SOIL ACIDITY, LIMING AND SOYBEAN PERFORMANCE UNDER NO-TILL

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ABSTRACT: The effects of soil chemical changes on soybean root growth, mineral nutrition and grain yield, as a result of surface application of lime under no-till (NT), are still under discussion. A field trial was carried out on a loamy dystrophic Typic Hapludox at Ponta Grossa, Paraná State, Brazil, using a completely randomized block design with three replicates, in a split-plot experiment. The main plots received four dolomitic lime rates applied on the surface (0, 2, 4, and 6 Mg ha^{-1}) in July 1993. In the subplots, two dolomitic lime rates were reapplied on the surface (0 and 3 Mg ha^{-1}) in June 2000. After nine years, liming increased pH, exchangeable Ca^{2+} and reduced exchangeable Al^{3+} as well as soil Al^{3+} saturation down to a 60 cm depth. Re-liming, after two years, also provided soil acidity amelioration to a 60 cm depth. Soybean total root length per soil surface area (0–60 cm) decreased with the surface lime application under NT. The reduction in soil exchangeable Al^{3+} with liming did not change Al concentrations in the soybean roots and leaves. Surface-applied dolomitic lime under NT brought an increase in Ca and Mg concentrations and a decrease in the Mn level in both soybean roots and leaves. Soybean grain yield was not influenced by surface liming because of the decreased Al toxicity and because root growth was stimulated by soil acidity stress under NT.
Key words: *Glycine max* (L.) Merrill, acidity, subsoil, root system, nutrient

ACIDEZ DO SOLO, CALAGEM E COMPORTAMENTO DA SOJA CULTIVADA EM PLANTIO DIRETO

RESUMO: Os efeitos das alterações químicas do solo ocasionadas pela aplicação superficial de calcário no crescimento radicular, na nutrição mineral e na produção de grãos de soja cultivada em sistema plantio direto são pouco conhecidos e foram estudados no presente trabalho. O experimento foi realizado em um Latossolo Vermelho distrófico textura média, em Ponta Grossa (PR). O delineamento experimental empregado foi o de blocos completos ao acaso em parcelas subdivididas, com três repetições. As parcelas receberam quatro doses de calcário dolomítico na superfície (0, 2, 4 e 6 Mg ha^{-1}), em julho de 1993, e, nas subparcelas, foram reaplicadas duas doses de calcário dolomítico na superfície (0 e 3 Mg ha^{-1}), em junho de 2000. A calagem, após nove anos, aumentou o pH e o Ca^{2+} trocável e reduziu o Al^{3+} trocável e a saturação por alumínio do solo, até a profundidade de 60 cm. A reaplicação de calcário, após dois anos, também proporcionou melhoria nas condições de acidez do solo até a profundidade de 60 cm. O comprimento total de raízes de soja por unidade de área superficial de solo (0–60 cm) foi reduzido com a calagem na superfície em plantio direto. A redução de Al^{3+} trocável no solo com a calagem não alterou as concentrações de Al nas raízes e nas folhas de soja. O calcário dolomítico aplicado na superfície em plantio direto aumentou as concentrações de Ca e Mg e reduziu o teor de Mn nas raízes e nas folhas de soja. A produção de grãos de soja não foi influenciada pela calagem na superfície por causa da baixa toxicidade do Al e ainda porque o crescimento radicular foi estimulado por condições de stress de acidez do solo no sistema plantio direto.
Palavras-chave: *Glicyne max* (L.) Merrill, acidez, subsolo, sistema radicular, nutrientes

INTRODUCTION

Brazilian soils are, on its majority, acidic with Al and Mn toxic levels, low base saturation and low P content (Olmos & Camargo, 1976). Under such conditions crop root growth is restricted, causing lower water and nutrient uptake, affecting aerial development (Pavan et al., 1982; Ritchey et al., 1982) and leading towards lower grain production.

