Comissão 3.2 Corretivos e Fertilizantes

SOYBEAN ROOT GROWTH AND CROP YIELD IN REPONSE TO LIMING AT THE BEGINNING OF A NO-TILLAGE SYSTEM[1]

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SUMMARY

Analyzing the soil near crop roots may reveal limitations to growth and yield even in a no-tillage system. The purpose of the present study was to relate the chemical and physical properties of soil under a no-tillage system to soybean root growth and plant yield after five years of use of different types of limestone and forms of application. A clayey Oxisol received application of dolomitic and calcitic limestones and their 1:1 combination in two forms: surface application, maintained on the soil surface; and incorporated, applied on the surface and incorporated mechanically. Soil physical properties (resistance to mechanical penetration, soil bulk density and soil aggregation), soil chemical properties (pH, exchangeable cations, H+Al, and cation exchange capacity) and plant parameters (root growth system, soybean grain yield, and oat dry matter production) were evaluated five years after setting up the experiment. Incorporation of lime neutralized exchangeable Al up to a depth of 20 cm without affecting the soil physical properties. The soybean root system reached depths of 40 cm or more with incorporated limestone, increasing grain yield an average of 31 % in relation to surface application, which limited the effect of lime up to a depth of 5 cm and root growth up to 20 cm. It was concluded that incorporation of limestone at the beginning of a no-tillage system ensures a favorable environment for root growth and soybean yield,

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while this intervention does not show long-term effects on soil physical properties under no-tillage. This suggests that there is resilience in the physical properties evaluated.

Index terms: dolomitic limestone, calcitic limestone, soil physical resilience, cone index.

RESUMO: *CRESCIMENTO RADICULAR E PRODUTIVIDADE DE SOJA EM RESPOSTA À CALAGEM, NO INÍCIO DO SISTEMA PLANTIO DIRETO*

Analisar o solo próximo às raízes pode revelar limitações ao crescimento e à produtividade das culturas, mesmo em sistema plantio direto. Este estudo teve o objetivo de relacionar algumas propriedades químicas e físicas de solos e o crescimento radicular e rendimento de soja, em decorrência de tipos de calcário e formas de sua aplicação. Na implantação do sistema plantio direto em área de Latossolo Vermelho distroférrico argiloso, foram aplicados calcários dolomítico, calcítico e a combinação de ambos (proporção 1:1), nas formas superficial e incorporado. Cinco anos após a implantação do experimento, foram avaliadas propriedades físicas (resistência à penetração, densidade do solo e agregação do solo) e químicas (pH, cátions trocáveis, H+Al e capacidade de troca de cátions) do solo e da planta (distribuição do sistema radicular e rendimento de grãos de soja e produção de matéria seca de aveia). Observou-se que a incorporação dos corretivos neutralizou o Al trocável até 20 cm de profundidade e as propriedades físicas avaliadas não se apresentaram influenciadas, após cinco anos da aplicação do corretivo. O sistema radicular da soja alcançou 40 cm de profundidade quando o corretivo foi incorporado, incrementando a produtividade de grãos de soja em média de 31 % em relação ao calcário superficial, que limitou o efeito nas propriedades químicas a 5 cm de profundidade e o crescimento radicular até 20 cm. Concluiu-se que a incorporação de calcários, no início do sistema plantio direto, garante um ambiente favorável ao crescimento radicular e ao rendimento de grãos de soja, enquanto seus efeitos sobre as propriedades físicas do solo deixam de ser perceptíveis após cinco anos da implantação do sistema, o que sugere uma resiliência das propriedades físicas após a calagem.

Termos de indexação: calcário dolomítico, calcário calcítico, resiliência física do solo, resistência mecânica à penetração.

INTRODUCTION

The deleterious effects of acidity on soil chemical properties and plant productivity are well known in several agroecosystems, which justifies lime application on acid soils. From a chemical point of view, depth application of lime is desirable (Kaminski et al., 2005); however, prior incorporation of lime in soil under a no-tillage system (NT) gives rise to controversy as to possible negative effects on soil structure.

