



Semina: Ciências Agrárias

ISSN: 1676-546X

semina.agrarias@uel.br

Universidade Estadual de Londrina  
Brasil

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Semina: Ciências Agrárias, vol. 36, núm. 2, 2015, pp. 4071-4082

Universidade Estadual de Londrina  
Londrina, Brasil

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# Effects of silicate application on soil fertility and wheat yield<sup>1</sup>

## Efeitos da aplicação de silicato na fertilidade do solo e rendimento do trigo

Marcos Vinícius Mansano Sarto<sup>2\*</sup>; Maria do Carmo Lana<sup>3</sup>; Leandro Rampim<sup>4</sup>; Jean Sérgio Rosset<sup>5</sup>; Jaqueline Rocha Wobeto<sup>6</sup>

### Abstract

An improvement in soil chemical properties and crop development with silicate application has been confirmed in several plant species. The effects of silicate application on soil chemical properties and wheat growth were investigated in the present study. The experiment was carried out in 8-L plastic pots in a greenhouse. Treatments were arranged in a randomized block design in a  $3 \times 5$  factorial: three soils [Rhodic Acrudox (Ox1), Rhodic Hapludox (Ox2) and Arenic Hapludult (Ult)] and five silicate rates (0, 1, 2, 4 and 6 Mg ha<sup>-1</sup> of calcium/magnesium silicate), with four replications. The plant length, number of spikes per pot, shoot dry matter and grain yield, were measured after 115 days of wheat (*Triticum aestivum* L.) growth. Changes in the soil chemical properties (pH, H<sup>+</sup> + Al<sup>3+</sup>, Al<sup>3+</sup>, P, K, Ca, Mg, Si, Cu, Zn, Fe and Mn) were analyzed after wheat harvest. Application of calcium/magnesium silicate reduces the potential acidity (H<sup>+</sup> + Al<sup>3+</sup>) and Al<sup>3+</sup> phytotoxic; and increases the soil pH, available Ca, Mg and Si, cation exchange capacity (CEC) and soil base saturation. Silicate application did not affect the available P, exchangeable K and availability of micronutrients (Cu, Zn, Fe and Mn) in the three soils. The application of calcium/magnesium silicate in an acid clayey Rhodic Hapludox improves the development and yield of wheat; however, the silicate application in soil with pH higher to 5.3 and high Si availability does not affect the agronomic characteristics and grain yield of wheat.

**Key words:** *Triticum aestivum* L., silicon, chemical properties, acidity correction source

### Resumo

Melhorias das propriedades químicas do solo e do desenvolvimento das culturas com aplicação de silicato foi confirmado em várias espécies de plantas. Os efeitos da aplicação de silicato nas propriedades químicas do solo e crescimento do trigo foram investigados no presente estudo. O experimento foi realizado em vasos plásticos de 8 L em estufa. Os tratamentos foram dispostos em um delineamento em blocos casualizados, em esquema fatorial  $3 \times 5$ : três solos [Latossolo Vermelho eutroférico (LVef), Latossolo Vermelho distroférico (LVd) e Argissolo Vermelho-Amarelo eutrófico (PVAe)] e cinco doses

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de silicato (0, 1, 2, 4 e 6 Mg ha<sup>-1</sup> de silicato de cálcio / magnésio), com quatro repetições. O comprimento da planta, número de espigas por vaso, matéria seca e rendimento de grãos, foram medidos após 115 dias de crescimento do trigo (*Triticum aestivum* L.). As alterações nas propriedades químicas do solo (pH, H<sup>+</sup> + Al<sup>3+</sup>, Al<sup>3+</sup>, P, K, Ca, Mg, Si, Cu, Zn, Fe e Mn) foram analisados após a colheita. A aplicação de silicato de cálcio/magnésio reduz a acidez potencial (H<sup>+</sup> + Al<sup>3+</sup>) e Al<sup>3+</sup> fitotóxico; e aumenta o pH do solo, Ca, Mg e Si disponível, capacidade de troca catiônica (CTC) e saturação por bases. Aplicação de silicato não afetou o P disponível, K trocável e disponibilidade de micronutrientes (Cu, Zn, Fe e Mn) nos três solos. A aplicação de silicato de cálcio/magnésio em um Latossolo Vermelho argiloso ácido melhora o desenvolvimento e a produtividade do trigo; no entanto, a aplicação de silicato em solos com pH superior a 5,3 e alta disponibilidade Si não afeta as características agronômicas e produtividade de grãos do trigo.

**Palavras-chave:** *Triticum aestivum* L., silício, propriedades químicas, correção da acidez

## Introduction

Soil acidity limits the crop production in considerable areas of the world. Calcium (Ca) deficiency and toxicity caused by aluminum (Al) and manganese (Mn) are the factors that most have limited the productivity of acid soils in tropical and subtropical regions. The problems of soil acidity are normally corrected through the use of limestone or silicate. Fageria and Zimmermann (1998) reported that the ideal pH for soybean, common bean, maize and wheat growth is around 6.0, which emphasizes the importance of correcting acid soils for appropriate crop development.

