

Residual effects of superficial liming on tropical soil under no-tillage system

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Abstract – The objective of this work was to evaluate the long-term effects of the surface application of lime on soil fertility and on the mineral nutrition and grain yield of soybean, and of black oat and sorghum in crop succession. The experiment was carried out on a clayey Oxisol, in a randomized complete block design, with four replicates. Treatments consisted of lime the rates of 0, 1,000, 2,000, and 4,000 kg ha⁻¹, applied in October 2002 and November 2004. Soil samples were collected at five soil layers, down to 0.60-m depth. Surface liming was effective in reducing soil acidity and increasing Ca²⁺ and Mg²⁺ contents in the subsurface. Moreover, it increased available phosphorus contents and soil organic matter in the long term (48 to 60 months after the last lime application). Surface liming improved plant nutrition, mainly for N, Ca, and Mg, and increased dry matter production and grain yield of the crops, even in years with regular distribution of rainfall. The greatest productivities of soybean, black oat, and sorghum were obtained with the respective estimated lime doses of 4,000, 2,333, and 3,281 kg ha⁻¹, for shoot dry matter, and of 2,550, 3,555, and over 4,000 kg ha⁻¹, for grain yield.

Index terms: crop rotation, long-term experiment, plant nutrition, soil fertility, subsurface soil acidity, yield components.

Efeitos residuais da calagem superficial em solo tropical com plantio direto

Resumo – O objetivo deste trabalho foi avaliar os efeitos em longo prazo da aplicação superficial de calcário sobre a fertilidade do solo e sobre a nutrição mineral e a produtividade de soja, e de aveia-preta e sorgo em sucessão. O experimento foi realizado em Latossolo Vermelho argiloso, em delineamento de blocos ao acaso, com quatro repetições. Os tratamentos consistiram das doses de calcário de: 0, 1.000, 2.000 e 4.000 kg ha⁻¹, aplicadas em outubro de 2002 e novembro de 2004. Amostras de solos foram tiradas de cinco camadas do solo, até a profundidade de 0,60 m. A calagem superficial foi efetiva em reduzir a acidez do solo e elevar os teores de Ca⁺² e Mg⁺² em profundidade. Além disso, ela elevou os teores de fósforo disponível e de matéria orgânica do solo, em longo prazo (48 a 60 meses após a última calagem). A calagem superficial melhorou a nutrição das plantas, principalmente quanto a N, Ca e Mg, e aumentou a produção de matéria seca e a produtividade de grãos das culturas, mesmo em anos com distribuição regular de chuvas. As maiores produtividades de soja, aveia-preta e sorgo foram obtidas com as respectivas doses de calcário estimadas em 4.000, 2.333 e 3.281 kg ha⁻¹, para a matéria seca da parte aérea, e de 2.550, 3.555 e mais de 4.000 kg ha⁻¹, para a produção de grãos.

Termos para indexação: rotação de culturas, experimentos de longa duração, nutrição de plantas, fertilidade do solo, acidez subsuperficial do solo, componentes da produção.

Introduction

Sustainable agricultural systems should avoid leaving the fields unplanted and the soils exposed, during the autumn-winter period, in the Brazilian Southeast Region agricultural off-season. In this period, the irregular distribution of rain and low rainfalls are the main factors that affect shoot dry matter production and yield of annual crops. Thus,

studies of techniques and crops that are well suited to these conditions are important to enable cultivation during water-deficit periods (Soratto & Crusciol, 2008c, 2008d).

Soybean [*Glycine max* (L.) Merrill] is one of the most widespread summer crops in the Brazilian Cerrado region. Because of its great economic importance, this crop has been successively cultivated even more often, causing crop rotation schemes to become overly

simplified. Black oat (*Avena strigosa* Schreber) and sorghum (*Sorghum bicolor*) are attractive succession crops for soybean, due to their relative tolerance to limited water availability.

Low pH values and low base saturation levels in tropical soils can affect root growth and water and nutrient uptake, especially in dry winter regions. Superficial liming is commonly used to reduce soil acidity in no-till (NT). This technique rapidly reduces the acidity on soil surface, but its effects at deeper layers are slow, particularly in soils with variable charges (Ernani et al., 2004). Lime movement through the soil varies with soil type and structure, intrinsic characteristics of the product, climatic conditions, acid fertilizer management, and crop systems (Ernani et al., 2004; Caires et al., 2005).