Soil acidity problems are commonly corrected by applying limestone. To control soil acidity under no-till (NT), lime is broadcast on the surface without incorporation. Surface liming ameliorates topsoil acidity in a relatively short term, but is generally slow in ameliorating subsoil acidity, particularly in variable charge soils (Ernani et al., 2004). The movement of lime to greater depths varies according to the timing and rate of liming, soil type, surface soil pH, weather conditions, management of acidic fertilizers, and cropping systems (Oliveira & Pavan, 1996; Gascho & Parker, 2001; Conyers et al., 2003; Ernani et al., 2004; Alleoni et al., 2005; Caires et al., 2005).

Field studies have attested high soybean yield in acid soils under NT (Caires et al., 1998, 1999, 2003, 2006a; Pöttker & Ben, 1998; Moreira et al., 2001), but the causes still remain unclear. The explanations for this have been associated to decreased Al toxicity through the formation of Al-organic complexes (Salet et al., 1999; Nolla & Anghinoni, 2006), sufficient availability of exchangeable Ca^{2+} and Mg^{2+} (Caires et al., 1998), and adequate nutrient uptake by the crop due to higher soil water availability (Caires & Fonseca, 2000). However, soil acidity limited wheat root growth and yield severely under NT, probably as a result of extended water deficits during the vegetative stage (Caires et al., 2006b).

This study evaluated the effects of amelioration of topsoil and subsoil acidity by surface liming and re-liming in a NT system on root growth, nutrient and Al concentrations in roots and leaves, and grain yield of soybean grown without rainfall limitation.

MATERIAL AND METHODS

The experiment was carried out in Ponta Grossa, State of Paraná (PR), Brazil (25º10'S, 50º05'W), on a loamy dystrophic Typic Hapludox. At the beginning of the experiment, soil chemical and texture analyses of the 0-20 cm layer presented the following results: pH (1:2.5 soil: 0.01 mol L^{-1} $CaCl_2$ suspension) of 4.5; exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, and K^{+} contents of 6, 16, 10, and 1.4 mmolc dm^{-3}, respectively; total acidity pH 7.0 (H + Al) of 58 mmolc dm^{-3}; P (Mehlich-1) of 9.0 mg dm^{-3}; total organic matter of 33 g dm^{-3}; base saturation of 32%; Al^{3+} saturation of 18%; and 295, 240, and 465 g kg^{-1} of clay, silt, and sand, respectively. Prior to the establishment of the experiment, the field site had been used for grain cropping under NT cultivation during 15 years.

A randomized complete block design was used, with three replications in a split-plot arrangement. The main plots (8.0 m × 6.3 m) consisted of surface dolomitic lime application at the rates of 0, 2, 4, and 6 Mg ha^{-1}. The lime rates were calculated to raise the base saturation of the topsoil (0–20 cm) to 50, 70, and 90%. The dolomitic lime used contained 176 g kg^{-1} Ca, 136 g kg^{-1} Mg, and 84% effective calcium carbonate equivalent (ECCE), and was broadcast on the soil surface in July 1993. In June 2000, the main plots were divided in two subplots (4.0 m × 6.3 m) for the study of surface re-liming influence (196 g kg^{-1} Ca, 130 g kg^{-1} Mg, and 90% ECCE) at the rates of 0 and 3 Mg ha^{-1}. The reapplied rate was calculated to raise the base saturation in the topsoil (0–20 cm) to 65% (Caires et al., 2000) of the treatment 4 Mg ha^{-1} of lime made in July 1993 (pH 0.01 mol L^{-1} $CaCl_2$ of 4.6; CEC pH 7.0 of 110.8 mmolc dm^{-3}; and 41% of base saturation). More details about the experimental area and cropping history are reported in Caires et al. (2006b).

Soybean, cv. CD 206, was sown on November 21st, 2001 and November 12th, 2002, after growing black oats during the autumn-winter season, at a seeding rate of 16 seeds m^{-1} and row spacing of 0.45 m. Seeds were inoculated with selected kinds of *Bradyrhizobium japonicum*. Fertilizers were applied at the rates of 220 kg ha^{-1} of 2–20–20 and 0–25–25 (N–P_2O_5–K_2O), on the first and the second sowings, respectively. During the development cycle of the soybean crop, rainfall was 770 mm in 2001–2002 and 880 mm in 2002–2003, well-distributed over both years. The average air temperature of both soybean cropping seasons was of 22°C.