Lime surface application maintains soil physical structure since the soil is not turned over mechanically. Lime application, either before NT or when the system is already consolidated, is generally performed periodically to eliminate soil reacidification (Rheinheimer et al., 2000; Caires et al., 2008). Nevertheless, in this case the effects of soil amendment in depth are limited and dependent on the lime neutralization depth limits (Rheinheimer et al., 2000) and lime particle migration (Amaral et al., 2004). In addition, the neutralization rate depends on various factors, such as the lime application rate, soil type, the presence of compacted layers, environmental conditions and the amount of plant residues in the NT system, among others.

Although the NT maintains physical quality, a layer of soil is frequently observed at the 8-12 cm depth with high soil bulk density, low index of water infiltration and high resistance to penetration (Reichert et al., 2009; Silva et al., 2009). The response of the soybean plants to the compacted soil layer is generally related to physical barriers to root growth and variable consequences in regard to grain yield response (Rosolem et al., 1994). Soil quality indexes have been proposed as indicators of problems in plant development (Vezzani & Mielniczuk, 2009). Soil resistance to penetration (RP) above 2 MPa indicates problems for root growth, which leads to grain yield reduction (Richart et al., 2005). However, the appearance of growth disorders and plant development problems may be observed with RP from 1 to 3.54 MPa (Silva et al., 2009). Thus, for compacted soil which visibly impedes vertical root growth, mechanical intervention is justifiable, even if there is no guarantee of long-term effects (Silva et al., 2009).

Morphological changes in roots, with or without an effect on crop yields, are commonly associated with soil physical factors (Ramos et al., 2010). Nevertheless, stresses of a chemical or physical order trigger hormonal alterations in plants (Hodge, 2004). That is why roots, as flexible and adaptable organs, search for new routes in the soil, or zones which offer lower stress levels (Hodge, 2004). Soil layers with lower nutrient availability or the presence of toxic elements are considered stressful zones for root growth, as well as soil zones which are compacted and present low water availability (Reichert et al., 2009). This plant mechanism may allow maintenance of crop productivity, even with morphological alterations in the visible roots when light or moderate soil stresses are present in the no-tillage system.

Plant root growth is severely affected by aluminum (Al^{3+}) toxicity, leading to degeneration, thickening and change in color of roots, the appearance of secondary branches and absence of root hairs (Delhaiza & Ryan, 1995). In this respect, the hypothesis to be tested in this study is that soil chemical stratification as a consequence of lime application on the soil surface, whether calcitic or dolomitic limestone, creates a chemical obstacle to root growth at a greater depth. This situation would possibly not occur if lime were incorporated in the soil at the beginning of the no-tillage system.

The aim of this study was to evaluate the effects of the type and the form of soil lime application performed at the beginning of the no-tillage system on the fundamental physical and chemical properties of a Latossolo argiloso (Oxisol), relating them to root development and soybean yield.

MATERIALS AND METHODS

The study was carried out in an experimental area located at the geographic coordinates 28° l5' 59" South and 54° 13' 51" West. The soil is a Latossolo Vermelho distroférrico típico (Oxisol), according to the Brazilian System of Soil Classification (Embrapa, 2006), and an Oxisol in the United States classification, managed under a no-tillage system since 2004. The chemical and physical properties of the soil in 2004 are shown in table 1.

The study treatments were: control (no limestone); 100 % calcitic limestone; 100 % dolomitic limestone, and mixture of calcitic and dolomitic limestone in a 1:1 (Cal:Dol) proportion, all of them in four replications. Each treatment was applied on half of the plot (split-plot) in two different forms: lime applied on the surface, called surface application, and lime applied and incorporated mechanically by plowing plus disking, called incorporated application. The experimental plots were 6 × 5 m.

The amount of lime applied in 2004 was 7.5 Mg ha^{-1} (at 100 % of total relative neutralizing power - TRNP) to increase soil pH to 6. The compositions for calcitic lime were: 45 % of CaO, 1.5 % of MgO, neutralizing power (NP) of 76 % and TRNP of 64 %. For dolomitic lime they were: 32 % of CaO, 14 % of MgO, NP of 77 % and TRNP of 70 %.

Soybeans were sown in the 2005/06, 2007/08, 2008/09 and 2009/10 crop seasons; oats were sown in the winter of 2005, 2006, 2007 and 2009, and wheat was sown in the 2008 winter crop season. In 2009, the area under the NT system was planted to black oat (*Avena strigosa* Schreb.) and, in the 2009/2010 crop season, soybean was grown. The final population of the soybean crop (cultivar BMX Apolo RR) was 250,000 plants ha^{-1}, and fertilization was performed according to chemical soil properties recommended by the Chemical and Fertilization Soil Commission of Rio Grande do Sul and Santa Catarina (CQFSRS-SC, 2004).