In subtropical regions of Brazil, where rainfall is well distributed throughout the year, there are several reports of a lack crop response to the lime application in no-till systems (Caires et al., 2006b, 2008a, 2008b, 2011). These findings have been attributed to a greater accumulation of organic matter and nutrients on the soil surface, which reduces the activity of Al by forming Al-organic complexes, and by increasing ionic strength of soil solution (Nolla & Anghinoni, 2006; Vieira et al., 2009). However, in the majority of the Cerrado biome, in Brazil, mainly in the areas with dry winter, increases of grain yield and fiber production are expected with lime application in no-till systems, even if it is done on the soil surface, unlike what has been observed elsewhere in the subtropical region. This possibility exists because, in these regions, the majority of cultivated areas have a low organic matter content and low amount of crop residues left on the soil surface, leading, respectively, to low water storage and high evaporation.

Superficial application of correctives can reduce soil acidity and improve nutrient availability (Caires et al., 2005; Soratto & Crusciol, 2008a, 2008b, 2008c, 2008d), which is reflected in increased biomass production, nutrient accumulation, and grain yield (Castro & Crusciol, 2013a), even in crops considered tolerant to water stress, such as black oat and sorghum. However, it should be emphasized that few studies have investigated the long-term effects (more than nine years) of superficial limestone application on soil chemical properties, and the response of black oat and sorghum in a tropical NT system with dry winter.

The objective of this work was to evaluate the long-term effects of the surface application of lime on soil fertility and on the mineral nutrition and grain yield of soybean, and of black oat and sorghum in crop succession.

Materials and Methods

The experiment was carried out at Lageado Experimental Farm, of the Universidade Estadual Paulista, in Botucatu, SP, Brazil (48°23' W, 22°51' S, at 765 m altitude). The soil in the area is a deep, acidic, clayey Oxisol. The climate is Cwa – tropical, with a dry winter and hot, rainy summer –, according to the classification of Köppen-Geiger. During the experiment, monthly averages for rainfall and temperatures were, in December 2008, 137 mm and 22.7°C, respectively; and in 2009, they were, respectively, as follows: 263 mm and 22.6°C, in January; 97 mm and 23.4°C, in February; 60 mm and 22.9°C, in March; 161 mm and 21.2°C, in April; 70 mm and 18.3°C, in May; 16 mm and 17.9°C, in June; 3 mm and 19.2°C, in July; 101 mm and 20.3°C, in August; 75 mm and 20.4°C, in September; 118 mm and 22.3°C, in October; 59 mm and 22.3°C, in November; 343 mm and 22.5°C, in December; and 2010: 180 mm and 22.5°C, in January; and 108 mm and 23.5°C, in February.

The research has been conducted since 2002, maintaining the same treatments of lime in an NT crop rotation. In 2002/2003, 2003/2004, 2004/2005, 2005/2006, 2006/2007, 2007/2008, 2008/2009, and 2009/2010, the following main and second crops were respectively grown: rice/oat, common bean/oat, peanut/oat, peanut/oat, corn intercropped with *Urochloa* grass, corn intercropped with *Urochloa* grass, soybean/black oat, and soybean/grain sorghum.

Topsoil (0.0–0.2 m) chemical characteristics were determined (Table 1) at the beginning of the experiment (October 2002), and before the last lime application (August 2004). On October 15, 2002, lime treatments were applied superficially. The last application was on November 19, 2004, based on the soil analysis carried out in August 2004.

A randomized complete block design was carried out with four replicates. The plot dimensions were 5.4x9.0 m. The treatments consisted of following four lime rates: necessary dose to raise the base saturation to 70%, which is the recommended rate (2,000 kg ha⁻¹),

according to Raji et al. (1997); half of the recommended rate (1,000 kg ha⁻¹); double of the recommended rate (4,000 kg ha⁻¹); and a control without liming. Dolomitic limestone was applied with the following composition: 23.3% CaO, 17.5% MgO, and 71% effective calcium carbonate equivalence (ECCE). In the physical analysis of the dolomitic limestone, 68.8, 92.4, and 99.7% of particles passed 50, 20, and 10 mesh sieves, respectively.

Soybean [*Glycine max* (L.) Merrill] was sown on December 11, 2008, and on October 29, 2009, using the cultivars MG/BR 46 Conquista and CD 216, respectively. The row spacing used was 0.45 m, and the seed rates were approximately 22 seeds m⁻¹. The base fertilization consisted of 250 kg ha⁻¹ of 04-20-20 N-P₂O₅-K₂O formula, according to the results of soil chemical analysis and soybean crop recommendations (Raji et al., 1997). Harvesting was performed on April 24, 2009, and on February 24, 2010. Samples were taken for determining yield components (plant population, number of pods per plant, number of grains per pod, and 100-grain weight) and final yield (130 g kg⁻¹ moisture content).