Limestone is the most applied source for acidity correction in Brazil due to its price and capacity to increase fertilizer efficiency. Nevertheless, limestone is not a very soluble material and its dissociated components show limited mobility, usually restricting correction effects in uppermost soil layers, mainly under non-mobilized conditions of no-till (CASTRO; CRUSCIOL, 2013; SORATTO; CRUSCIOL, 2008). However, other materials may be applied for acidity correction, as long as the product is constituted by neutralizing components such as calcium and/or magnesium oxides, hydroxides, carbonates and silicates. Calcium and magnesium silicates are similar to carbonates in composition; so, those sources can potentially replace lime even more advantageously (CASTRO; CRUSCIOL, 2013; CAMARGO et al., 2007; CARVALHO-PUPATTO et al., 2004). Thus,

studies have shown that the calcium/magnesium silicates can be used as corrective of soil acidity and as silicon (Si) source (CASTRO; CRUSCIOL, 2013; CRUSCIOL et al., 2009; PULZ et al., 2008; CARVALHO-PUPATTO et al., 2004), in addition to increasing Ca, Mg, CEC values and base saturation soil (SARTO et al., 2014a). Recommendation for silicate application can be based on any methods of limestone requirement (KORNDÖRFER et al., 1999b). Compared to limestone, there are fewer studies on silicate application as an acidity correction source for crop yield in agricultural production systems. Field research on the application of calcium/magnesium silicate indicate this source can be more efficient than other materials (limestone, aqueous lime and sewage sludge) for correction of deeper soil layers due to their higher solubility (CASTRO; CRUSCIOL, 2013; CORRÊA et al., 2007).

Beneficial effects of silicate application on the crop development and yield has been confirmed in several crops such as rice (CARVALHO-PUPATTO et al., 2004), sugar cane (REIS et al., 2013), maize (CASTRO; CRUSCIOL, 2013) and wheat (PROVANCE-BOWLEY et al., 2010), which are considered Si-accumulating species. Silicate benefits may be related to silicon (Si) effects on plants under biotic or abiotic stress conditions even though it is not considered an essential element for plant growth, either physiologically or metabolically (EPSTEIN; BLOOM, 2005). The largest growth and grain yield of plants grown with

the Si supply is associated to the changes in plant architectures, making them more erect, improving the leaves angle and light interception, avoiding the excessive self-shading, delaying senescence, increasing the structural rigidity of the tissues and improving photosynthesis and reducing lodging (GONG; CHEN, 2012; MA; YAMAJI, 2008). These beneficial effects are attributed to Si deposited in the cell wall of various plant organs (MA; YAMAJI, 2006) and by other mechanisms. High deposition of Si in tissues forms a physical barrier that enhances the strength and rigidity of the tissues.

Considering that the use of silicate tends to be most common agricultural practice in Brazil, an improved understanding of the effects of silicate on soil properties and wheat crop development is essential in order to adopt management strategies for improving crop production. In this context, the purpose of this study was to investigate the effects of silicate application soil chemical properties and wheat (*Triticum aestivum* L.) yield in the three soils of the western region of Paraná - Brazil.

## Material and Methods

Pot experiments were carried out in a greenhouse in Marechal Cândido Rondon, Paraná State, Brazil (24° 31' S, 54° 01' W, and 420 m a.s.l.), where the environmental conditions were: minimum and maximum mean air temperature of 18 and 36 °C, respectively; mean air relative humidity of 65%.

Surface samples (0.0–0.20 m) from three representative soils of the western region of Paraná

State were selected for silicon fertilization studies (Table 1). The physical and chemical properties of the soils were determined by adopting standard procedures, and some properties are shown in Table 2. Soil pH in 0.01 mol L<sup>-1</sup> CaCl<sub>2</sub> solution was determined potentiometrically in a 1:2.5 (soil:solution) suspension using a combined calomel reference glass electrode and pH meter. Organic matter was quantified by oxidation with potassium dichromate in the presence of sulfuric acid, followed by titration with ammonium Fe (II) sulfate (EMBRAPA, 2009). Available phosphorus (P), exchangeable potassium (K) and cationic micronutrients (Cu, Zn, Fe and Mn) were extracted by Mehlich-1 solution in a 1:10 (w:v) soil-to-extractant solution ratio (EMBRAPA, 2009) and P was determined by colorimetry at 725 nm wave length and K and micronutrients were determined by atomic absorption spectrophotometry. Calcium (Ca) and magnesium (Mg) were extracted by 1 mol L<sup>-1</sup> KCl solution and determined by atomic absorption spectrophotometry (EMBRAPA, 2009). Cation exchange capacity (CEC) was estimated by the summation method (CEC = H + Al + Ca + Mg + K). Soluble silicon was extracted by 0.5 mol L<sup>-1</sup> acetic acid solution in a 1:10 (w:v) soil-to-extractant solution ratio (KORNDÖRFER et al., 1999a) and determined by beta molybdosilicic complex formation, using a spectrophotometer at 660 nm wave length. Particle size analysis was performed by the pipette method (EMBRAPA, 1997), based on decantation speed of different soil particles after dispersion in 0.015 mol L<sup>-1</sup> (NaPO<sub>3</sub>)<sub>6</sub>·NaO/1.0 mol L<sup>-1</sup> NaOH by overnight shaking.