Soil samples were collected in 2009/2010 within a useful area of each plot, leaving a 1-m border area in all directions (borderline). Samples were collected in between the rows of the soybean crop to represent the general experimental conditions (Study 1) and in the crop row to evaluate root morphology and physical and chemical soil properties, representing the conditions of soybean root system development (Study 2). In these places, two kinds of soil samples were collected: disturbed samples, before soybean sowing (2009 crop season), for chemical analysis (20 subsamples per experimental unit), with the aid of a soil auger at the depths of 0-5, 5-10 and 10-20 cm; and undisturbed samples (soil clods), before the soybean crop (2010), for physical analysis. A spade was used to collect layers of preserved soil (soil clods) collected in triplicate at the depths of 0-5, 5-10 and 10-20 cm.

Table 1. Chemical and physical properties of an Oxisol in 2004 before setting up the experiment

Layer	Clay	SOM	pH (H_2O)	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	V	m
cm	g kg^{-1}			mg kg^{-1}		cmol$_c$ kg^{-1}			%	
0-10	880	32	5.1	17.1	276	3.7	1.8	0.7	47	10
10-20	620	23	5.0	8.4	124	3.3	1.6	1.9	30	31

Data adapted from Miotto (2009). SOM: soil organic matter; P and K extracted by Melhich-1; Ca, Mg and Al extracted using KCl solution (1 mol L^{-1}); V: base saturation; m: Al saturation.

Samples of black oat straw were harvested in 2009, cut at ground level in a 2 m^2 area in each experimental plot using a hand sickle. Dry matter (DM) of black oat was determined after the samples were dried in a greenhouse at 65 °C. In 2010, soybean plants were harvested in an 8 m^2 area divided into four 2 m^2 areas, randomly distributed in the plot, for the purpose of estimating the grain yield at 13 % moisture. In each experimental plot, five soybean plants were harvested with their roots, digging a small trench with the aid of a spade. The maximum length of the longest root (distance from the end of the root to the root collar) was determined. Volume of the root system was determined by submerging the roots in a graduated cylinder and calculating the volume of water dislocated.

Soil chemical analysis was based on Tedesco et al. (1995). Soil pH in water was determined through the potentiometric method at a 1:1 soil/water ratio. Exchangeable calcium and magnesium were determined by flame atomic absorption spectrometry (FAAS) after extraction with KCl (1 mol L^{-1}) solution. Aluminum extracted using a KC1 (1 mol L^{-1}) solution was estimated by acid-base titration with NaOH (0.0133 mol L^{-1}).

Soil resistance to penetration (RP) was evaluated in the field at a depth of 0-40 cm using a Falker penetrometer device, model PenetroLOG®. For each experimental plot, six replications were performed, for a total of 24 readings for each treatment. Mean RP was calculated for the 0-10, 10-20, 20-30 and 30-40 cm layers.

Aggregate stability was determined following the method proposed by Kemper & Chepil (1965). Weighted mean diameter (WMD) and geometric mean diameter (GMD) were determined by the following equations:

$$WMD = \sum_{i=l}^{n} (xi.wi) \quad (1)$$

$$GMD = EXP \frac{\sum_{i=l}^{n} wp.\log xi}{\sum_{i\text{-}1}^{n} wi} \quad (2)$$

where *wp* = weight of material in each category; *wi* = proportion of each class in relation to the total; *xi* = mean class diameter.

The aggregate stability index (ASI) was calculated from the ratio of total weight and the weight that remained in the sieve (0.21 mm).

