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RESEARCH ARTICLE

Surface application of limestone and calcium-magnesium silicate in a tropical no-tillage system

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Abstract

Although lime is currently the most commonly applied material for soil acidity correction in Brazil, calcium-magnesium silicate application may efficiently replace this source due to its higher solubility and silicon supply, which is beneficial for plant development. This study aimed to evaluate the efficiency of surface liming and silicate application on soil chemical attributes as well as soybean and maize nutrition, yield components, and grain yield. The experiment was conducted in a Rhodic Hapludox in Botucatu-SP, Brazil. The randomized complete block design contained 16 replications. Treatments consisted of two materials for soil acidity correction (dolomitic lime, calcium/magnesium silicate), applied on October 2006 to raise base saturation up to 70%, and a control, with no acidity correction. Soybean and maize were sown in 2006/2007 and 2007/2008, respectively. After 18 months Ca-Mg silicate corrected soil acidity up to 0.60 m, and increased exchangeable base levels up to 0.40 m. Silicate increased silicon concentrations in plant tissues in both crops as well as phosphorus in soybean. The application of both sources increased calcium and magnesium concentrations as well as yield components and yield grains of soybean and maize. Soil acidity correction improved the efficiency of fertilizers applied for grain production.

Keywords: acid soils, Brazilian ‘Cerrado’, liming, annual crops

1. Introduction

Many tropical soils in biomes similar to the Brazilian Cerrado and the African Savannah have limited yield potentials because of soil acidity and other fertility issues. Soil acidification is a natural process that can be minimized by using appropriate agricultural management techniques, such as the application of lime. In a soil-plant system, soil acidity interacts with physical, chemical and biological factors, and can result in erosion, low water-holding capacity, low exchangeable base retention capacities, and Al and Mn toxicity (Fageria and Baligar, 2008).

Lime is the most commonly used material for correcting acidity in Brazil due to its price and its ability to increase the efficiency of any fertilizers applied for grain production. Nevertheless, lime is not very soluble and its dissociated components show limited mobility. Consequently, the effects of liming are usually restricted to the soil's surface layers (Caires *et al*., 2006; Soratto and Crusciol, 2008; Castro *et al*., 2011). Other materials may be applied for acidity correction as long as the source is composed of neutralizing components or active ingredients, such as calcium and/or magnesium oxides, hydroxides, carbonates, and silicates.

Some of the materials studied for their soil acidity amendment are sugar foam (Navarro *et al*., 2009), mussel shells (Álvarez *et al*., 2012), pulp mill sludge (Gallardo *et al*., 2016) and calcium and magnesium silicates (Crusciol *et al*., 2016), and all have given good results. The calcium and magnesium silicates use is increasing, particularly, due the similar composition to carbonates. Therefore, these materials could potentially replace lime and have additional advantages. Silicate application is recommended based on the same methods used for lime requirements (Korndörfer *et al*., 2004).

According to Alcarde and Rodella (2003), calcium silicate is 6.78 times more water-soluble than calcium carbonate ($CaSiO_3$ = 0.095 g dm^{-3}; $CaCO_3$ = 0.014 g dm^{-3}); therefore, this material is a good option for surface application, such as application in no tillage systems (Castro *et al*., 2011; Crusciol *et al*., 2016), and for supplying Si. In grasses, Si is scattered over leaf cell walls, stems, and the epidermis of grain coats as a double layer of silica-cuticle and silica-cellulose (Ma and Yamaji, 2006). The deposition of Si may decrease water losses through evapotranspiration and increase tolerance to pests, diseases (Haynes, 2014), heavy metals, toxic aluminum (Prabagar *et al*., 2010), and lodging. In addition, plants become more erect and show improved photosynthetic efficiency in the presence of Si (Pulz *et al*., 2008; Dorneles *et al*., 2016).

Studies have been published regarding the soil acidity amendment sources as an alternative to liming. Navarro *et al*. (2009), working with sugar foam during a 25-year experiment, observed an increase on soil pH, N, P and Ca, as well as in the organic matter in a red soil in Spain. The authors stated that the use could replace the traditional liming sources.

Mussel shells are also another alternative, with similar effects on soil pH and Al^{3+} neutralization (Álvarez *et al*. 2012). However, there are researches on grain production with slag application, and indicates that this source can be more efficient than other materials (aqueous lime and sewage sludge) for correcting deeper soil layers due to its higher solubility (Corrêa *et al*., 2007).

Furthermore, supplying Si may improve yield stability by enhancing the tolerance of crops to water stress because almost all of the soybean and maize-producing regions in Brazil are not irrigated and are liable to drought, particularly in the Brazilian Cerrado region. Most studies emphasize the effects of liming materials for correcting soil acidity, which subsequently affect soil fertility, crop nutrition, and crop yield (Corrêa *et al*., 2008; Soratto and Crusciol, 2008). Because climatic conditions, soil fertility, and agricultural management influence all yield components, it is important to evaluate these factors individually, especially regarding their relationships with Si.

The purpose of this study was to evaluate the effects of surface liming and Ca-Mg silicate application on soil chemical attributes, plant nutrition, yield components, and yields of soybean and maize in a pre-established no tillage system in a dry-winter region.

2. Materials and Methods

This experiment was conducted in Botucatu in the State of São Paulo, Brazil (geographical coordinates are 48° 23′ W, 22° 51′ S and 765 meters above sea level) during two consecutive growing seasons (2006–2007 and 2007–2008). The soil in this area is classified as a deep acid clayey Rhodic Hapludox. According to the Köeppen's classification system, the climate in this region is Cwa, which corresponds to a tropical altitude with a dry winter and a hot wet summer. During the experiment, the rainfall and monthly average temperatures were registered (Figure 1). Before initiating the experiment, the chemical characteristics of the soil (in the top 20 cm) were determined according to the methods of *Raij et al*. (2001). The following results were obtained: an organic matter content of 18.25 g dm^{-3}, pH ($CaCl_2$) of 4.2, P (resin) concentration of 3.62 mg dm^{-3}, exchangeable K, Ca, and Mg values of 0.76, 11.62, and 5.75 $mmol_c dm^{-3}$, respectively, CEC of 74.98 $mmol_c dm^{-3}$, and a base saturation of 24.2%. The soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil/solution). The organic matter content of the soil was determined using the calorimetric method. Total acidity in pH 7.0 (H + Al) was estimated by SMP-buffer solution method (van Raij, Andrade, Cantarella and Quaggio, 2001).