**Table 1.** Brazilian soil classification, approximate equivalence to soil taxonomy and sampling site of the three soils from Paraná State.

Soil	Brazilian soil classification <sup>†</sup>	Soil taxonomy <sup>††</sup>	Sampling Municipality
Ox1	Eutroferic Red Latosol	Rhodic Acrudox	Marechal Cândido Rondon
Ox2	Distroferic Red Latosol	Rhodic Hapludox	Cascavel
Ult	Red-Yellow Argisol	Arenic Hapludult	Goioerê

<sup>†</sup> According to EMBRAPA (2013). <sup>††</sup> USDA Soil Taxonomy (SOIL SURVEY STAFF, 2010).

The experimental design was a  $3 \times 5$  factorial in complete randomized blocks, with four replications. Treatments consisted of three soils [Rhodic Acrudox (Ox1), Rhodic Hapludox (Ox2) and Arenic Hapludult (Ult)] and growing wheat plants with 0 (control), 1, 2, 4 and 6 Mg ha<sup>-1</sup> of calcium/magnesium silicate. The silicate source used was AgroSilício® (Si 10.5%; Ca 25%, Mg 6%

and ECCE 88%). The corrected soils were kept for 15 days with water content at 60% field capacity. Then the soils were placed in 8-L plastic pots and fertilized with applying 30 mg kg<sup>-1</sup> of N (urea), 60 mg kg<sup>-1</sup> of P (simple superphosphate) and 45 mg kg<sup>-1</sup> of K (potassium chloride). At 30 days after plant emergence, the application of 45 mg kg<sup>-1</sup> N as urea a solution was also performed.

**Table 2.** Some physical and chemical properties of the soils.

Soil characteristics	Soil		
	Acrudox	Hapludox	Hapludult
Soil pH	5.3	4.1	6.2
Clay (g kg <sup>-1</sup> )	550.0	535.0	100.0
Silt (g kg <sup>-1</sup> )	370.0	430.0	45.0
Sand (g kg <sup>-1</sup> )	80.0	35.0	855.0
Organic matter (g kg <sup>-1</sup> )	26.0	39.6	22.0
Available P (mg kg <sup>-1</sup> )	37.1	22.5	40.7
H + Al (cmol <sub>c</sub> kg <sup>-1</sup> )	4.6	10.7	2.0
Exchangeable Al (cmol <sub>c</sub> kg <sup>-1</sup> )	0.0	2.4	0.0
Exchangeable K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.15	0.20	0.20
Calcium (cmol <sub>c</sub> kg <sup>-1</sup> )	4.8	4.0	2.5
Magnesium (cmol <sub>c</sub> kg <sup>-1</sup> )	1.8	0.5	0.7
CEC (cmol <sub>c</sub> kg <sup>-1</sup> ) <sup>†</sup>	11.4	15.4	5.4
Soil base saturation (%)	60.0	30.0	63.0
Copper (mg kg <sup>-1</sup> )	15.0	8.2	9.9
Zinc (mg kg <sup>-1</sup> )	132.0	110.0	247.0
Iron (mg kg <sup>-1</sup> )	41.1	35.4	28.5
Manganese (mg kg <sup>-1</sup> )	3.9	8.2	5.4
Silicon (mg kg <sup>-1</sup> )	19.3	15.8	18.0

<sup>†</sup> CEC: cation exchange capacity.

Five seeds of wheat (*Triticum aestivum* L., cv. BRS Pardela) were sown, and nine days after seedling emergence, they were thinned to three plants per pot. The pots were irrigated daily for maintain soil moisture near at the field capacity.

At maturity (115 days after plant emergence), the crop yield was evaluated in terms of shoot dry matter production (SDM, g pot<sup>-1</sup>) and grain yield (g pot<sup>-1</sup>). Plants of all treatments were harvested separately, dried for four days at  $60 \pm 2$  °C, and then weighed. The shoot length was measured (cm

plant<sup>-1</sup>) using meter scale. The number of spikes per pot was also measured.

After wheat harvest, soil samples were collected for evaluation of changes in the soil chemical properties (pH, H + Al, P, K, Ca, Mg, Al<sup>3+</sup>, Si, Cu, Zn, Fe and Mn). Soil samples were oven-dried at 50 °C for 48 h, ground to pass through a 2 mm mesh screen and analyzed as previously described by EMBRAPA (2009) and Korndörfer et al. (1999a).