The data obtained in study 1 were subjected to analysis of variance (ANOVA) and the mean values were compared by the Turkey test at 5 % probability. For Study 2, one soybean plant was chosen within each treatment as a reference. From the position of this plant, resistance to penetration (RP) was estimated. This procedure was performed at 10 cm distance to the left and to the right of the plant row composed of three readings parallel to the plant row at distances of 5 cm (each reading here was considered as a replication). After RP measurements, trenches of 90 × 60 × 30 cm were dug at the reference plant and transversal to the plant row. The plant root system was carefully exposed to allow images to be recorded (Sony camera, model DSC H55) of a 30 cm extension of the roots and trench depth of 30 cm. The images were worked with on CorelDraw® and Adobe Photoshop®, using a ruler as a scale parameter. Starting at the reference plant and on the trench wall, undisturbed samples were collected for chemical analysis (in three replications) and physical analysis (in four replications) at the depths of 0-10, 10-20, 20-30 and 30-40 cm. The pH and Al determinations were performed according to Tedesco et al. (1995). Soil bulk density (Bd) was determined by the paraffin-sealed clod method. The data were subjected to analysis of variance in blocks with split-plots. The blocks consist of the main treatments (kinds of lime) and the split-plots consist of the forms of lime application. The mean values were compared by the Turkey test at 5 % probability.

RESULTS AND DISCUSSION

Soil pH was not statistically different either for the type of lime or for the forms of application, even when the values of the control samples were excluded (Table 2). In general, exchangeable Al values tend to increase with depth, while pH, Ca and Mg values decreased, regardless of how the lime was applied. Lime applications alone were enough to reduce Al contents in relation to the control. Also, incorporation of lime allowed reduction in exchangeable Al values at soil depths in greater magnitudes than surface application (Table 2).

The exchangeable Ca and Mg contents evaluated in the soil after five years of liming are consistent with the type of lime used. Higher Ca contents were found in the calcitic limestone treatment than in the dolomitic limestone treatment and control, however, they were similar to Cal:Dol treatment in all depths. The dolomitic limestone treatment presented more Mg in all soil depths than the other treatments. Lime effects at soil depths are observed even five years after incorporation of the lime as compared to surface application.

The properties WMD, GMD, AIE and RP showed no difference either for the form of lime application or for the kinds of lime five years after application (Table 3). However, WMD, GMD and AIE values differed considering depth, especially in the 0-5 and 5-10 cm layers when compared to the 10-20 cm layer. WMD and GMD values were lower in the 10-20 cm layer compared to the other layers, and lime application presented no effect on these properties compared to the control. This may be due to the low sensitivity of the method proposed by Kemper & Chepil

Table 2. Values of pH and of exchangeable Al, Ca and Mg in an Oxisol collected in the planting row and subjected to different forms of lime application and kinds of limestone

Factor of variation	pH		Al		Ca		Mg	
			$cmol_c\ kg^{-1}$					
Lime application								
Surface (S)[ns]	5.6		0.73		5.84		1.86	
Incorporated (I)	5.8		0.30		6.07		2.07	
Controls: S+I	5.2		1.40		2.74		1.22	
CV (%)	6.4		86.2		47.1		35.3	
Kind of limestone								
Calcitic	5.69 a		0.55 b		6.56 a		1.29 c	
Cal:Dol	5.67 a		0.45 b		6.22 a		1.91 b	
Dolomitic	5.67 a		0.54 b		5.11 b		2.68 a	
Control	5.17 b		1.39 a		2.77 c		1.21 c	
CV (%)	6.1		65.9		25.5		27.3	
				Lime/Control				
Depth (cm)	S	I	S	I	S	I	S	I
0-5	1.18	1.17	0.02	0.06	2.7	2.3	2.1	1.5
5-10	1.05	1.10	0.40	0.20	2.1	2.2	1.8	1.6
10-20	0.98	1.07	0.80	0.30	1.4	2.0	1.2	1.5

CV: coefficient of variation. Mean values followed by the same small letter in the column do not differ by the Tukey test ($p \leq 0.005$); ns: not significant by the t test; lime/control: ratio between the values of the properties of the treatments in which lime was applied and the control.

Table 3. Weighted mean diameter (WMD), geometric mean diameter (GMD), aggregate stability index (ASI) and soil resistance to penetration (RP) between rows in an Oxisol under a no-tillage system for five years subjected to different forms of lime application and kinds of limestone

Factor of variation	WMD	GMD	ASI	RP
	mm		%	kPa
Lime application				
Surface[ns]	0.51	1.21	77	1640
Incorporated	0.49	1.22	78	1604
Control	0.54	1.29	79	1582
CV (%)	46.9	33.2	12.7	11.3
Kind of limestone				
Calcitic[ns]	0.51	1.23	77	1620
Cal:Dol	0.49	1.22	78	1634
Dolomitic	0.48	1.20	78	1612
Control	0.54	1.29	78	1583
CV (%)	20.9	19.8	12.2	11.2
Depth (cm)				
0-5	0.58 a	1.33 a	77 a	812 c
5-10	0.54 a	1.28 a	79 a	1342 b
10-20	0.40 b	1.10 b	77 a	1837 a
CV (%)	18.6	13.5	8.4	13.9

CV: coefficient of variation. Mean values followed by the same small letter in the column do not differ among themselves by the Tukey test ($p \leq 0.05$); ns: not significant.