Samples of soybean leaves and roots were collected at the beginning of flowering. The third leaf from the apices of the plants was collected from 30 plants of each subplot. Samples of roots were collected by means of a sampling tube of 3.5 cm diameter, at the depths of 0–10, 10–20, and 20–60 cm. Six subsamples of roots (three from the sowing row and three between rows) were taken in the subplot to form a composite sample. The roots were separated from the soil by dispersion in water using a 0.5 mm mesh sieve. Root length was estimated by the method of Tennant (1975), in a 1 × 1 cm grid. The concentrations of N, P, K, Ca, Mg, S, Zn, Mn, and Al in soybean leaves and roots were analyzed through the methods described by Malavolta et al. (1997). After maturation, the soybean grain was harvested from 6.75 m^2 plots (middle six rows of 2.5 m length). Grain yield was expressed at the 130 g kg^{-1} moisture content.

Soil samples were taken after soybean harvest in 2002 with a tubular probe sampler. Twelve soil core samples per subplot were taken to constitute a composite sample at 0–5, 5–10, and 10–20 cm depths, and five cores at 20–40, and 40–60 cm depths. Soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil/solution, v/v). Exchangeable Al^{3+}, Ca^{2+}, and Mg^{2+} were extracted with neutral 1 mol L^{-1} KCl, and K^{+} with double acid (Mehlich–1), in a 1:10 (v/v) soil/solution ratio, according to standard methods (Pavan et al., 1992). Exchangeable Al^{3+} (KCl-exchangeable acidity) was determined by titrating with 0.025 mol L^{-1} NaOH; Ca^{2+} and Mg^{2+} by titrating with 0.025 mol L^{-1} EDTA; and K^+ by flame photometry. The effective cation exchange capacity (ECEC) was calculated by summation of exchangeable cations, and the aluminum saturation as: Al^{3+} saturation = 100 (Al^{3+}/ECEC).

Results were submitted to variance and polynomial regression analyses. Regression equations were adjusted to the obtained data according to lime rates, adopting as criterion for model choice the regressions with coefficients significant at 5%. The effects of re-liming were compared through the F-test.

RESULTS AND DISCUSSION

The variance analysis of the results of soil chemical attributes has shown significant interaction between lime rates and re-liming for pH and exchangeable Ca^{2+} at 0–5 cm depth, and for exchangeable Al^{3+} and Al^{3+} saturation at 0–5, 5–10, 10–20, and 20–40 cm depths. The absence of interaction on the other depths demonstrated that the effects of the lime rates were equal for absence or presence of surface re-liming.

Surface-applied lime rates and re-liming on the surface after nine and two years respectively, increased soil pH and the exchangeable Ca^{2+} level over the five depths (Figure 1). Such increases occurred in a more expressive way in the soil surface layer (0–5 cm), mainly for the plots submitted to surface re-liming.

Exchangeable Al^{3+} and Al^{3+} saturation levels decreased in the five depths, according to lime rates as well as re-liming on the surface, after nine and two years respectively (Figure 2). Liming in 2000 on the previously no limed plots lead to an accentuated reduction in the exchangeable Al^{3+} and Al^{3+} saturation levels to a 40 cm depth. Due to this, the slope of the adjusted equations for the liming rates in 1993 was lower with the re-liming in 2000.

Similar effects of amelioration of topsoil and subsoil acidity by surface liming under NT have been obtained in other studies (Oliveira & Pavan, 1996; Caires et al., 2000). A relatively fast effect of the surface re-liming on soil acidity neutralization to a 20 cm depth, after only nine months, was observed by Caires et al. (2000). In the present study the effects of amelioration of soil acidity by surface re-liming were observed in almost all soil profiles after two years.

The liming residual effect varies according to the soil acidity level, rate and type of lime, soil type, management of acidic fertilizers, and cropping systems (Oliveira & Pavan, 1996; Gascho & Parker, 2001; Conyers et al., 2003; Caires et al., 2005). In a field trial conducted on a sandy soil under NT (Rheinheimer et al., 2000), very little change on the exchangeable Al^{3+}, Ca^{2+}, and Mg^{2+} contents was observed nine years after surface lime application compared with the liming initial effect. Azevedo et al. (1996) found that soil pH and exchangeable Ca^{2+} and Mg^{2+} contents remained high, and the exchangeable Al^{3+} level was low, for over 23 years after liming on a clayey soil with high organic matter content.