Original data were analyzed by ANOVA and regression analysis, and significant equations with

the highest coefficients of determination (F test,  $P \leq 0.05$ ) were adjusted. All analyses were performed using Saeg 8.0 software for Windows (Statistical Analysis Software, UFV, Viçosa, MG, BRA).

## Results and Discussion

The results of the soil chemical analyses showed that there was significant interaction between soil type and calcium/magnesium silicate rates (Figure 1).

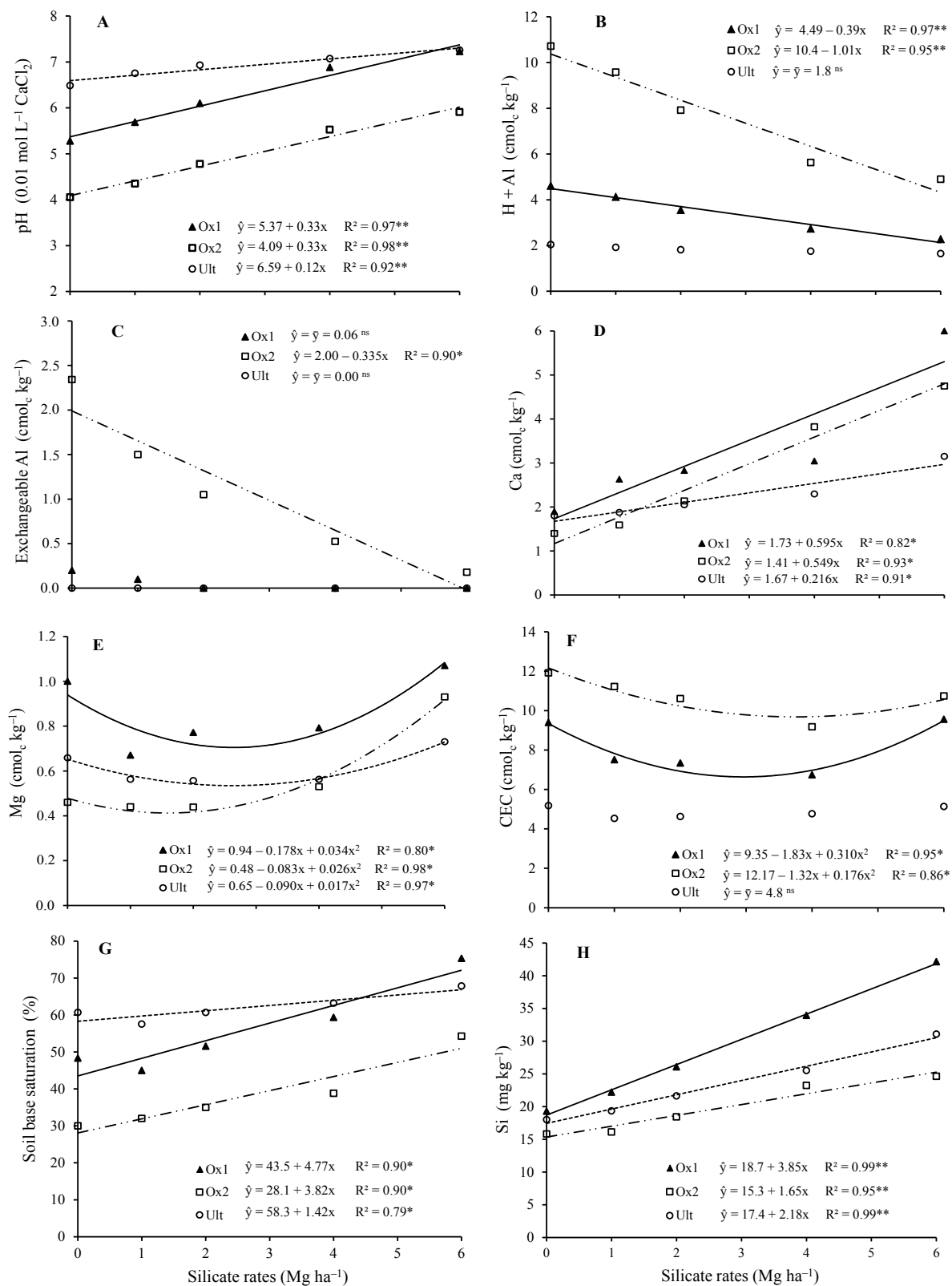
Application of calcium/magnesium silicate increased the pH of the three soils (Figure 1A). Studies show that silicate materials have great potential to improve soil chemical characteristics, mainly by increasing the pH (SARTO et al., 2014b; CASTRO; CRUSCIOL, 2013; CORRÊA et al., 2007; CAMARGO et al., 2007; CARVALHO-PUPATTO et al., 2004), confirming that the calcium/magnesium silicate can be used as corrective of soil acidity. As silicate dissolves in the soil, calcium (Ca) moves to the surface of soil particles, replacing the acidity ( $H^+$ ). The acidity reacts with the silicate ( $SiO_3^{2-}$ ) to form orthosilicic acid ( $H_4SiO_4$ ) and water ( $H_2O$ ) (ALCARDE; RODELLA, 2003). The result is a soil that is less acidic (has a higher pH). Calcium and magnesium silicate can be source for soil acidity correction more efficient than other materials such as limestone and sewage sludge. Corrêa et al. (2007) found that pH was increased by silicate application down to 0.40 m after 15 months, whereas liming effects were confined down to 0.10 m, on profile of a dystrophic Rhodic Hapludox, medium texture. Evaluate the superficial application of limestone and calcium/magnesium silicate in a deep acid clayey Rhodic Hapludox, Castro and Crusciol (2013) verified that, after 12 months from their application, liming effects had only influenced pH down to 0.05 m, while silicate increased pH at 0.10–0.20 m depth. Compared to lime, silicate is more efficient in correcting acidity down the profile due to its higher solubility (ALCARDE; RODELLA, 2003). As silicate reaction is faster in uppermost soil layers, an alkalization front is formed to correct acidity of