(Kemper & Chepil, 1965) in estimation of soil micro-aggregation (Bortoluzzi et al., 2010). RP values differed among the depths evaluated but did not go beyond the value of 1,837 kPa. However, the form of application of lime did not significantly affect RP values (Table 3).

In table 4, dry matter (DM) production of the above ground part of black oats (used as a cover crop) did not present any variation in regard to the kinds of lime applied and forms of lime application. Soybean root volume (SRV) was not sensitive to the forms of application or to the kinds of lime. In contrast, the main root length of the soybean plant (SMR) responded to the forms of application, but not to the kinds of lime. Calcitic and dolomitic limestones and the mixture of both (Cal:Dol) presented similar SMR values; however, these values were superior to the control. On average, in all the treatments that received lime application, the control excluded, presented higher SMR when lime was incorporated in the soil.

Soybean grain yield (SGY) did not differ in regard to the kind of lime, it only presented differences in comparing application of lime with the control (Table 4). It is important to observe that the method of lime application affected grain yields five years after the experiment was set up, which suggests a residual chemical effect of lime application and also an effect of the form it was applied. Miotto (2009), evaluating soybean yield in the third year after the experiment was set up, did not find any influence from the types of lime, or from the form of application (data shown in table 4). Five years after lime application, the incorporated application contributed to an average increase of 31 % in grain yield when compared to surface lime application. Within the control, the simulation of lime incorporation (plowing and disking) led to a 7.6 % greater yield when compared to the control which had no mechanical intervention. In fact, lime application, regardless of the type and the mixture, increased soybean yield by 29 and 44 % in relation to the control when lime was kept on the surface and incorporated, respectively. Although surface lime application presented good results in a no-tillage system (Caires et al., 2008), a decrease in crop yields in some cases in consolidated NT systems can be verified, which can especially be attributed to the physical quality of the soil (Silva et al., 2009).

Surface lime application affected root growth in soybean plants through thickening and shortening of the main root; however, it presented no results in soybean root volume (SRV) (Table 4). When lime was incorporated in the soil, the roots were thinner, longer and presented more branches (Figure 1). In addition, the soybean root system was limited to a depth of 20 cm when lime was kept on the surface. In the treatments with incorporated lime, the roots reached depths of 40 cm or more. The distribution of the soybean root system in the treatments with incorporated lime presented the same behavior, in contrast with the control without lime application. Depth lime application is a concrete factor which provides better conditions for soybean root growth. This interpretation is confirmed since the two root systems presented in both controls (surface and incorporated lime) were limited to 20 cm depth and were similar to each other (Figure 1).

The results of pH, Al^{3+}, Ds and RP in different treatments and depths (study 2) are presented in table 5. According to Tavares Filho et al. (1999), it is crop profile (soil zone where there is root growth) analysis which enables assessment of morphological root responses to soil factors, i.e. physical and chemical soil properties.

Soil pH responds according to the form of application and the depth at which lime is applied (Table 5). Soil pH remains above 5.0 (0-30 cm) in soils which received lime, regardless of the kind of lime. When lime was applied and kept on the surface, the pH values were higher in the 0-20 cm layer, but decreased with depth. There was an interaction between depth and forms of application only for calcitic limestone. In this case, pH was higher in the surface layer when lime was kept on the surface and lower for the intermediate layers, equalizing in the 30-40 cm layer. The activity of lime applied on the surface is no deeper than 10 cm (Rheinheimer et al., 2000). As for the controls, the form of lime application did not affect either the pH or the Al because in these treatments there was only the mechanical effect of simulation of liming.