Black oat (*Avena strigosa* Schreb.) and sorghum [*Sorghum bicolor* (L.) Moench] were sown on June 22, 2009, and on March 08, 2010, using the variety "comum" and the hybrid AG 1020, respectively. The row spacings were 0.17 m and 0.60 m, with seed rates at 60 kg ha⁻¹ and 18 seeds m⁻¹, respectively. Black oat and sorghum were harvested on October 19, 2009, and July 21, 2010, respectively. Samples were taken for determining yield components as follows: for both black oat and sorghum, grain yield (130 g kg⁻¹ moisture content); for black oat, panicles per square meter, spikelets per panicle, and 1,000-grain weight;

and for sorghum, panicles per square meter, grains per panicle, 1,000-grain weight.

Soil samples were collected after 48 and 60 months from lime reapplication (August 2004), at 0.0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.40, and 0.40–0.60 m soil depths. Seven subsamples were taken randomly from each plot, between the rows, and combined into one composite sample. Soil pH was determined in a 0.01 mol L⁻¹ CaCl₂ suspension (1:2.5 soil/solution). Total acidity in pH 7.0 (H + Al) was estimated with the SMP-buffer solution method (Raji et al., 1997). Exchangeable Al was extracted with neutral 1 mol 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 and Mg were extracted with ion-exchange resin, and determined by atomic absorption spectrophotometry. Base saturation values were calculated using the results of exchangeable bases and total acidity at pH 7.0 (H + Al) (Raji et al., 1997).

Growing season means (only for soybean plant results) were compared using Fisher's protected LSD test at 5% probability. The dolomitic limestone rates were analysed using regression analysis, testing regression coefficients significant at 5% probability with the t-test.

Results and Discussion

The sampling carried out 48 months after the last surface liming exhibited linear increase of soil pH, and reduction of potential acidity (H + Al), at all depths. These effects were also observed after 60 months, but only up to 0.40 and 0.20 m soil depths, respectively (Figure 1). Lower pH values were observed in the latter sampling, compared to the previous one. Reductions of Al³⁺ levels were observed up to 0.20 m soil depth, at both samplings.

Those last reductions can be partly explained by the fact that the area was maintained in an NT system since 2002, and by the higher soil organic matter contents (Figure 1) and Ca²⁺ concentration (Figure 2) derived from lime which may have acted in the formation of complexes of Al³⁺ with clay and organic matter through the cation bridge (Bronick & Lal, 2005). These complexes also contribute to the improvement of soil aggregation and aggregate stability (Briedis et al., 2012). Moreover, low disturbance in NT also favors the maintenance or formation of channels by biological

Table 1. Soil chemical characteristics before the experiment (October 2002), and before the last lime application (August 2004).

Soil depth (m)	pH CaCl ₂	SOM	P _{resin}	H+Al	Al	K	Ca	Mg	CEC	BS (%)
----- (mmol _c dm ⁻³) -----										
October 2002										
0.0–0.2	4.2	21	9	37	6.5	1.2	14	5	58	37
August 2004										
0.0–0.2	4.9	27	35	35	2.3	1.1	24	10	70	50

SOM, soil organic matter (g dm⁻³); P-resin (mg dm⁻³).