In the NT systems the addition of correctives, fertilizers, and vegetable residues on the soil surface occurs frequently. This implies in modifications of soil chemical, physical, and biological attributes, in comparison to the conventional tillage system. The following mechanisms might be involved in the amelioration of the subsoil acidity by surface liming under NT: (i) formation and migration of $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ to deeper soil layers (Costa, 2000); (ii) moving of exchangeable Ca^{2+} and Mg^{2+}, and reduction of exchangeable Al^{3+} in the subsoil by formation of water soluble organic complexes present in plant residues (Franchini et al., 1999; Miyazawa et al., 2002); (iii) displacement of fine lime particles downwards in the soil profile with the water infiltration as a result of a soil aggregation amelioration due to increased organic carbon under NT (Amaral et al., 2004) and (iv) transportation of lime by the activity of soil biological agents, specially of those from the macrofauna (Silva et al., 1997; Chan, 2003). Regardless of the mechanism involved, the results revealed that surface liming was effective in alleviating the topsoil and subsoil acidity, showing long-term effect in this NT system.

The interaction between lime rates and re-liming was not significant for none of the attributes evaluated in the plant. This was the reason for the separate analyses of the soybean crops due to lime rates and re-liming.

Soybean total root length per soil surface area down to the depth of 60 cm was linearly reduced with liming rates, independently of surface re-liming (Figure 3). On the contrary of observations carried out in acid solutions (Sanzonowicz & Smyth, 1995; Sanzonowicz et al., 1998), soybean root growth was stimulated by soil acidity stress under NT. An aspect which has been slightly underestimated over soil acidity in NT system studies is the presence of H^+ ion as a component of acidity. In this study, the majority of acidity was caused by H^+ and the soil had high organic carbon content. An increasing of the H^+ activity might have caused the change of the negative charges of the cellular walls and favored root elongation (Moloney et al., 1981), once there were proper soil moisture conditions. Soil Al^{3+} saturation of the no lime plots was 20% at the surface layer (0–5cm) and 30% at deeper layers (Figure 2). The grown soybean cultivar is moderately susceptible to Al. Muzilli et al. (1978) reported