Soil Al contents followed a tendency opposite to the pH (Table 5). The calcitic limestone treatment presented interaction between the forms of lime application and the depths evaluated. Greater Al contents were found at all depths when lime was applied on the surface as compared to incorporated lime, except at the 0-10 cm depth. Al contents increased according to depth, more intensively up to 30 cm when lime was applied on the surface and, to a lesser extent, when incorporated. When lime was incorporated, Al^{3+} values greater than 1 $cmol_c$ kg^{-1}

Table 4. Black oat dry matter (DM), soybean root volume (SRV), soybean main root length (SMR) and soybean grain yield (SGY) as a function of different types and forms of lime application (S, surface; I, incorporated) in a no-tillage system in an Oxisol

Factor of variation	Soybean 05/06-07/08(1)		Black oat		Soybean 2009/10					
	SGY		DM		SRV		SMR		SGY	
	S	I	S	I	S	I	S	I	S	I
	kg ha^{-1}				cm^3		cm		kg ha^{-1}	
Kind of limestone										
Calcitic	5410	4710	5119	5015	12.5	11.2	23.2^{ns}	35.4a	2020	2426
Cal:Dol	5000	4920	5105	5000	14.0	13.4	24.3	36.4a	1945	2599
Dolomitic	4930	5140	5239	5134	12.1	10.5	23.0	35.9a	1834	2585
Control	4600	4260	5263	5158	10.6	12.9	20.8	22.8b	1561	1680
Mean	4980^{ns}	4810	5182^{ns}	5077	12.3^{ns}	12.0	22.8*	32.6	1840*	2323
CV (%)			14.4		17.5		11.8		19.4	

(1) Accumulated crop yields in 2005/06 and 2007/08 crop seasons, results extracted from Miotto (2009). S: surface lime application; I: application and incorporation of limestone. CV: coefficient of variation. Mean values followed by the same small letter in the column do not differ from each other by the Turkey test ($p \leq 0.05$); * significant by the t test ($p \leq 0.05$); ns: not significant ($p \leq 0.05$).