deeper layers in a shorter period of time (CASTRO; CRUSCIOL, 2013).

Calcium and magnesium silicate reduced the potential acidity ( $H^+ + Al^{3+}$ ) levels of Ox1 and Ox2 soils (Figure 1B). The decrease of  $H^+$  and  $Al^{3+}$  values occurs by increasing the hydroxyl ( $OH^-$ ) concentration in the soil, resulting from silicate application, in which a fraction of these  $OH^-$  reacts with the excess of  $H^+$  in solution, increasing the soil pH, and the remainder of these promotes aluminum precipitation in  $Al(OH)_3$ , which on is non-toxic to plants (STEINER et al., 2012). Application of up to 6 Mg ha<sup>-1</sup> of silicate did not change the soil potential acidity of Ult (Figure 1B), due to high initial pH value (6.2) and low  $H^+$  and  $Al^{3+}$  levels (2.0 cmol<sub>c</sub> kg<sup>-1</sup>) compared with the other soils (Table 2).

Silicate reduced the  $Al^{3+}$  phytotoxic levels of Ox2 soil (Figure 1C). Exchangeable  $Al^{3+}$  levels can be both decreased by increasing pH (CARVALHO-PUPATTO et al., 2004) or by reactions with Si and later precipitation as hydroxoaluminosilicate, which reduces its availability (HODSON; SANGSTER, 1999). Castro and Crusciol (2013) found that silicate is more efficient than limestone to reducing toxic aluminum in soil profile, due to their greater solubility (CORRÊA et al., 2007).  $SiO_3^{2-}$  is the neutralizing agent in silicates, which reacts with water releasing  $OH^-$  ions that neutralize  $H^+$  and  $Al^{3+}$  phytotoxic, consequently increasing Ca, Mg and base saturation (ALCARDE; RODELLA, 2003). For the Ox1 and Ult,  $Al^{3+}$  levels were low or zero due to the high pH values and were not affected by the silicate application (Figure 1C). The soil pH is probably the single most important management factor controlling the amount of  $Al^{3+}$  phytotoxic in the soil solution. Exchangeable Al is present in the soil when the pH begins to drop below pH 5.5. Even then, it is rarely a problem until the soil pH drops below pH 5.0. However, the amount of  $Al^{3+}$  phytotoxic increases dramatically in the majority of soils as the soil pH drops below pH 5.0 (MOTTA; MELO, 2009), reporting the importance of soil acidity correction to reduce the soil Al level.

**Figure 1.** Effects of silicate application in three soils of the western region of Paraná State on the pH (A), H + Al (B), exchangeable Al (C), Ca (D), Mg (E), CEC (F), base saturation (G) and Si (H) after wheat harvest. ns: not significant. \* and \*\*: statistical significance at 5% and 1%, respectively, by F test.



Silicate application increased Ca levels in the three soils (Figure 1D). The application of 6 Mg ha<sup>-1</sup> calcium/magnesium silicate increased the Ca levels in the Ox1, Ox2 and Ult soils in 206%, 234% and 78%, respectively, compared to the control treatment. The results presented here are similar to those reported by Castro and Crusciol (2013), who found increases on Ca levels in the soil after the silicate application. This increase in Ca level in the soils is due to supply of this nutrient with calcium/magnesium silicate rates.

Magnesium levels were affected by soil correction with silicate in the three soils (Figure 1E). The minimum Mg level in the Ox1, Ox2 and Ult were 0.71, 0.41 and 0.55 cmol<sub>c</sub> kg<sup>-1</sup> obtained with the application of 2.62, 1.60 and 2.65 Mg ha<sup>-1</sup> of calcium/magnesium silicate, respectively.