Exchangeable Al was extracted with neutral 1mol L^{-1}KCl at a 1:10 soil/solution ratio and determined by titration with 0.025 mol L^{-1}NaOH solution. Phosphorus and exchangeable Ca, Mg and K were extracted with ion-exchange resin and P was determined by colorimetry and Ca, Mg and K by atomic absorption spectrophotometry. Using the exchangeable bases and total acidity at pH 7.0 (H + Al) results, base saturation (1) and CEC (2) values were calculated using the following equation (van Raij *et al*., 2001):

$$\text{Base Saturation (\%)} = (Ca_{ex} + Mg_{ex} + K_{ex})\ 100/CEC \quad (1)$$

Where Ca_{ex}, Mg_{ex}, and K_{ex} are basic exchangeable cations and CEC is the total cation exchange capacity, calculated as Equation (2).

$$\text{CEC } (mmol_c\ dm^{-3}) = Ca_{ex} + Mg_{ex} + K_{ex} + \text{total acidity in pH 7.0 } (H + Al) \quad (2)$$

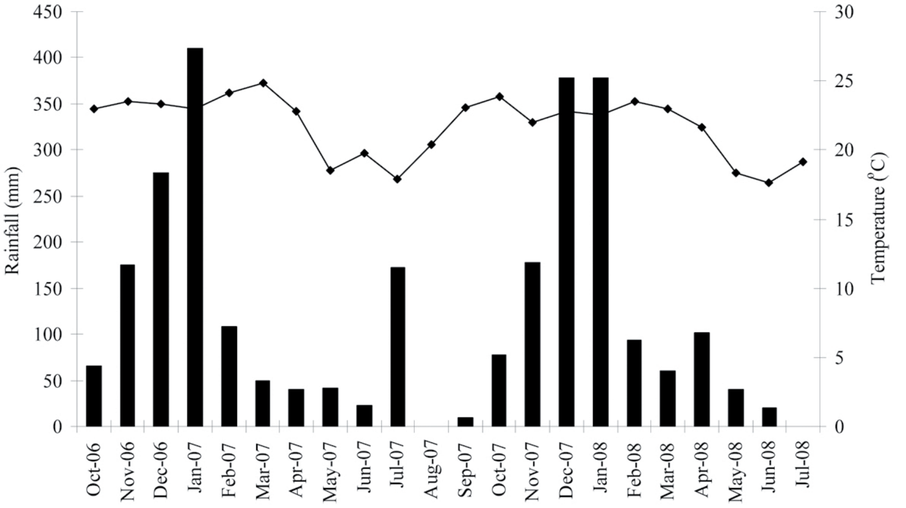


Figure 1. Temperature and rainfall during the study period, from October 2006 to July 2008.

The experiment was conducted using a completely randomized block design with sixteen replications. The treatments (5.4×10-m plots) consisted of two sources for soil acidity correction (dolomitic lime: Effective Calcium Carbonate (ECC)=90%, CaO=36% and MgO=12%; calcium/magnesium silicate: ECC=80%, CaO=34%, MgO=10% and SiO_2=22%) and a control with no soil correction.

The application rates were calculated to increase the soil base saturation by up 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 soil surface.

Soybean (*Glycine max* (L.) Merril) cultivar Embrapa 48 was sown on November 29th 2006 using a row spacing of 0.45m and a sowing rate of 22 seeds m^{-1}. This intermediate maturation-cycled genotype is highly demanding for soil fertility. Seeds were treated with fungicide (vitavax + thiram – 50 + 50 g of the active ingredient every 100 kg of seeds) and an inoculant (*Bradyrhizobium japonicum*). Base fertilization consisted of 250 kg ha^{-1} of a 04-20-20 NPK formula, which was based on the soil chemical analysis results and the recommendations for soybean crops (*Raij et al*., 1996).

The full flowering stage of the soybean plants occurred 45 days after seedling emergence. At full flowering, 10 plants were sampled and evaluated for their shoot dry matter production. Additionally, the 3rd leaf (with the petiole) was sampled from 30 plants in each plot according to the methods of Raij *et al*. (1996) for macronutrient and silicon concentration analysis. Subsequently, the leaf samples were washed with deionized water dried using forced-air circulation at 65 °C for 72 h and ground. Then, the macronutrients were determined according the methods of Malavolta *et al*. (1997), and Korndörfer *et al*. (2004) for Si. The N was extracted using H_2SO_4, and the other nutrients were extracted using a nitro-perchloric solution. Both acid extraction were performed in a block digester. The N concentration was determined from the extracted solution using the Kjeldahl distillation method, and the P, K, Ca, Mg, and S concentrations were determined using atomic absorption spectrophotometry. The Si concentration were determined by 0.1 g from the plant tissue were wet with 2 mL of 50% H_2O_2 in polyethylene tubes. Next, 3 mL of 50% NaOH was added to each tube at room temperature.

The tubes were placed in a double boiler for 1 h and 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 before a 1-mL aliquot of the supernatant solution 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 Si concentration was determined with a spectrophotometer at a wavelength of 410 nm.

The soybean crops were harvested on April 3rd, 2007, and samples were collected to evaluate the yield components (plant population, number of pods per plant, number of grains per pod and the mass of 100 grains) and grain yields (13% moisture content).