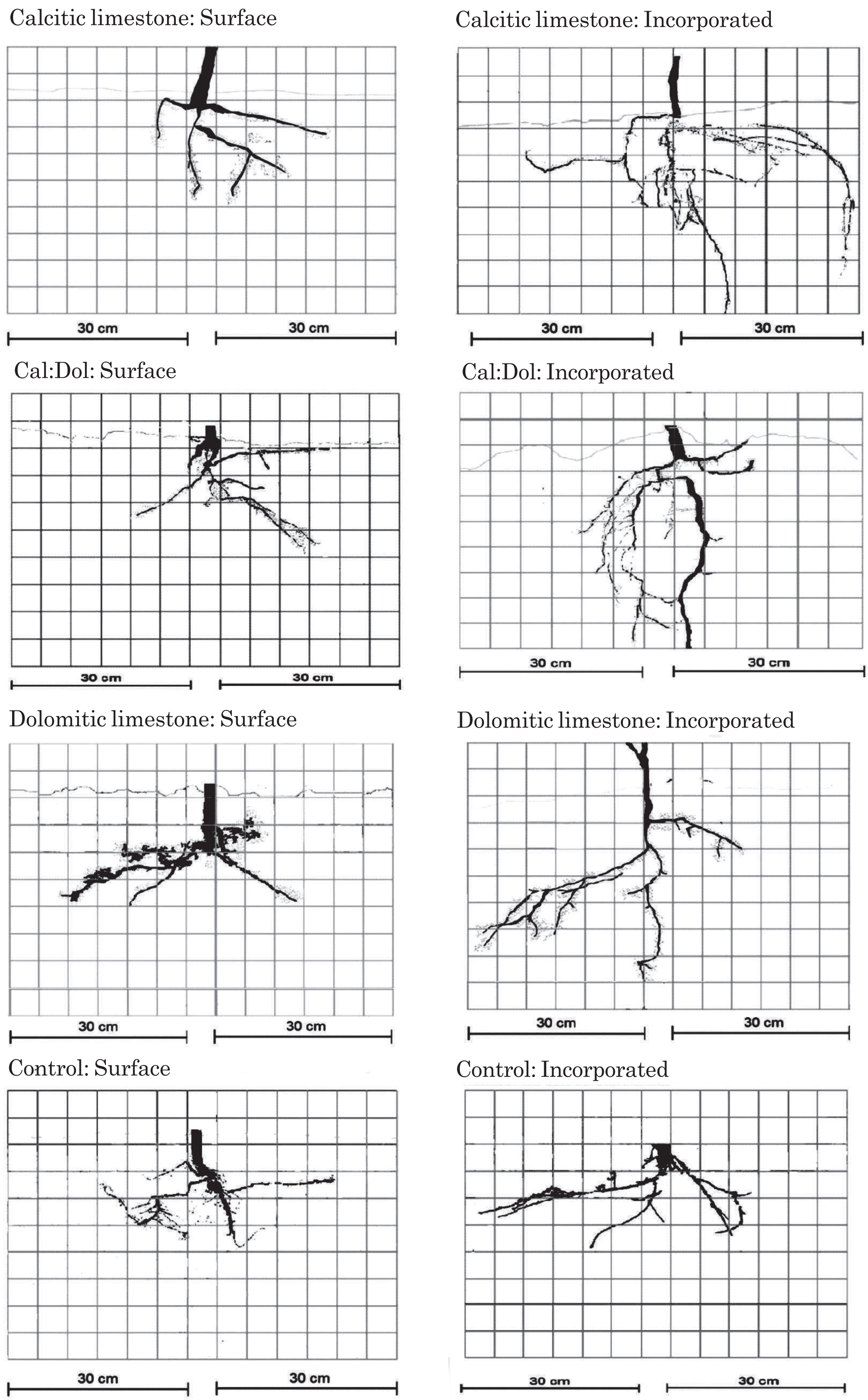

Figure 1. Perpendicular profile of the root system of soybean plants grown under a no-tillage system with different kinds of limestone and forms of application in an Oxisol in Rio Grande do Sul. Each square represents an extension of 5 cm.

were found only in the 30-40 cm depth layer, while in the control these values were found as of 20 cm.

The form of lime application did not affect RP. The Ds values were very similar for the calcitic limestone treatments, whether surface application alone or incorporated (Table 5). RP increased with depth and in a similar way among all treatments, including the controls. In addition, RP values above 2 MPa, which limit normal plant development, were verified only at the depth of 20 cm. The greatest RP value (2,882 kPa) was found in the 30-40 cm layer of the control. The wide range of RP found among various depths did not seem to have affected root system distribution of the lime treatments (calcitic and dolomitic limestones) (Figure 1).

The problematic of lime application in NT systems is, *a priori*, in amending soil acidity in depth at the beginning of the NT system. Furthermore, after five years under an NT system, soil surface layer reacidification does not appear to be so apparent. Consequently, the application of limestone on the surface, without incorporation, at the beginning of the system is not justified, due to the reduced extension of the alkalization process at greater depths

Table 5. Soil pH, Al content, soil bulk density (Bd) and soil mechanical resistance to penetration (RP) in a profile transversal to the soybean crop row as affected by different kinds of lime and forms of lime application (Surface - S, or Incorporated - I) in a no-tillage system in an Oxisol

Factor of variation	pH (H_2O)		Al		Bd		RP	
	S	I	S	I	S	I	S	I
			$cmol_c$ kg^{-1}		Mg m^{-3}		kPa	
Calcitic limestone								
Depth (cm)								
0-10	6.25 Aa	5.83 Ba	0.00 Ac	0.00 Ac	1.39 c		400 d	
10-20	5.35 Bb	5.85 Aa	0.90 Ab	0.20 Bc	1.42 b		1,350 c	
20-30	5.00 Bc	5.28 Ab	1.18 Aab	0.50 Bb	1.47 a		2,400 b	
30-40	4.80 Ac	4.93 Ac	1.35 Aa	1.03 Ba	1.49 a		2,900 a	
CV (%)	2.4		18.5		1.1		4.9	
Mean	5.35	5.47	0.86	0.43	1.48*	1.41	1,800	1,750
Cal:Dol								
Depth (cm)								
0-10	6.11 a		0.01 c		1.41 ns		400 d	
10-20	5.53 b		0.33 c		1.43		1,200 c	
20-30	5.13 bc		0.88 b		1.47		2,200 b	
30-40	4.89 c		1.65 a		1.48		2,600 a	
CV (%)	5.6		35.8		5.1		10.9	
Mean	5.26*	5.56	0.84*	0.60	1.45	1.45	1600	1600
Dolomitic limestone								
Depth (cm)								
0-10	5.95 a		0.10 Ac	0.15 Ac	1.42 b		450 d	
10-20	5.40 b		0.80 Ab	0.25 Bc	1.46 ab		1,300 c	
20-30	5.07 bc		1.50 Aa	0.90 Bb	1.50 a		2,300 b	
30-40	4.76 c		1.60 Aa	1.33 Aa	1.50 a		2,700 a	
CV (%)	5.6		28.6		2.9		13.8	
Mean	5.21*	5.38	1,0	0,66	1.47	1.46	1,700	1,700
Control								
Depth (cm)								
0-10	5.25 a		0.00 d		1.43 b		450 d	
10-20	4.95 b		0.59 c		1.46 ab		1,300 c	
20-30	5.07 b		1.16 b		1.49 ab		2,100 b	
30-40	4.84 b		1.70 a		1.50 a		2,800 a	
CV (%)	2.62		34.27		3.4		13.0	
Mean	4.98 ns	4.97	0.89 ns	0.83	1.47	1.46	1,600	1,700