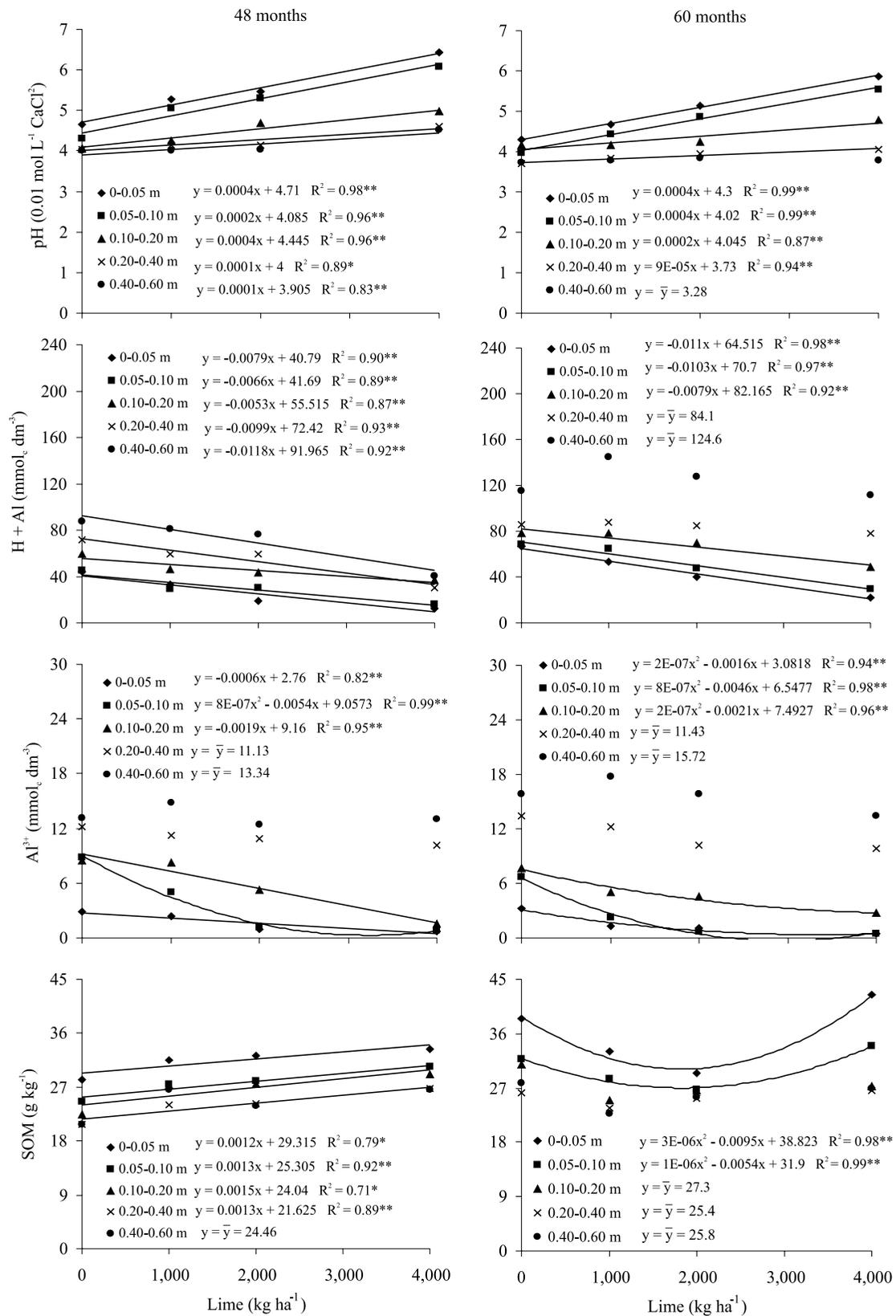


Figure 1. Effects of superficial liming on pH, soil organic matter (SOM), H + Al, and Al³⁺, after 48 and 60 months from the last lime application, at different soil depths. *, **Significant at 1 and 5% probability, respectively.