Maize (*Zea mays* L.) was sown on December 2nd, 2007 using a row spacing of 0.45 mand a sowing rate of 3 seed sm^{-1}. The intermediate maturation-cycle 2B570 hybrid was chosen for this study. In addition, the seeds were treated with fungicide (vitavax + thiram – 50 + 50 g of the active ingredient every 100 kg of seeds), and the base fertilizer consisted of 300 kg ha^{-1} of the 08-28-16 NPK formula and plus side dressing N (January 10th, 2008) of 90 kg ha^{-1} of N as urea, accounting for the soil chemical analysis results and the recommendations for the maize crops (*Raij et al* 1997).The full flowering state of maize occurred 64 days after seedling emergence. At the full flowering stage, 10 plants were sampled per plot to evaluate the shoot dry matter production. Additionally, the central, third portion of the 30 leaves was sampled at the base of the ear (*Raij et al*., 1997) for analyzing the macronutrient (N, P, K, Ca, Mg, and S) and Si concentrations according to the methods of Malavolta *et al*. (1997) and Korndörfer *et al*. (2004), respectively.

Maize harvest occurred on April 1st, 2008, and sampling was carried out to evaluate the yield components (plant population, ears per plant, number of grains per ear and the mass of 100 grains) and the final yield (13% moisture content).

Soil samples were taken 6 (April 2007), 12 (October 2007) and 18 months (April 2008) after applying the correction materials at depths of 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.40 and 0.40-0.60 m. Six simple samples were randomly collected from the useful area of each plot and between the rows of the previous crop to form a compound sample. Next, these samples were dried, sieved (2-mm sieves) and analyzed according to Raij *et al*. (2001). The soil chemical characteristics (pH, organic matter, potential H + Al, P, K, Ca, Mg, exchangeable Al^{+3} and Si). The soluble Si concentrations in the soil were determined using a 0.01 mol L^{-1} $CaCl_2$ solution and were quantified based on the formation of beta-molybdosilicic complexes using a spectrophotometer at 660 nm, a described by Korndörfer *et al*. (2004). The efficiency use of fertilizer (EUF) applied on crops were calculated (3):

EUF (kg kg^{-1}) = Acumulated grain yield / Total Fertilizer applied (3)

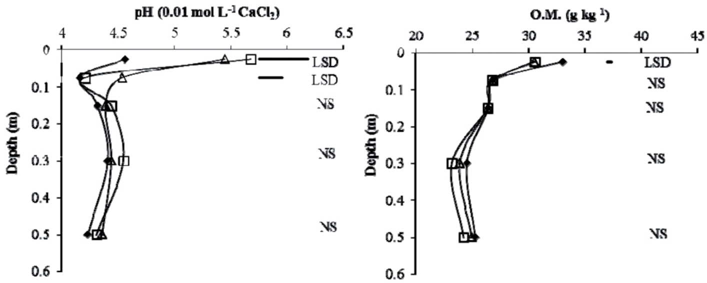
The data for all variables were analyzed by conducting an analysis of variance in the SISVAR statistical software package. The mean separations were conducted using the LSD test. The effects were considered as statistically significant at $p \leq 0.05$.

3. Results

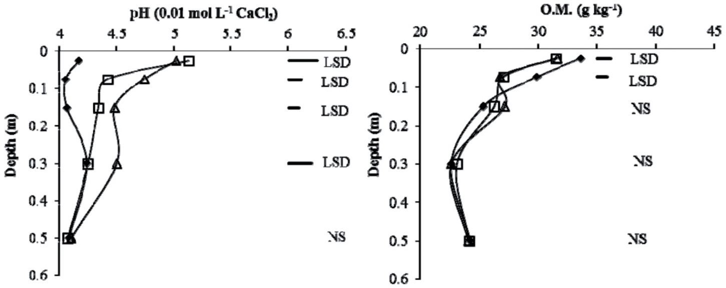
The Figures 2, 3 and 4 shows the pH, organic matter, H+Al, Al^{+3}, and Si values after correcting soil acidity with lime and Ca-Mg silicate. The addition of lime and Ca-Mg silicate increased the soil pH at the depths 0.05 and 0.1 m, respectively, 6 months after application.

In addition, the soil correction as a function of silicate and lime application was also observed 12 months after the application of the treatments even in deeper layers, down to 0.4 and 0.2 m, respectively. By the 18th month, the effects of lime were not found in the deeper layers. However, the products from silicate dissociation had reacted throughout the entire profile. The organic matter contents decreased at 0.05 and 0.1 m at 6 and 12 months after the application of lime and Ca-Mg silicate, respectively. However, soil correction increased the organic matter contents at depths of 0.1-0.2 m after 18 months as a consequence of the treatments application (Figure 2).

--6 months--



--12 months--



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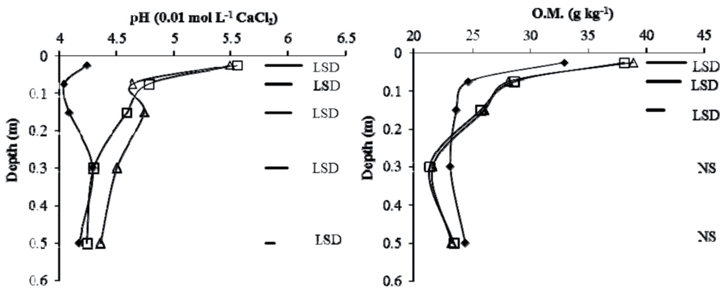
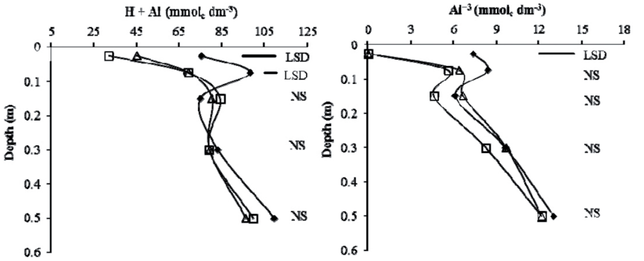


Figure 2. pH and organic matter (O.M.) level after 6, 12 and 18 months from the application of lime ( ), silicate ( ) and the control (f). Vertical bars indicate the least significant difference (LSD).