CV: coefficient of variation. Mean values followed by the same capital letter in the line and small letter in the column did not differ from each other by the Turkey test ($p \leq 0.05$); * significant by the t test ($p \leq 0.05$); ns: non-significant.

(Figure 1, Tables 1 and 5). This interpretation is in agreement with the literature, which states that lime application on the surface is efficient in impeding a surge of exchangeable Al; however, it shows limitations at greater depths (Rheinheimer et al., 2000; Caires et al., 2008). The effects of mechanical intervention on the soil structure at the beginning of the experiment diminished three years after setting up the NT (Miotto, 2009) and were totally mitigated after five years (Tables 2 and 5). This fact reaffirms the interpretation that certain soil physical properties subject to mechanical intervention have the capacity to be resilient in some situations (Vezzani & Mielcnizuc, 2009). Nevertheless, soil acidity, if not neutralized, will continue without change at greater depths, which is a limiting factor for soybean root growth (Figure 1) and will have yield consequences (Table 4). Barriers to soybean root growth cannot be explained only by Ds and RP variations at greater depths because these properties are very similar in all the treatments evaluated. It was observed that soil layers or zones which are chemically poor hinder root lengthening and branching in the soybean crop, limiting its yield. However, this was not enough to reduce dry matter production in the oat crop because oat is a more aggressive crop (Figure 1 and Table 4).

Finally, the form of lime application highlights the chemical factor, which hinders root growth and distribution, especially related to Al contents at the depth of 20 cm (Figure 1 and Table 5). This is clear upon observing that in the treatments that received incorporated lime, there was root development up to 40 cm (Figure 1 and Table 5). Plant roots avoid soil zones which offer stress, especially stress linked to Al toxicity (Delhaiza & Ryan, 1995; Hodge, 2004). This response was enough for soybean grain yield in the treatments with incorporated lime to be 482.97 kg ha^{-1} greater than surface lime treatment (Table 4). Lime incorporation tends to improve the chemical properties in the growth layer (Delhaiza & Ryan, 1995; Hodge, 2004). The neutralization of exchangeable Al in deeper soil layers is necessary at the beginning of a no-tillage system, or it must be considered as a remedial practice in a consolidated NT system, taking into consideration the physical resilience of the soil and environmental factors at the time of lime application.

CONCLUSIONS

1. Limestone application, regardless of the kind (calcitic, dolomitic or its 1:1 mixture), is determinant for improving soil chemical quality, allowing for greater soil availability of Ca or Mg according to the composition of the lime;

2. The form that lime is applied at the beginning of the no-tillage system is a fundamental factor for ensuring soil chemical quality in depth in the long term. The incorporation of different kinds of limestone in the soil ensures better soybean root system distribution at a depth of up to 40 cm and better soybean grain yield compared to surface application and to the control without lime application, even after five years from the beginning of a no-tillage system;

3. Resistance to the occurrence of soybean roots in depth (up to 40 cm) coincides with the presence of high contents of Al^{3+}, suggesting that the main factor that hinders root growth is chemical and not physical;

4. The physical properties evaluated (mechanical resistance to penetration, soil bulk density and aggregate stability) proved to be resilient five years after lime application performed at the beginning of a no-tillage system.

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