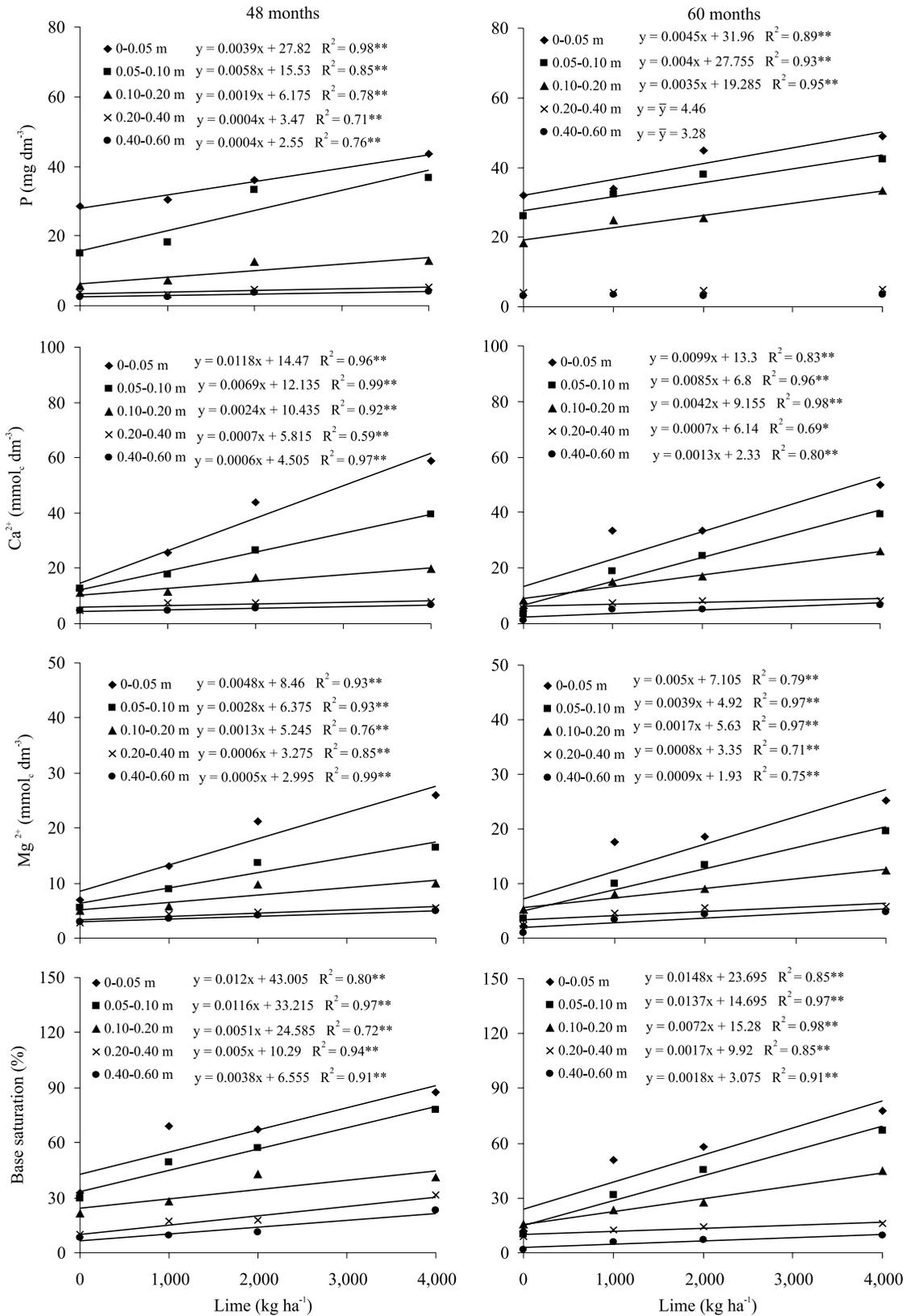


Figure 2. Effects of superficial liming on the availability of P, Ca, and Mg in the soil, and on base saturation, after 48 and 60 months from the last lime application, at different soil depths. *, **Significant at 1 and 5% probability, respectively.

activity, which is considered an important route for the physical movement of corrective particles along with downward water movement, which makes the carbonate reaction possible at higher depths (Corrêa et al., 2009).

The pH increase on soil surface due to superficial liming can accelerate the rate at which HCO_3^- ions, followed by Ca^{2+} and Mg^{2+} , move into the subsoil to react with acidity, an effect known as an “alkalizing front” (Caires et al., 2005, 2008b, 2008c, 2011; Soratto & Crusciol, 2008a). In addition, the high amount of plant residues left on soil surface in no-till systems can mobilize cations and increase the mobility of surface-applied lime, due to the release of low molecular-weight organic acids from the soluble fraction of residues (Pavan & Roth, 1992; Oliveira & Pavan, 1996; Miyazawa et al., 2002; Franchini et al., 2003). In this context, the Ca-fulvate complex stands out, since it is very stable and Ca^{2+} release occurs very slowly while the complex is transported downwards into the soil profile (Watt et al., 1991). Irrespective of the mechanism involved, it is evident that the already established surface liming in NT is effective to reduce the soil acidity in depth.

Soil acidity increased over time, which can be attributed to the maximum limestone reaction within 48 months (Figure 1). Ciotta et al. (2002) also reported soil acidification in NT system, and related this result to ammonium nitrification process from fertilizers. Several studies have shown that the maximum duration time of liming on soil surface is variable, with representative values including 48 months, in a dystrophic Ultisol with medium texture (Rheinheimer et al., 2000), and 18 months in a clayey Oxisol (Soratto & Crusciol, 2008a, 2008b).

At 48 months after liming, soil organic matter levels increased linearly up to 0.40 m soil depth (Figure 1), which is related to the increased dry matter production of shoots and roots of the preceding crop (maize). After 60 months, this effect was limited to 0.10 m (Figure 1), which corresponds to lower dry matter production of shoots and roots by soybean and black oat. A clear accumulation of soil organic matter occurs in the long run. However, it is dependent on the plant species used in the crop rotation; therefore, the use of plants with different root systems and inputs of shoot dry matter should be prioritized.

Liming caused linear increase of P, Ca^{2+} , and Mg^{2+} levels at all depths, after 48 months; most of these were significant up to 0.20 m soil depth (Figure 2). After 60 months, similar effects of liming were observed, but P level trend was restricted to 0.20 m depth. Greater P levels can be attributed to the reduced P adsorption, due to the increasing soil pH (Figure 1), and to the following increased solubility of iron and aluminium phosphates (Souza et al., 2006). Thus, the annual P addition by fertilization increases P availability, as lime reduces the force with which the element is retained in the soil. Similar results were observed by Castro & Crusciol (2013a).