Similarly, the potential acidity (H+Al) was neutralized down to 0.1 m after 6 months and 0.4 m after 12 months by both corrective sources. However, by the 18th month, the Ca-Mg silicate reduced the acidity up to 0.4-0.6 m soil depth. In this final evaluation, liming effects were observed up to 0.1-0.2 m depth in comparison with the control (Figure 3).

--6 months--



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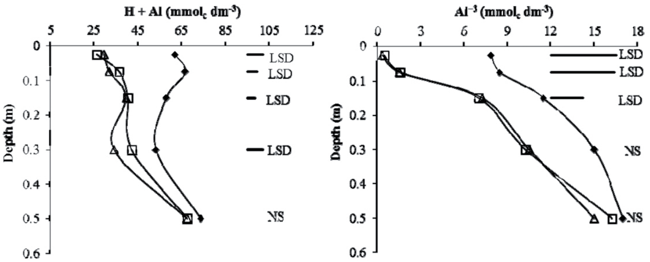


--18 months--

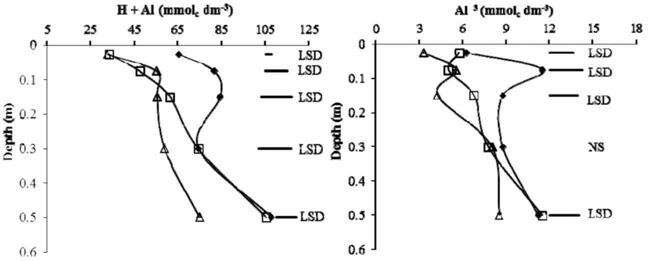


Figure 3. H + Al andAl^{3+} levels after 6, 12 and 18 months from the application of lime ( ), silicate ( ) and the control (f). Vertical bars indicate the least significant difference (LSD).

Soil correction decreased the Al^{+3}concentrations until the depths of 0-0.05 and 0.1-0.2 m after 6 and 12 months, respectively. These effects were observed in the deepest soil layer 18 months following Ca-Mg silicate application. The liming effects were confined to depths of 0.1-0.2 m (Figure 3).

For silicon, after 6 months of Ca-Mg silicate application, there was an increase in soil concentrations to a depth of 0.20 m. This effect was extended until 0.60 m after 12 and 18 months following Ca-Mg silicate application. It is noteworthy that, liming after 12 months was also observed increase in Si concentrations, which were restricted to the soil depths of 0.05-0.10 and 0.10-0.20 m (Figure 4).

The Figures 4, 5 and 6 shows the P, K^+, Ca^{+2}, and Mg^{+2} concentrations and the base saturation in the soil. Both materials for acidity correction efficiently improved the P concentrations in the uppermost soil layer by the 6th month after application. However, the P concentrations increased after the addition of silicate at depths of 0.05-0.1 m, which differed from the lime treatment and the control. Both sources increased the P concentrations at depths of 0-0.05 and 0.1-0.2 m. However, the effects of silicate were also observed from 0.05-0.1 m at 12 months after the application. After 18 months, silicate was more efficient than lime for increasing the P levels, which reached 0.1-0.2 m.

The concentrations of K in the soil were not affected by the application of lime or silicate at 6 and 18 months after the application of the treatments (Figure 5). However, the K concentrations increased until 0.1 m depth as a consequence of the application of lime and silicate at 12 months after application.

Furthermore, the concentrations of Ca in the soil increased over time with the application of lime and silicate, even in the deepest soil layer (Figure 5). The addition of silicate resulted in greater Ca concentrations compared to lime and control treatments at depths of 0.10-0.20 and 0.20-0.40 m at 12 months after the application of the treatments, and at depths of 0.10-0.20 and 0.40-0.60-m at 18 months after the application of the treatments.

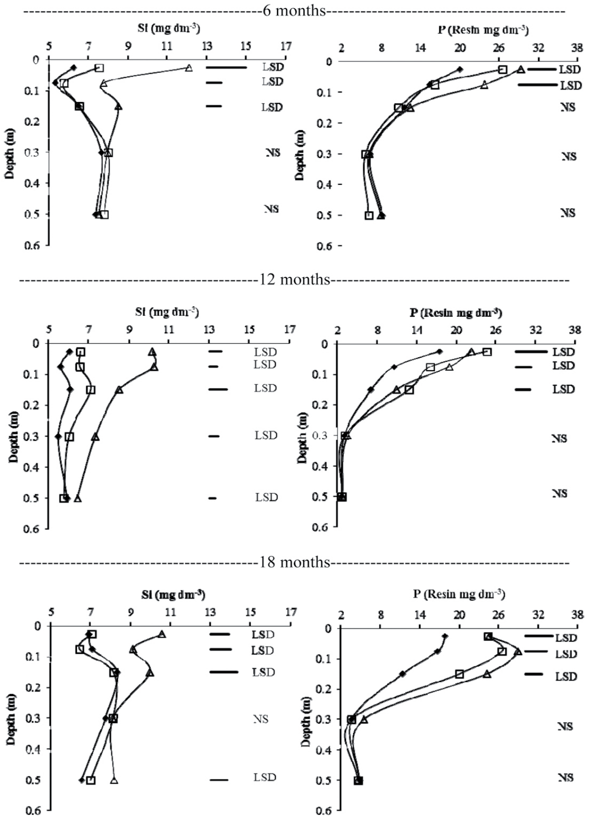


Figure 4. Si andP_{resin} levels after 6, 12 and 18 months from the application of lime ( ), silicate ( ) and the control (f). Vertical bars indicate the least significant difference (LSD).