The soil correction with calcium/magnesium silicate affected the cation exchange capacity (CEC) of Ox1 and Ox2, and did not alter the CEC of Ult (Figure 1F). The minimum CEC value in the Ox1 and Ox2 was 6.65 and 9.70 cmol<sub>c</sub> kg<sup>-1</sup> obtained with the application of 2.95 and 3.75 Mg ha<sup>-1</sup> of silicate, respectively. The Ox2 has the highest CEC values compared to the other soils (Figure 1F), but it also has the highest potential acidity levels (Figure 1B), indicating that a significant portion of the soil negative charges are occupied by H<sup>+</sup> and Al<sup>3+</sup> ions. On the other hand, the fact of soil correction with silicate have not affected the CEC of the Ult can be explained by the high initial pH value and low buffering capacity of this soil due to its sandy texture (Table 2). In addition, the correction effect decreases when the pH reaches high values (ASSIS et al., 2007).

Effects of soil correction on H<sup>+</sup> + Al<sup>3+</sup>, Ca and Mg levels reflected in changes on soil base saturation in the three soils (Figure 1G). The application of 6 Mg ha<sup>-1</sup> silicate increased the base saturation in the Ox1, Ox2 and Ult in 66%, 81% and 15%, respectively, compared to the control treatment. The increase in the base saturation values

is related to increase of soil pH and increase the Ca and Mg levels, confirming the results reported by Korndörfer et al. (2010) and Sarto et al. (2014b). Regarding the Ox2 soil, the low percentage of base saturation indicates that a significant portion of the exchange sites being occupied by H<sup>+</sup> and Al<sup>3+</sup> ions (Figure 1B). Prates et al. (2011) found that the CEC and base saturation were higher with the application of calcium/magnesium silicate in relation to the Ca supply contained in this corrective. The use of calcium/magnesium silicate can be applied as soil corrective, with the advantage of also supply Si to the plants, which makes crops less susceptible to environmental stress (GUNES et al., 2008).

Silicate application increased available Si levels of the three soils (Figure 1H). Application of 6 Mg ha<sup>-1</sup> silicate increased the available Si levels in the Ox1, Ox2 and Ult in 124%, 65% and 75%, respectively, compared to the control treatment. The increasing of Si availability in the soil with silicate application is normally reported in other studies (SARTO et al., 2014b; CASTRO; CRUSCIOL, 2013; CORRÊA et al., 2007). This result may be attributed to the supply of this element with the silicate and solubilization of silica compounds as pH increases or reduced capacity of Si bonds to colloid sorption sites, increasing its concentration in soil solution, as reported by Pulz et al. (2008). The increases in availability of Ca, Mg and Si with application of calcium/magnesium silicate were expected because this source has high solubility in the soil (CASTRO; CRUSCIOL, 2013) and possess in their chemical composition 10.5% of Si, 25% of Ca and 6% of Mg. According to Alcarde and Rodella (2003), silicate is 6.78 times more soluble than limestone. The results presented here are similar to those reported by Castro and Crusciol (2013), Korndörfer et al. (2010), Corrêa et al. (2007).

Application of calcium/magnesium silicate did not affect the available P, exchangeable K and availability of micronutrients in the three soils (Table 3). On the other hand, Castro and Crusciol (2013)

found that the silicate application, in soil with low P, was capable of increasing P availability. According to these authors, these results are attributed to the competition between Si and P for the same sorption

sites of soil colloids, increasing P availability to plants. However, in this study the silicate application does not affected the soil P availability, probably due to high initial concentration of P in the soils studied.

**Table 3.** Available P, exchangeable K, and availability of micronutrients (Cu, Zn, Fe and Mn) after wheat harvest as affected by silicate application in three soils of the western region of Paraná State.