Ca^{2+} and Mg^{2+} increased proportionally to the applied dose (Figure 2), as lime is a source of these nutrients. Several authors reported an increase of the exchangeable Ca^{2+} in the soil from lime surface application (Caires et al., 2005, 2006b, 2006c, 2006d, 2008a, 2008b, 2008c; Soratto & Crusciol, 2008a). It is noteworthy that the increase of these nutrients in the subsurface layers may be related to the formation of inorganic ion pairs with NO_3^- , HCO_3^- , OH^- (Rheinheimer et al., 2000), Cl^- , and SO_4^{2-} (Caires et al., 2006a) from mineral fertilizers or plant residues.

There was a slight decrease of Ca^{2+} and Mg^{2+} levels over time, similarly to what was observed in pH values (Figure 1). These reductions can be attributed to the extraction of the elements by previous crops. Soratto & Crusciol (2008a) also observed a reduction in the exchangeable Ca^{2+} levels over time following superficial liming, especially in the surface layers.

Base saturation increased linearly with lime doses throughout the soil profile (Figure 2). This effect in the subsurface shows the technical viability of this practice in cultivated tropical soils under NT.

There was no significant interaction between treatments and years, for none of the nutrients evaluated on soybean leaves (Table 2). Concentrations of P and Fe were not influenced by liming; and concentrations of N, or Zn^{2+} , or Mn^{3+} were not influenced by year. The highest P, K^+ , Ca^{2+} , Mg^{2+} , S, Cu^{2+} , and Fe^{3+} concentrations were observed in 2008/2009 (Table 2), which is in accordance with the high nutrient levels in the previous soil sampling (48 months).

Nitrogen concentrations, increased by liming in soybean and sorghum leaves (Table 3), showed their beneficial effects of this practice on symbiotic N_2 fixation process and on soil nitrate availability. The

symbiotic efficiency of N₂ fixation is associated with the higher availability of Mo and less Mn³⁺, due to the reduction of soil acidity, which can also increase nitrate availability, since the nitrification activity can increase up to 5-fold with increasing pH values (Islam et al., 2006).

No effects of lime were observed on nutrient levels in oat leaves, which was also reported by other authors for white oat (Castro & Crusciol, 2013a) and black oat (Soratto & Crusciol, 2008d).

Superficial liming positively influenced Ca²⁺ and Mg²⁺ uptake, as observed for soybean, sorghum, and black oat, in established NT systems (Table 3). These results corroborate those obtained by Castro & Crusciol (2013a, 2013b) for several crops. These results had a direct effect on potassium uptake by soybean and sorghum, which shows an antagonist effect between the nutrients, as they compete for the same uptake sites. Similar results were observed by Caires et al. (2002) in corn, but without consequence for grain yield.

Liming increased P uptake by sorghum (Table 3), and this agrees with the increased levels of P in the soil after the correction of soil acidity (Figure 2). The

greater uptake of S by soybean and sorghum after liming may be a consequence of adsorbed sulphate release due to the increase of the topsoil pH (Caires et al., 1999), or to the greater mineralization of organic S.

Micronutrient concentrations in the leaves of soybean (Cu²⁺, Zn²⁺ and Mn³⁺), black oat (Mn³⁺ and Fe³⁺), and sorghum (Mn³⁺) were also reduced with liming (Table 3). The pH increase after liming especially reduces the availability of cationic micronutrients in the soil (Malavolta et al., 1997). Sávio et al. (2011) also reported reductions of Zn²⁺ and Mn³⁺ contents in soybean leaves, under NT with increased soil pH.

There was no significant interaction between the factors for soybean yield components (Table 2). In 2008/2009, shoot dry matter yield, plant population, and 100-seed weight were higher than in 2009/2010; however, in 2009/2010, a higher number of grains per pod resulted in higher grain yield. Soybean yield was higher in 2009/2010, due to the larger number of grains per pod, which is a characteristic of the selected cultivar (CD 216).

Table 2. Nutrient content in leaves, shoot dry matter yield, yield components, and grain yield of soybean, black oat, and sorghum, followed by the significance values of the F test from the analysis of variance.

