and its potential utility in no-tillage systems. When comparing the effects of lime and slag application, Corrêa et al. (2007) found similar results. Conversely, Miranda et al. (2005) observed that superficial liming alone influenced the mobility of exchangeable bases down to 0.05 m in a clayey Oxisol. It is important to mention that pH and base saturation variations, as well as cation mobility through the soil, depend on the absence of acid cations in superficial soil layers, as these cations prefer to form chemical bonds. According to Fageria & Baligar (2008), those bonds are observed at a pH between 5.5 and 6.0, consistent with the results of this study and in contrast with those of Miranda et al. (2005).

Macronutrient levels in soybean leaves (Table 1) were within the range considered appropriate for crop development (van Raij et al., 1997). Treatments did not influence P, K and S levels, most likely because of the quantities of P and K supplied at sowing, which were sufficient for plant growth, even in control plots. Soil correction increased N, Ca and Mg levels compared to the controls, but only silicate application increased Si levels.

Caires et al. (2006) also reported that N availability increased with soil correction. These authors suggested that low soil acidity leads to increasing activity of nitrogen-fixing bacteria. The application of both materials for acidity correction increased Ca and Mg levels in the soil (Figure 3) and, consequently, in leaves. Superficial liming positively influenced Ca and Mg nutrition in soybean cropped under a well-established no-tillage system, once lime dissociation products also reached a large area explored by plant roots (Caires et al., 2006). Silicate is an efficient source of silicon for plants, and it was expected to significantly influence Si levels.

Soybean dry matter production, yield components and grain yields were affected by the different treatments (Table 1). Soil correction increased shoot dry matter, evaluated at flowering, compared to control plots. Nevertheless, dry matter benefitted more from silicate application than from liming.

Soil correction improved soil fertility and provided better conditions for plant development (Figures 2 and 3). Therefore, the application of both materials increased the final plant population, number of pods per plant, mass of 100 grains and, consequently, grain yields. Liming did not efficiently increase the number of grains per pod compared to the control. In contrast, silicate application increased the number of grains per pod. Both lime and silicate application increased grain yield, by 26.2 and 32.5%, respectively. Corrêa et al. (2007) also found that liming and slag applied to soybean increased yield components and final yields. Soybean responds better to liming whenever it is cropped in soils with low exchangeable Mg levels, under any crop system (Oliveira & Pavan, 1996).

Soil correction efficiently raised P, Ca and Mg levels in millet leaves (Table 2). Silicate was the only material that increased N content, compared to liming and the control. Si levels were also increased by silicate application. Other nutrient levels were not affected by the treatments.

Upon evaluating lime doses, Souza et al. (2006) observed that soil correction increased base saturation and, consequently, Ca and Mg levels in the dry matter of different tropical grasses. However, these authors did not find any effects of lime application on other macronutrients.

Energy stored in adenosine triphosphate (ATP) can be transferred to other coenzymes required for sucrose and cellulose synthesis. As ATP molecules contain a central phosphorus atom, this nutrient is intimately related to crop yield and dry matter production (Epstein & Bloom, 2005). According to these authors, calcium plays important roles in the structure and in the regulation of metabolism in plants; also, chlorophyll molecules contain magnesium, which is essential for converting solar energy into carbohydrates in plants. Interactions among these three nutrients may be important for increasing the dry matter of both millet cuts and thus total production (Table 2).

Macronutrient levels were within the range considered appropriate for maize nutrition (van Raij et al., 1997), with the exception of K levels, which were low (Table 3). Treatments did not influence P, K and S levels. Nevertheless, N, Ca and Mg levels were increased after soil correction,

as previously observed for soybean. Oliveira et al. (1997) studied lime doses and found similar results.

The application of both materials for acidity correction increased Si levels in leaves compared to the control, although silicate was more beneficial than lime. Miles et al. (2014) also observed that liming increased Si availability by increasing pH.