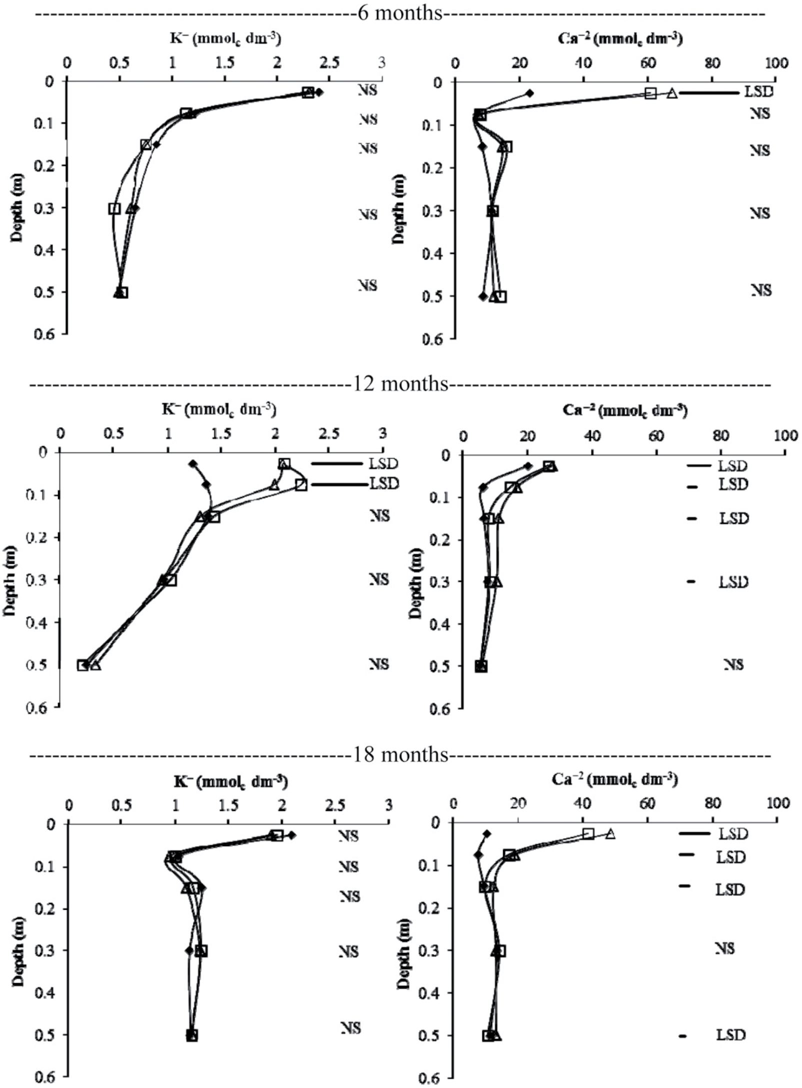


Figure 5. K^+ andCa^{2+} levels after 6, 12 and 18 months from the application of lime ( ), silicate ( ) and the control (f). Vertical bars indicate the least significant difference (LSD).

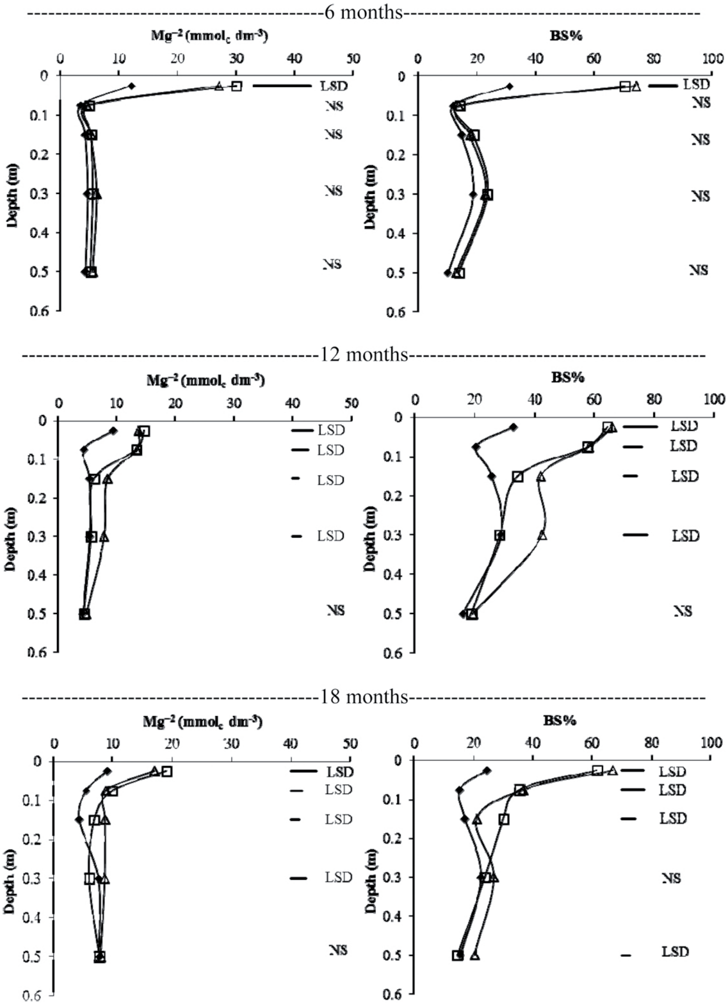


Figure 6. Mg^{2+} andBase Saturation (BS) levels after 6, 12 and 18 months from the application of lime ( ), silicate ( ) and the control (f). Vertical bars indicate the least significant difference (LSD)