Factor	N	P	K	Ca	Mg	S	Cu	Zn	Mn	Fe	Shoot DM (kg ha ⁻¹)	Yield Component			100-grain weight (g)	Grain yield (kg ha ⁻¹)
												1	2	3		
Soybean																
Year																
2008/2009	44*	4.8*	29.8*	21.4*	6.7*	3.3*	16.4*	73*	132*	218*	4,222*	258*	38.0*	2.0*	18.0*	3,000*
2009/2010	43	4.6	24.9	20.6	6.1	2.3	12.0	69	123	178	3,412	218	37.9	2.9	15.4	3,277
F significance																
Block	0.101	0.656	0.206	0.644	0.053	0.443	0.4789	0.144	0.062	0.549	0.120	0.959	0.848	0.442	0.105	0.376
Lime (L)	<0.001	0.055	0.0079	<0.001	0.002	<0.001	0.0048	<0.001	<0.001	0.073	<0.001	0.067	<0.001	0.085	<0.001	<0.001
Year (Y)	0.098	0.021	<0.001	0.028	0.001	<0.001	0.0050	0.075	0.503	0.001	<0.001	<0.001	0.951	<0.001	<0.001	<0.001
L x Y	0.086	0.367	0.240	0.091	0.102	0.085	0.0905	0.109	0.992	0.111	0.220	0.389	0.510	0.085	0.067	0.086
Black oat																
Year																
2009	18.7	3.9	30.1	15.6	5.1	2.3	13.1	54	211	141	5,122	171	48	82	1.89	1,221
F significance																
Block	0.160	0.981	0.777	0.090	0.275	0.932	0.116	0.1952	0.104	0.999	0.984	0.985	0.122	0.119	0.838	0.991
Lime	0.142	0.655	0.659	<0.001	<0.001	0.635	0.126	0.619	<0.001	0.002	<0.001	<0.001	0.153	0.445	0.747	<0.001
Sorghum																
Year																
2010	28.7	3.9	17.3	9.3	4.1	7.7	9.9	42	36	322	3547	14.8	183	-	3.57	1017
F significance																
Block	0.111	0.186	0.998	0.999	0.968	0.056	0.999	0.2414	0.980	0.9122	0.530	0.965	0.788	-	0.853	0.963
Lime	0.004	<0.001	<0.001	0.001	0.063	<0.001	0.220	0.1239	0.001	0.3574	<0.001	<0.001	<0.001	-	0.144	<0.001

*Significant differences for year means, by the t test, at 5% probability. Yield component 1: population, for soybean; panicles per square meter, for black oat and sorghum. Yield component 2: pods per plant, for soybean; spikelets per panicle, for black oat; and grains per panicle, for sorghum. Yield component 3: grains per pod, for soybean; and spikelet fertility, for black oat.

Surface lime application increased shoot dry matter yield of soybean, black oat, and sorghum, with the greatest values of lime estimated doses at 4,000, 2,333, and, 3,281 kg ha⁻¹ (Table 3). These maximum values were near to those reported by other authors for soybean (Caires & Fonseca, 2000), black oat (Soratto & Crusciol, 2008d), and sorghum (Barbosa et al., 2008).

Liming increased soybean plant population and 100-seed weight, with direct impact on grain yield (Table 3). The highest grain yield (3,400 kg ha⁻¹) – 21% higher than that of the control plot – was achieved with 2,550 kg ha⁻¹ estimated lime dose. For black oat, only the number of panicles per square meter was influenced by liming (Table 2), which had a quadratic

effect (Table 3). This component positively impacted grain yield, with the highest yield (1,480 kg ha⁻¹) – 61% higher than that of the control – obtained with 3,555 kg ha⁻¹ lime estimated dose.

Surface liming did not influence the 1,000-seed weight of sorghum (Table 2), but the number of panicles per square meter and grains per panicle of sorghum quadratically increased with liming (Table 3), which reflected on grain yield; however, the maximum productivity was not achieved with the studied doses. It is noteworthy that the low temperatures during the initial development of sorghum extended the vegetative period, and flowering occurred at a time of low water availability (mid-May 2010), which increased the flower sterility.

Table 3. Regression equations, and coefficients of determination, between different factors and lime rates.