Silicate rates	Available P			Exchangeable K			Available Cu		
	Acrudox	Hapludox	Hapludult	Acrudox	Hapludox	Hapludult	Acrudox	Hapludox	Hapludult
Mg ha <sup>-1</sup>	mg kg <sup>-1</sup>			cmol <sub>c</sub> kg <sup>-1</sup>			mg kg <sup>-1</sup>		
0	37.7	55.0	49.4	0.13	0.19	0.20	16.7	6.6	4.6
1	66.3	48.3	42.6	0.15	0.15	0.16	15.8	6.0	6.5
2	35.3	37.7	53.9	0.19	0.15	0.16	16.6	5.9	7.0
4	41.5	23.3	52.8	0.17	0.16	0.17	16.9	5.6	5.7
6	48.7	36.2	77.7	0.19	0.15	0.20	17.0	5.7	5.9
Mean	45.9	40.1	55.3	0.17	0.16	0.18	16.6	6.0	5.9
Teste F	0.63 <sup>ns</sup>			0.56 <sup>ns</sup>			0.38 <sup>ns</sup>		
CV (%)	53.0			21.6			12.4		
Silicate rates	Available Zn			Available Fe			Available Mn		
	Acrudox	Hapludox	Hapludult	Acrudox	Hapludox	Hapludult	Acrudox	Hapludox	Hapludult
Mg ha <sup>-1</sup>	mg kg <sup>-1</sup>			mg kg <sup>-1</sup>			mg kg <sup>-1</sup>		
0	14.2	10.7	18.2	46.0	38.2	24.1	7.8	8.5	15.3
1	20.9	11.2	7.4	48.4	39.8	32.2	20.9	16.8	7.0
2	11.2	7.0	14.2	55.6	41.6	28.2	11.2	9.0	14.4
4	13.8	17.3	5.7	60.8	40.1	28.0	13.8	18.3	9.5
6	14.8	29.2	17.5	55.9	41.7	41.6	14.8	26.1	14.5
Mean	15.0	15.1	12.6	53.4	40.3	30.8	13.7	15.7	12.1
Teste F	0.88 <sup>ns</sup>			0.93 <sup>ns</sup>			1.20 <sup>ns</sup>		
CV (%)	68.7			14.9			62.5		

ns: not significant by F test. CV: coefficient of variation.

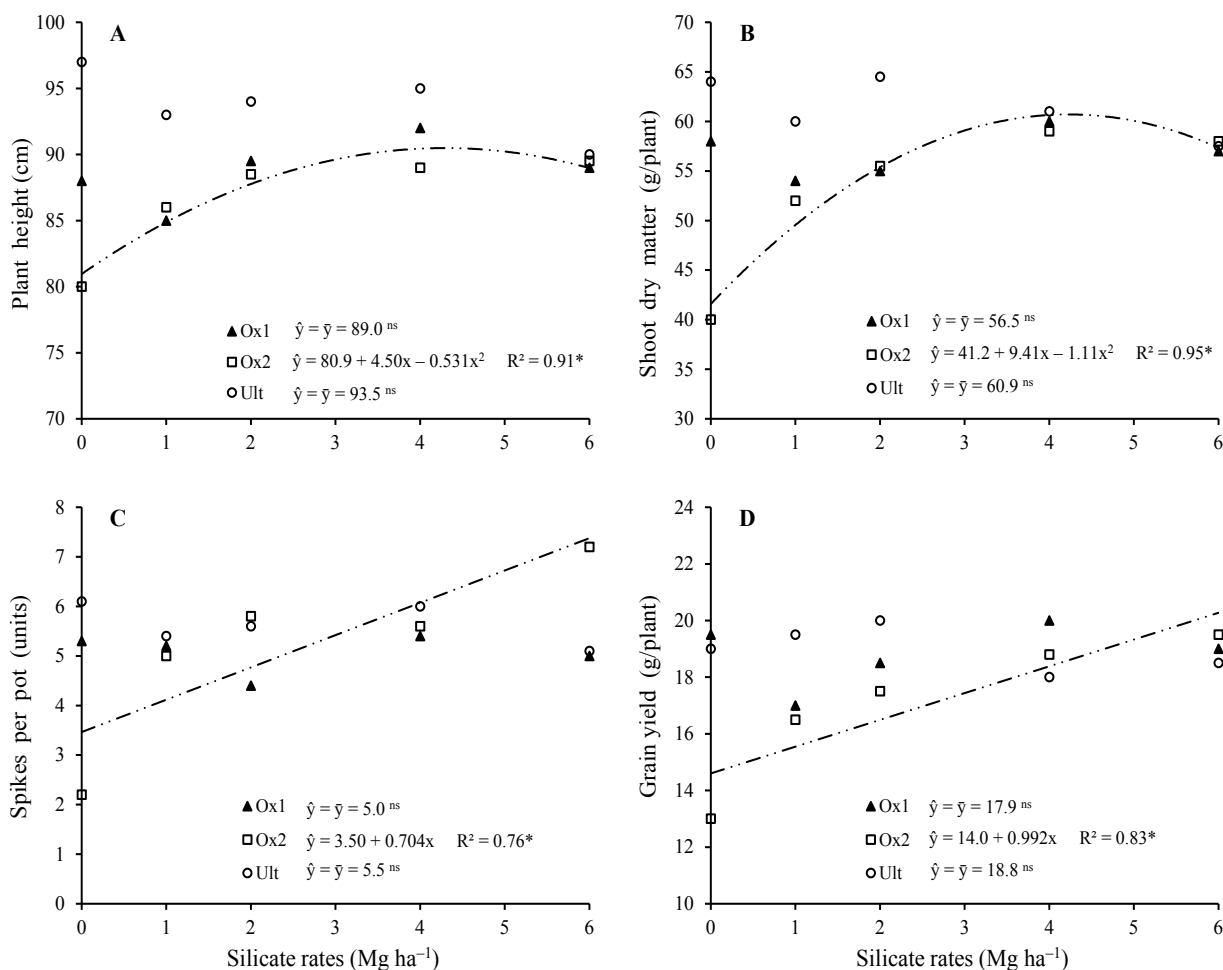
The increase of soil pH caused by increased rates of soil acidity correction reduces the availability of cationic micronutrients, such as Cu, Zn, Fe and Mn (PEGORARO et al., 2006). However, in this study the silicate application does not alter the availability of soil micronutrients. According to Prado et al. (2004), the controversial effects of silicate application on micronutrients availability in the soil can be attributed to variations resulting from the parent material and the process used by the steel industry, which influences the chemical composition of the acidity corrective.