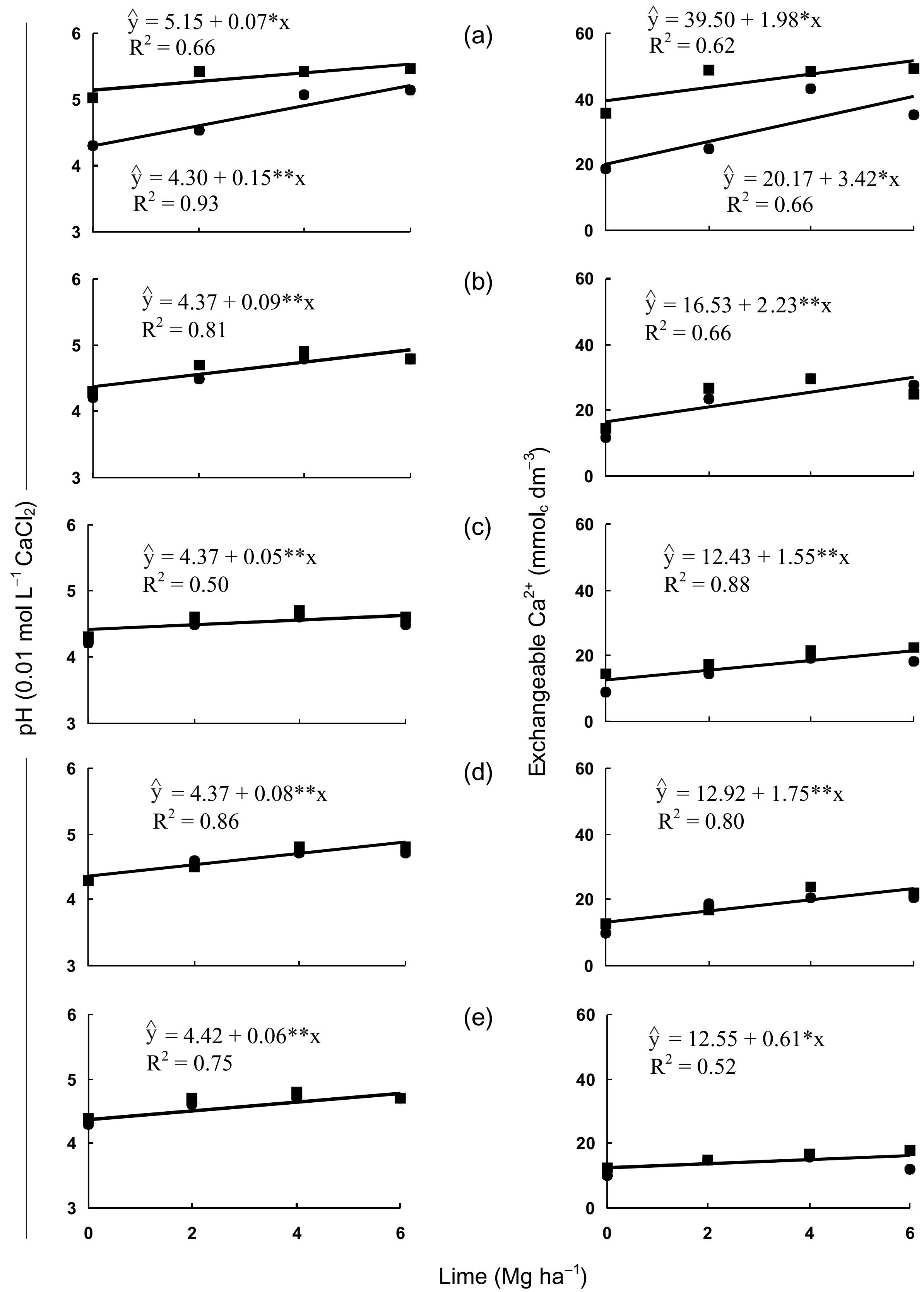

Figure 1 - Changes in soil pH and base saturation for different depths: 0–5 cm (a), 5–10 cm (b), 10–20 cm (c), 20–40 cm (d), and 40–60 cm (e), as a fuction of surface liming rates, after 9 yr, without (●) and with (■) surface re-liming at the rate of 3 Mg ha^{-1}, after 2 yr, in a no-till system. *: p < 0.05, and **: p < 0.01.