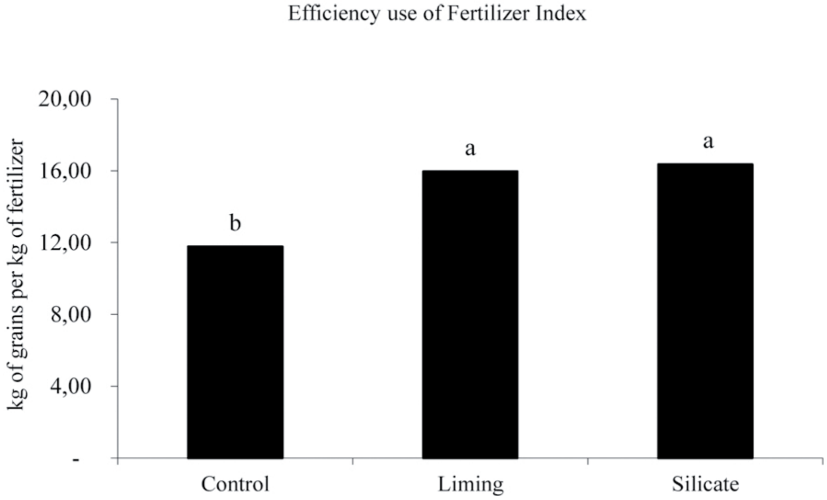


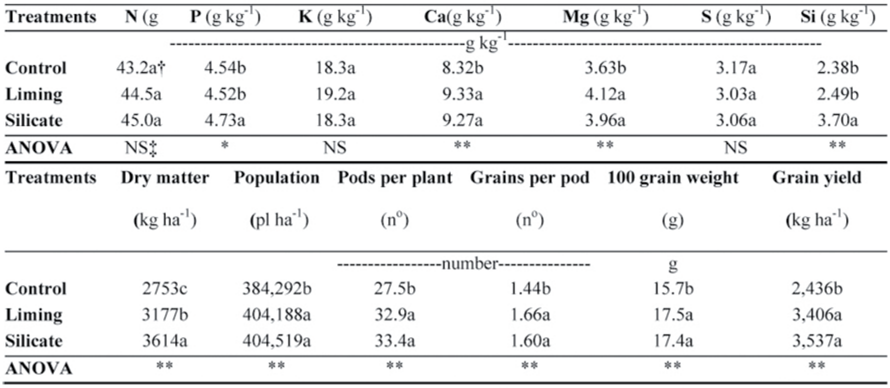
Figure 7. Efficiency use of fertilizers applied on soybean and maize affected by surface liming and silicate application under no tillage system. Columns followed by different letters differ statistically by the t test ($p<0.05$).

The effects of soil correction on the H+Al, Ca and Mg concentrations were reflected by the base saturation (Figure 6). Significant differences were found until the soil depths of 0.05, 0.40, and 0.60 m at 6, 12 and 18 months after the treatments application, respectively. The main differences between the lime and silicate treatments were observed at depths of 0.20-0.40 m and 0.40-0.60 m at 12 and 18 months after their application, respectively.

The concentrations of N, K, and S in the soybean leaves were not affected by the treatments at 6 months after the application (Table 1), but the application of lime and silicate increased the Ca and Mg concentrations in the leaves and silicate application P and Si concentrations in the leaves relative to the other treatments (Table 1).

The yield components and grain yields of soybean were affected by soil acidity correctives both treatments (Table 1). Both sources increased the shoot dry matter, although was higher after silicate application. Both sources increased the soybean dry matter production, plant population, number of pods per plant, number of grains per pod, the 100-grain weight and, consequently, the grain yield (Table 1). The application of lime and silicate increased the grain yield by 39.8 and 45.2%, respectively.

Table 1. Macronutrient (N, P, K, Ca, Mg, S and Si) concentrations, dry matter production, yield components (plant population, number of pods per plant, number of grains per pod and 100 grain weight) and soybean yield affected by surface liming and silicate application under no tillage system. Botucatu, State of São Paulo, Brazil, 2006-2008.



Treatments	**N** (g	**P** (g kg^{-1})	**K** (g kg^{-1})	**Ca**(g kg^{-1})	**Mg** (g kg^{-1})	**S** (g kg^{-1})	**Si** (g kg^{-1})
	g kg^{-1}						
Control	43.2a†	4.54b	18.3a	8.32b	3.63b	3.17a	2.38b
Liming	44.5a	4.52b	19.2a	9.33a	4.12a	3.03a	2.49b
Silicate	45.0a	4.73a	18.3a	9.27a	3.96a	3.06a	3.70a
ANOVA	NS‡	*	NS	**	**	NS	**

Treatments	**Dry matter** (kg ha^{-1})	**Population** (pl ha^{-1})	**Pods per plant** (n°)	**Grains per pod** (n°)	**100 grain weight** (g)	**Grain yield** (kg ha^{-1})
			number		g	
Control	2753c	384,292b	27.5b	1.44b	15.7b	2,436b
Liming	3177b	404,188a	32.9a	1.66a	17.5a	3,406a
Silicate	3614a	404,519a	33.4a	1.60a	17.4a	3,537a
ANOVA	**	**	**	**	**	**

†Means followed by different letters in the column differ statistically by the t test ($p<0.05$). ‡NS: non-significant.

The treatments did not influence the N, P, K, and S concentrations in the maize leaves (Table 2). However, the Ca and Mg concentrations increased following the application of lime and silicate. This trend was also observed for soybean. The application of soil acidity correctives increased the Si concentrations in the plant leaves, especially with the silicate application.

Among the yield components of maize, the treatments did not influence the ear index and 100-grain mass (Table 2). In contrast, as a consequence of the lime and silicate application the shoot dry matter production, plant population, and the number of grains per ear increased, which was directly reflected by the yield increases of 33.5 and 36% after lime and silicate application, respectively. The fertilizer use efficiency also increased from 11.7 kg of grains per kilogram of fertilizer applied (control) to 16.0 and 16.4 kg after the application of lime and silicate, respectively (Figure 7).

Table 2. Macronutrient (N, P, K, Ca, Mg, S and Si) concentrations, dry matter production, yield components (plant population, ear index, number of grains per ear and 100 grain weight) and maize yield affected by surface liming and silicate application under no tillage system. Botucatu, State of São Paulo, Brazil, 2006-2008.