Application of calcium/magnesium silicate improved the wheat development in the Ox2 soil (Figure 2), as can be seen by the increase in the plant height, shoot dry matter, number of spikes per pot and grain yield of wheat with increasing rates of calcium/magnesium silicate. The maximum plant height and shoot dry matter was 90.4 cm (Figures 2A) and 61.1 g/pot (Figures 2B), respectively, both obtained with the application of 4.2 Mg ha<sup>-1</sup> of silicate. The percentage of increase in the number of spikes per pot and grain yield of wheat was 120% and 42%, respectively, when comparing the

growing wheat plants with 0 (control) and 6 Mg ha<sup>-1</sup> of silicate (Figures 2C and 2D). The increase in the wheat development and yield was due to improve of soil chemical properties (Figure 1). This soil was initially acid and had low amounts of basic cations (Table 2). Aluminum (Al<sup>3+</sup>) toxicity and Ca deficiency are considered the main factors limiting

plant growth in acid soils, mainly by inhibiting root growth (STEINER et al., 2012). The damage to the root system results in exploration of a smaller volume of soil by the plants and losses in nutrient uptake and utilization of soil water and consequently the productive potential of plants (CHAFFAI et al., 2005).

**Figure 2.** Effects of silicate application in three soils of the western region of Paraná State on the plant height (A), shoot dry matter (B), number of spikes per pot (C) and grain yield (D). ns: not significant. \* and \*\*: statistical significance at 5% and 1%, respectively, by F test.



Beneficial effects of silicate application on wheat development and yield was expected as reported by Provance-Bowley et al. (2010), who found a 10% increase of wheat yield with silicate application. Silicate benefits in increased wheat yield is related

to improvement in soil properties and the Si effects on plant growth. Silicon positively influences plant growth and grain yield, especially monocotyledons, as a consequence of improved structural rigidity of the tissues, better angle of leaves and light

interception, improving photosynthetic rate (GONG; CHEN, 2012; MA; YAMAJI, 2008). According to Elawad et al. (1982) Si is involved in cell elongation and division processes as well as in hormone balance.

Silicate application did not affect plant height, shoot dry matter, number of spikes per pot and grain yield of wheat in the Ox1 and Ult soils (Figure 2). The results presented here are similar to those reported by Korndörfer et al. (2010) and Tokura et al. (2007); these authors found that the silicate application did not affect dry matter yield of *Brachiaria* grasses and rice, respectively. We can identify two basic factors for justify this lack of response to application of calcium/magnesium silicate: the first factor, is associated with high initial pH value of these soils (i.e., initial pH of 5.3 in the Ox1 and 6.2 in the Ult, Table 2). According to Fageria and Zimmermann (1998), the ideal soil pH for wheat growth is around 6.0. Therefore, the use of soil acidity corrective had little effect on improving of soil properties for growing wheat. The second factor related to the lack of response to silicate application is due to the high Si level in these soils at the beginning of the experiment (Table 2). According to Korndörfer et al. (1999b), when the levels of soil available Si extracted by 0.5 mol L<sup>-1</sup> acetic acid solution, are greater than 10.0 mg kg<sup>-1</sup> increased grain yield of grass species to the Si supply is unlikely. These values correspond to the critical Si level in the soil and are sufficient to achieve 90% of maximum grain yield. In general, the beneficial effects of silicate application are reported under biotic or abiotic stress conditions.

## Conclusions

Application of calcium/magnesium silicate reduces the potential acidity (H<sup>+</sup> + Al<sup>3+</sup>) and Al<sup>3+</sup> phytotoxic; and increases the soil pH, availability of Ca, Mg and Si, cation exchange capacity (CEC) and soil base saturation.

Silicate application did not alter the availability of P, K and cationic micronutrients in the soils.

The application of calcium/magnesium silicate in an acid clayey Rhodic Hapludox improves the development and yield of wheat; however, the silicate application in soils with pH higher to 5.3 and high Si availability does not affect the agronomic characteristics and grain yield of wheat.

## Acknowledgments

To CAPES (Coordination for the Improvement of Higher Education Personnel), for financial support and providing scholarship to the first author.

To CNPq (National Council for Scientific and Technological Development), for an award for excellence in research to the second author.

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