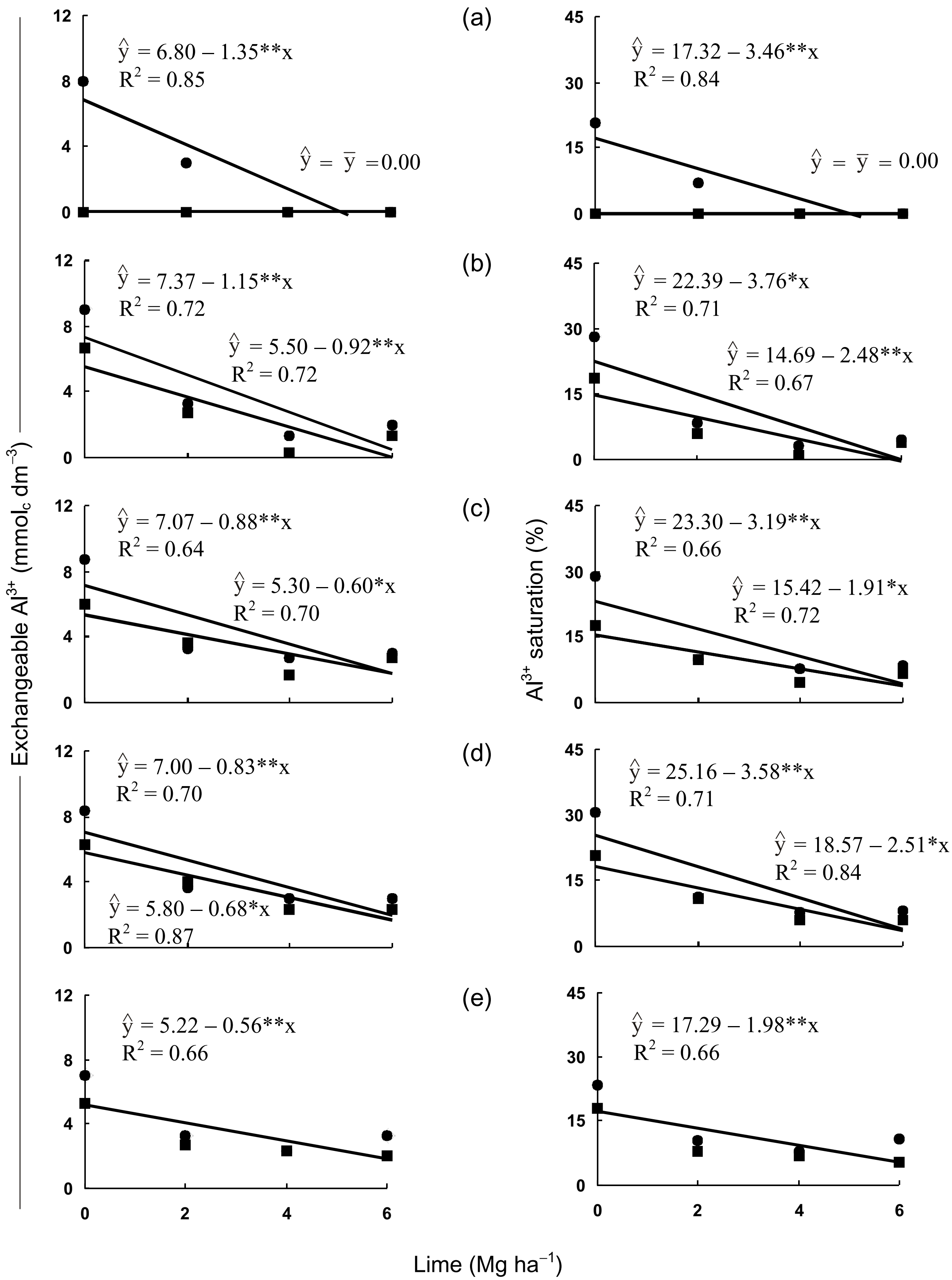

Figure 2 - Changes in soil exchangeable Al^{3+} and Al^{3+} saturation for different depths: 0–5 cm (a), 5–10 cm (b), 10–20 cm (c), 20–40 cm (d), and 40–60 cm (e), as a function of surface liming rates, after 9 yr, without (●) and with (■) surface re-liming at the rate of 3 Mg ha^{-1}, after 2 yr, in a no-till system. *: p < 0.05, and **: p < 0.01.

limit values of 16 to 20% of Al^{3+} saturation for soybean genotypes with such tolerance to acidity. Therefore, it was expected to obtain positive response from the soybean root system, mainly below the 0–5 cm soil depth, with the reduction of Al^{3+} saturation by liming. Absence of the Al toxic effect for the soybean root growth was also observed by Caires et al. (2001) and could be associated with increased organic matter content in the upper few soil centimeters under NT.

Lima et al. (2003) found that the Al^{3+} toxic effect for the soybean crop was lower in a clayey soil with high organic matter content (53 g dm^{-3}) than in a sandy soil with low organic matter content (8 g kg^{-1}), in spite of the clayey soil displaying an exchangeable Al^{3+} level 2.5 times higher than the sandy soil. Aluminum in soil solution from NT systems is largely associated with organic ligands of high molecular mass because of increased organic matter (Cambri, 2004). Since the formation of Al-organic complexes decreases Al toxicity, soybean root growth was not affected by Al concentrations in solution from NT soil (Anghinoni & Salet, 1998). This explains why there was low toxicity of Al for soybean root growth (Figure 3) in an acidic soil with toxic levels of exchangeable Al^{3+} (Figure 2).