Treatments	**N** (g kg^{-1})	**P** (g kg^{-1})	**K** (g	**Ca**(g	**Mg** (g kg^{-}	**S** (g kg^{-1})	**Si** (g kg^{-}
Control	31.7a[†]	2.64a	15.6a	3.36b	2.98b	2.35a	9,9c
Liming	31.8a	2.60a	15.5a	4.20a	3.73a	2.34a	10,7b
Silicate	32.4a	2.79a	15.5a	4.28a	3.70a	2.33a	11,9a
ANOVA	NS[‡]	NS	NS	**	**	NS	**

Treatments	**Dry**	**Population**	**Ear index**	**Grains**	**100 grain**	**Grain yield**
		(pl. ha^{-1})		**per ear**	**weight** (g)	(kg ha^{-1})
Control	15,752b	57,291b	1.11a	351b	36.2a	5,098b
Liming	17,852a	61,110a	1.12a	414a	36.6a	6,805a
Silicate	18,153a	60,638a	1.08a	408a	36.5a	6,934a
ANOVA	**	**	NS	**	NS	**

[†] Means followed by different letters in the column differ statistically by the t test ($p<0.05$).

[‡] NS: non-significant.

4. Discussion

The lime and silicate application increased the soil pH, which reduced the H+Al levels (Figures 2 and 3). The silicate effects on pH and H+Al were observed throughout the soil profile after 18 months, while the effects of lime were limited to the superficial layers.

Corrêa *et al*. (2007) compared the effects of surface liming (2.000 kg ha^{-1}; ECC = 71%) with three rates of Ca-Mg silicate as slag (2.000, 4.000 and 8.000 kg ha^{-1}; ECC = 48%). These authors found that silicate were more efficient to correct soil acidity because all the slag rates increased the soil pH up to 0.40 m15 months after the application. In contrast, the superficial limingonly corrected the soil pH up to 0.10 m15 months after the application. Costa and Crusciol (2016) in a long term study verified that the pH values increased until 0, 20 m in a Rhodic Hapludox at 48 months after the surface reapplication of lime.

The hydroxyl concentration increased and the H$^+$ concentration decreased in the soil solution as a function of the application of the sources of soil acidity correction, which increased the soil pH (Oliveira and Pavan, 1996).

Many no tillage system studies have demonstrated the effects of surface liming on correcting the subsurface soil layers (Caires *et al*., 2011; Correa *et al*., 2007; Soratto and Crusciol, 2008; Costa and Crusciol, 2016).

Soratto and Crusciol (2008) observed that surface liming decreased the H+Al concentrations at depths of 0.05-0.1 m and 0.1-0.2 m at 6 and 12 months after surface liming, respectively. This effect was dependent on the product dose and particle size, and on the application method, soil, climate factors (especially rainfall), tillage system and time of application (Oliveira and Pavan, 1996; Soratto and Crusciol, 2008). All of the cited factors affected this management efficiency, particularly when applied for subsurface correction of the soil acidity. Additionally, correctives sources appear to have distinct solubility properties and dissociation rates that affect their ion mobility throughout the profile.

One hypothesis that explains why silicate is more efficient in correcting acidity throughout the soil profile is its higher solubility when compared to lime (Alcarde and Rodella, 2003). Because silicate reacts faster in the uppermost soil layers, and analkalinization front occurs which corrects the acidity of deeper layers over a shorter period.

The organic matter content decreased due to lime and silicate at 6 and 12 months after the application (Figure 2), potentially due to the higher microbial activity that resulted from the higher pH values (Fuentes *et al*., 2006), and can promote accelerated soil organic matter (SOM) decomposition (Yao *et al*., 2009) and can lead to significant loss of C, especially in the light fraction C (Briedis *et al*., 2012). However, after medium-term (18 months), this effect was reduced due to the greater biomass productivity per area, shoots (Table 1 and 2) and roots by liming (Ridley *et al*., 1990; Hati *et al*., 2008), and occurred as a consequence of improvements in soil fertility attributes such as pH, the Ca and Mg supply, and reductions of Al^{3+} concentration (Figure 2, 3, 5 and 6). When comparing the Al^{+3} with Si concentrations in the soil, the Si concentrations were greater at depths where the concentrations of toxic Al^{+3} were reduced (Figures 3 and 4). Thus, in addition to the effects of increasing soil pH and organic matter (Álvarez *et al*., 2012), the Al^{+3}content may be reduced due to its reaction with and later precipitation as hydroxoalumino silicate (HAS) (Exley, 1998) and Al organic complexation (Álvarez *et al*., 2012).

The Si concentrations in the soil increased at 12 and 18 months after the application of lime at depths of 0.05-0.10 m, similarly to Pulz *et al*. (2008). In addition, the application of silicate resulted in greater Si concentrations at all soil depths 12 months after the application (Figure 4), which emphasized the efficiency of silicate for supplying Si.

Both sources of acidity correction efficiently improved the P concentrations in the uppermost soil layer (Figure 4). This result occurred due to the interactions of several factors that increased the hydroxyl concentrations and ionic activities in the soil solution (Monfort *et al*., 2015), including the pH and the precipitation of Fe and Al.

In contrast, the precipitation of P-Fe and P-Al minerals with low solubility decreased. Additionally, negative charges are generated by OH^-deprotonation and exposed by clays and organic matter. Consequently, phosphate is repelled by the adsorption surface (Mcbride, 1994), which releases P into the soil solution. Thus, it was expected that both materials for the acidity correction would increase the availability of P.

Nevertheless, the benefits of silicate applications increased due to the competition between Si and P for the same soil colloid sorption sites, which increased the P availability to the plants (Pulz *et al*., 2008). These sites are saturated or blocked by the silicate anion, which improved the efficiency of P fertilization.

The potassium concentrations in the soil were only influenced by the lime and silicate application in the superficial layers (0-0.10m) at 12 months after the application (Figure 5). Flora *et al*. (2007) reported better K availability in the soil after liming due to reduced leaching. Soil correction increased the pH and the amount of negative charges in the uppermost soil layers (Albuquerque *et al*., 2003) where K^+ ions were adsorbed. The acidity correction sources decreased the K^+ mobility with soil depth.