Factor	Lime rates (kg ha ⁻¹)				Regression	R ²
	0	1,000	2,000	4,000		
Soybean						
N (g kg ⁻¹)	40.6	42.6	43.5	46.3	y = 0.0014x + 40.875	0.98
K (g kg ⁻¹)	28.1	28.0	27.6	25.7	y = -0.0006x + 28.455	0.90
Ca (g kg ⁻¹)	17.9	21.1	22.0	22.9	y = -0.0000005x ² + 0.0031x + 18.045	0.97
Mg (g kg ⁻¹)	6.0	6.5	6.8	6.3	y = -0.0000002x ² + 0.0007x + 5.9932	0.99
S (g kg ⁻¹)	2.5	3.3	2.9	2.5	y = -0.0000001x ² + 0.0005x + 2.6023	0.67
Cu (mg kg ⁻¹)	18.4	15.1	12.3	11.0	y = -0.0018x + 17.325	0.87
Zn (mg kg ⁻¹)	93.8	71.6	67.1	51.1	y = 0.000002x ² - 0.0181x + 92.117	0.96
Mn (mg kg ⁻¹)	193.9	140.8	94.4	79.9	y = 0.00001x ² - 0.0689x + 195.46	0.99
Shoot dry matter (kg ha ⁻¹)	3143	3873	4173	4078	y = -0.0001x ² + 0.8179x + 3,159.9	0.99
Population (x1000 ha ⁻¹)	222.0	247.0	251.0	232.0	y = -0.000006x ² + 0.0278x + 222.98	0.97
Pods per pod	35.1	37.4	37.3	42.1	y = 0.0017x + 35.05	0.92
100-grain weight (g)	16.0	16.6	17.4	16.9	y = -0.0000002x ² + 0.0011x + 15.935	0.95
Grain yield (kg ha ⁻¹)	2771	3350	3254	3181	y = -0.00009x ² + 0.459x + 2829	0.78
Black oat						
Ca (g kg ⁻¹)	10.6	15.4	13.0	23.4	y = 0.0029x + 10.454	0.82
Mg (g kg ⁻¹)	4.6	4.9	5.4	5.4	y = -0.00000008x ² + 0.0005x + 4.5913	0.92
Mn (mg kg ⁻¹)	258.8	242.4	195.0	150.1	y = -0.0284x + 261.23	0.97
Fe (mg kg ⁻¹)	173.1	153.4	110.0	128.7	y = 0.000008x ² - 0.0456x + 177.93	0.88
Shoot dry matter (kg ha ⁻¹)	4632	4897	5856	5103	y = -0.0002x ² + 0.9332x + 4502.5	0.75
Panicles per square meter	137.5	166.5	215.8	165.8	y = -0.00001x ² + 0.0636x + 131.79	0.87
Grain yield (kg ha ⁻¹)	960	1113	1476	1339	y = -0.00006x ² + 0.3667x + 919.26	0.87
Sorghum						
N (g kg ⁻¹)	27.2	28.3	28.8	30.7	y = 0.0009x + 27.26	0.98
P (g kg ⁻¹)	3.9	3.7	4.0	4.1	y = 0.00007x + 3.8	0.51
K (g kg ⁻¹)	18.0	18.4	17.9	15.2	y = -0.0008x + 18.7	0.77
Ca (g kg ⁻¹)	9.4	10.7	11.2	11.8	y = 0.0006x + 9.8	0.87
S (g kg ⁻¹)	1.8	2.0	2.7	2.7	y = -0.00000008x ² + 0.0006x + 1.7209	0.88
Mn (mg kg ⁻¹)	41.0	34.0	34.0	32.0	y = -0.0019x + 38.6	0.69
Shoot dry matter (kg ha ⁻¹)	1513	3788	4084	4804	y = -0.0003x ² + 1.9688x + 1678.4	0.94
Panicles per square meter	11.0	13.7	17.2	17.4	y = -0.0000006x ² + 0.0043x + 10.749	0.98
Grains per panicle	11.0	116.0	245.0	360.0	y = -0.00001x ² + 0.1389x + 5.1364	0.99
Grain yield (kg ha ⁻¹)	45	602	1452	1968	y = -0.00009x ² + 0.8512x - 11.264	0.98

Grain yield showed the same pattern observed for yield components, with high correlations ($p < 0.01$) in soybean (100-seed weight, $r = 0.62$), black oat (panicles per square meter, $r = 0.91$), and sorghum (panicles per square meter, $r = 0.78$; and grains per panicle, $r = 0.98$) (Table 3). Similar results were observed by Sávio et al. (2011), for soybean, and Soratto & Crusciol (2008d), for black oat.

It is noteworthy that grain production in the subtropical region does not always benefit from liming, particularly under water deficiency. This highlights the importance of the results reported here, in the tropical region, where liming always benefited grain production, even in years with regular rainfall distribution.

Conclusions

1. Surface liming is effective for reducing soil acidity and for increasing soil organic matter and P, Ca^{+2} , and Mg^{+2} contents on the subsurface.

2. Surface liming improves plant nutrition, especially of N, Ca^{+2} , and Mg^{+2} ; and it increases dry matter production and productivity of the evaluated crops, even in years with regular distribution of rainfall.

3. The reduction of limestone rates is not recommended, even in areas with great accumulation of soil organic matter.

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