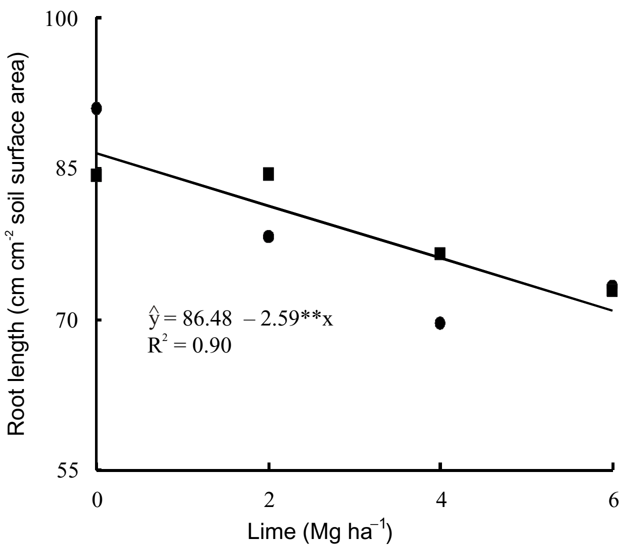

Figure 3 - Soybean root length per unit soil surface area to a depth of 60 cm as affected by surface liming rates, without (●) and with (■) surface re-liming at the rate of 3 Mg ha^{-1}, in a no-till system. Mean of two soybean crops (2001–2002 and 2002–2003). **: $p < 0.01$.

The relative length of roots was influenced on a quadratic form at the soil surface layer (0–10 cm) and also at the subsoil (20–60 cm) with liming rates (Figure 4). There was a higher concentration of soybean roots at the soil surface layer in relation to the subsoil layer on both plots without lime and with the highest lime rate (6 Mg ha^{-1}). Surface re-liming at 3 Mg ha^{-1} did not influence the distribution of soybean roots to the depth of 60 cm. Caires et al. (2002) also verified a higher concentration of corn roots on a higher acidity in the NT soil surface layer, and that the liming improved the distribution of the root system in the soil profiles.

The nutrient levels in the leaves were adequate for the soybean crop (Malavolta et al., 1997), independently of the liming treatments (Table 1). Surface-applied lime increased the Ca and Mg concentrations and reduced the Mn concentration in both soybean roots and leaves. There was also an increase of K in soybean roots with lime rates and a reduction of Zn in soybean leaves with lime rates and re-liming. The increase in the concentrations of Ca and Mg in the soy-

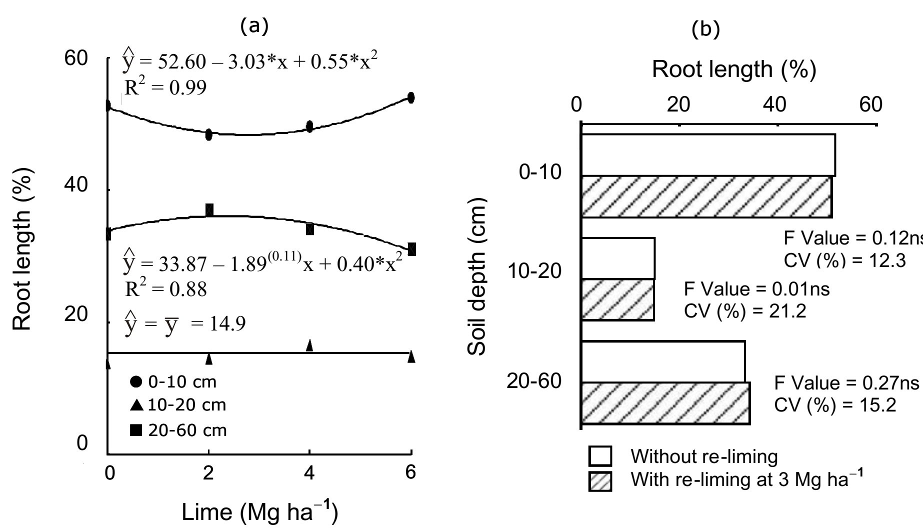

Figure 4 - Soybean relative root length for different soil depths as affected by surface liming rates (a) and surface re-liming at the rate of 3 Mg ha^{-1} (b), in a no-till system. Mean of two soybean crops (2001–2002 and 2002–2003). ns: non-significant, and *: $p < 0.05$.

Table 1 - Influence of surface liming rates and surface re-liming at the rate of 3 Mg ha^{-1} on nutrient and aluminum concentrations in roots and leaves of soybean grown in a no-till system in 2002-2003.