Maize nutrition was improved by soil correction because of soil fertility enhancement (Figures 2 and 3). The differences observed between the second (12 months) and third (18 months) soil samplings were reflected in higher dry matter production (Table 3). Likewise, liming and silicate application both increased the number of grains per ear, mass of 100 grains, and, consequently, final yields (Table 3). These correction treatments increased grain yields by 43.8 and 43.1% compared to the control, respectively.

Maize responds positively to the application of correction materials. Although genetic variability influences plant tolerance to soil acidity, Caires et al. (2006) and Miranda et al. (2005) reported that soil correction increases maize yields. Oliveira et al. (1997) obtained maximum maize yield in Brazilian Cerrado soils with the application of 6.6 Mg ha^{-1} of lime.

Although K and S levels in pigeon pea leaves were not affected by the treatments, silicate application increased N levels (Table 4). Si fertilization may also increase chlorophyll in leaves. Elawad et al. (1982) observed that chlorophyll levels increased by 65% in sugar cane after 15 t ha^{-1} of silicate was applied.

On the other hand, both materials increased P, Ca, Mg and Si levels in pigeon pea leaves. P and Si levels benefited more from silicate application compared to liming and the control. Thus, the Si supply appears to improve P availability for plants. According to Exley (1998), silicate application increases P solubility in the soil and decreases fixation. However, it is still doubtful why Si favors P uptake and increases dry matter production. These effects may be due to the following: (a) higher Si uptake; (b) a reduction in P fixation as pH increases, once silicate corrects soil acidity; (c) competition between silicate and phosphate for the same sorption sites in soil or (d) an interaction between these effects (Haynes, 2014; Pulz et al., 2008). Hence, silicate

Table 4. Nitrogen, P, K, Ca, Mg, S, and Si leaf concentrations and pigeon pea shoot dry matter production affected by superficial liming and silicate application under no tillage system. Botucatu, State of Sao Paulo, Brazil, 2006-2008

Treatments	N	P	K	Ca	Mg	S	Si	Dry matter
	\multicolumn{7}{c}{g kg^{-1}}	kg ha^{-1}
Control	39.00 b	2.47 c	18.27 a	16.09 b	4.06 b	1.48 a	2.44 c	1,309 c
Lime	39.16 b	2.66 b	18.13 a	27.81 a	4.99 a	1.49 a	2.67 b	1,878 b
Silicate	40.92 a	3.26 a	18.08 a	27.29 a	5.25 a	1.49 a	2.95 a	2,228 a
ANOVA	**	**	NS	**	**	NS	**	**
LSD (p≤0.05)	1.05	0.13	1.09	1.46	0.39	0.15	0.14	105

** and NS: significant at a probability level of 1% and not significant, respectively, by the F test. Means followed by different letters in the column statistically differ from each other by the t test (p≤0.05).

application for soil correction increases pH and may increase P availability for plants, by either displacing P adsorbed in colloids into the soil solution or decreasing P fixation from phosphate fertilizers.

Few studies have correlated soil correction and pigeon pea dry matter. In this experiment, greater dry matter production was obtained after superficial application of silicate (2,228 kg ha^{-1}) followed by liming (1,878 kg ha^{-1}) compared with the control (1,309 kg ha^{-1}). Compared with the control, plant nutrition was improved by soil correction. Upon comparing both materials, silicate was superior to lime, most likely due to increased N, P and Si levels.

4. CONCLUSION

Silicate corrected soil acidity and increased exchangeable base levels in soil at greater depths faster than does liming.

The application of both acidity-correcting materials increased N, Ca and Mg leaf concentrations, and all yield components and grain yield in soybean; but in maize, just silicate also increased N and Si when compared with lime, whereas both acidity-correcting increased just two yield components: grains per ear and mass of 100 grains, resulting in highest grain yield.

The application of both acidity-correcting materials increased dry matter production of green manures, but for pigeon pea the silicate provided the best result in dry-winter region.

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