According to Flora *et al*. (2007), the amount of negative charges increased and retained K. Furthermore, the addition of K may be related to ion leaching from plant tissues (Rosolem *et al*., 2007) because as a consequence of the application of both sources of soil acidity correction greater dry matter production was observed in comparison to the control treatment (Tables 1 and 2).

The Ca and Mg concentrations were influenced by soil correction similarly (Figures 5 and 6). The effects of silicate were observed at depths of 0.00-0.05 and 0.20-0.40 m at6 and 12 months after the application, respectively.

The lime application provided 10% more Mg than silicate, but both sources affected the Mg concentrations in the uppermost soil layer similarly 12 and 18 months after their application. Nevertheless, their effects were different from 0.10 to 0.40 m depth. Specifically, higher Mg concentrations were observed as a consequence of silicate application in comparison to lime (similar results were observed by Corrêa *et al*., 2007) and may be explained by the higher silicate solubility which can intensify the leaching of Mg to deeper depths.

The mobility of basic cations in tropical soils (K^+, Ca^{2+}, and Mg^{2+}) is hindered by their adsorption to variable negative charges as the pH increases (Caires *et al*., 2006). Therefore, mobility may have been favored by the formation of ionic pairs between cations and inorganic compounds. These compounds potentially originated from the dissociation of correction sources of soil acidity or anions released through root exudation in the rhizosphere, such as OH^- and HCO_3^-, as well as nitrate (NO_3^-), sulphate (SO_4^{2-}), and chloride (Cl^-) from fertilizer mineralization or residue decomposition at the soil surface (Crusciol *et al*., 2011). In addition, organic ionic pairs formed by soil cations and water-soluble compounds with low molecular weight (originated from residue decomposition through C=O-OH radicals) may improve ion mobility throughout the profile (Castro *et al*., 2012).

The variations in the pH and base saturation and the cation mobility through the soil profile depend on the absence of acid cations in the surface soil layers, which are preferentially bound. According to Fageria and Baligar (2008), this result can be observed at pH (H_2O) values between 5.2 and 5.5.

Regarding the soil macronutrient concentrations (Tables 1 and 2), all of the concentrations were within the range that was considered appropriate for soybean and maize with the exception of the K levels for soybeans (Raij *et al*., 1997). The different treatments did not influence the N, K, and S concentrations, likely because they did not have enough time to increase the microbial activity and improve the organic matter mineralization (Fuentes *et al*., 2006).

The increases in Ca and Mg in the plants due to the superficial application of correctives of soil acidity (Tables 1 and 2) have also been observed by other authors (Mali and Aery, 2008; Costa and Crusciol, 2016). These effects have been attributed to the increases in the exchangeable Ca and Mg in the soil profile (Figure 5 and 6) that allows the plant roots explore a large volume of soil.

The application of silicate resulted in greater P in the soybean leaves (Table 1). In contrast, increasing the P concentrations in the leaves by the addition of silicate in the soil is related to the competition of silicate ($H_3SiO_4^-$) and phosphate ($H_2PO_4^-$) for the same sorption sites (Figure 3) (Plucknett, 1972). Pulz *et al.* (2008) also observed higher P availability in soils and in the leaves of potato plants after the application of silicate in comparison to lime.

The correction of soil acidity with silicate increased Si concentration in soybean and maize leaves, and in maize higher values were found after lime application compared to the control (Tables 1 and 2). The silicate is a source of Si that increases their availability in the soil (Figure 2). The increased Si concentrations in the soil by liming was also observed by Ramos *et al.* (2006), and they explained that pH is extremely important to Si availability for plants.

The yield components and grain yields of soybean and maize were greater following the application of lime and silicate (Tables 1 and 2). Corrêa *et al*. (2008) studied surface liming and the application of silicate as slag and observed that both treatments increased the yield components individually, which increased the soybean yield. Miranda *et al*. (2005) also observed similar results for maize with the superficial application of the correction sources of soil acidity. In fact, the maize yield is correlated to soil pH (Nájera *et al*., 2015).

Nevertheless, research conducted in Southern Brazil has shown that soybeans do not respond significantly to surface liming in no-till systems. According to Caires and Fonseca (2000), organic matter conservation and moisture contents in topsoil layers improve in no tillage systems, which favor nutrient uptake by plants even in acid soils. Consequently, the beneficial effects of liming may be minimized under appropriate rainfall conditions.

The response to soil acidity correction is potentially greater in locations with lower amounts of crop residues at the soil surface. For example, this situation occurs in dry-winter regions in Brazil, such as the Cerrado biome, where most areas are only cropped once each year. Significant results have been observed in soils with low exchangeable Mg concentrations for all cropping systems (Oliveria and Pavan, 1996).

The soil acidity correction increased efficiency of fertilization (Figure 7). According to Crusciol and Soratto (2010), fertilizer efficiency depends on soil management practices, such as tillage system, crop rotation, crop succession, green manure application, and the application of conservation practices. The efficient use of fertilizers and correction sources has become increasingly relevant to Brazilian agriculture due to increased input prices, higher crop yields, higher production, and the risk of environmental contamination due to inappropriate input use. Thus, it is important to study all factors that influence fertilizer efficiency and to identify the best management practices for maximizing fertilizer efficiency.

5. Conclusions

Considering the results of this experiment, the hypothesis that silicate is an efficient source for acidity correction is valid because it increases the number of exchangeable bases in the soil equivalent than lime. Additionally, silicate increases the availability of Si for plants and phosphorus concentrations in the soybean shoots due to the greater phosphorus concentrations in the soil. Nevertheless, the application of both lime and silicate increased the calcium and magnesium concentrations, the yields components, and the yields of soybean and maize. Consequently, both sources of soil acidity correction improved the efficiency of fertilizer use when applied for grain production.

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