Treatment	N	P	K	Ca	Mg	S	Zn	Mn	Al
	------------------------ g kg^{-1} ------------------------						----------- mg kg^{-1} -----------		
Lime (Mg ha^{-1})					Roots				
0	-	1.0	5.9	32.1	3.4	0.7	89.7	39.5	7,888.7
2	-	0.8	6.2	32.8	3.6	0.7	101.7	35.8	7,500.0
4	-	1.0	6.1	32.8	3.6	0.7	92.8	34.0	7,526.7
6	-	0.8	6.0	33.5	3.7	0.6	90.1	29.1	6,976.7
Effect	-	ns	Q*	L**	L**	ns	ns	L**	ns
CV (%)	-	17.5	2.8	2.0	2.7	26.8	19.7	13.8	19.0
Reapplication of lime									
Without re-liming	-	0.9	6.1	32.5	3.5	0.7	93.7	36.2	7,035.0
With re-liming at 3 Mg ha^{-1}	-	0.9	6.0	33.1	3.7	0.7	93.4	33.0	7,910.0
F Value	-	2.6ns	0.8ns	6.2*	34.6**	0.4ns	0.0ns	4.3ns	2.2ns
CV (%)	-	12.1	3.4	2.0	3.1	21.0	14.1	11.1	19.3
Lime (Mg ha^{-1})					Leaves				
0	59.0	3.9	15.2	6.7	3.8	2.2	53.2	76.3	105.0
2	58.8	3.7	15.0	7.2	4.1	2.2	50.5	60.5	74.3
4	61.9	3.8	14.4	7.5	4.2	2.1	48.0	57.5	105.5
6	59.5	3.8	13.9	7.8	4.3	2.0	48.0	56.3	115.0
Effect	ns	ns	ns	L**	L**	ns	L*	L**	ns
CV (%)	4.5	12.0	14.1	5.4	5.4	15.7	9.2	9.1	66.3
Reapplication of lime									
Without re-liming	60.2	3.8	14.9	7.3	4.0	2.1	52.3	67.2	101.4
With re-liming at 3 Mg ha^{-1}	59.5	3.8	14.3	7.4	4.2	2.1	47.5	58.1	98.5
F Value	0.5ns	0.04ns	1.0ns	2.5ns	10.6*	0.3ns	6.8*	24.6**	0.01ns
CV (%)	4.5	11.0	10.0	3.2	4.7	14.3	9.0	7.2	64.2

Q and L: quadractic and linear effect by polynomial regression. ns: non-significant, *: $p < 0.05$, and **: $p < 0.01$.

bean plant is related with a higher availability of exchangeable Ca^{2+} and Mg^{2+} in the soil due to dolomitic lime application (Caires et al., 2001). The decrease in the concentrations Zn and Mn in soybean is caused by their lower availability in the soil due to pH increase by liming (Caires & Fonseca., 2000). The Al concentration was higher in the soybean roots than in the leaves, in agreement with Mengel & Kirkby (2001). There were no changes in Al concentrations in the soybean roots and leaves (Table 1), despite the reduction in the exchangeable Al^{3+} and Al^{3+} saturation levels in the soil with liming treatments (Figure 2).

Soybean grain yield was not influenced by surface liming. The mean yields of the two soybean crops were 3754, 3659, 3667, and 3640 kg ha^{-1} of grains, for the surface-applied lime at the rates of 0, 2, 4, and 6 Mg ha^{-1}, and 3708 and 3652 kg ha^{-1} of grains, for the treatments with and without surface re-liming at 3 Mg ha^{-1}, respectively. These results are common for acidic soils under NT systems without rainfall limitation during the growing cycle of soybeans in Southern Brazil (Caires et al., 1998, 2003, 2006a; Pottker & Ben, 1998; Moreira et al., 2001). When water in the topsoil is available in a NT system, soybean grain yield is not influenced by surface liming because of decreased Al toxicity for root growth (Anghinoni & Salet, 1998) due to the formation of Al-organic complexes (Nolla & Anghinoni, 2006) and even because root growth is stimulated by soil acidity stress.

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