INCREASE OF GRAIN AND GREEN MATTER OF CORN BY LIMING(1)

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SUMMARY

Despite the fact that aluminum toxicity to crops is eliminated near soil water pH of 5.5, lime recommendation in many regions aims to increase soil pH up to 6.0 or even higher. For highly buffered soils, high rates of limestone are required to raise the pH from 5.5 to 6.0, resulting in additional, sometimes unnecessary, costs. The objective of this study was to evaluate the effect of soil pH on corn yield in a very acid Hapludox. The experiment was carried out in Lages, Southern Brazil, from 1992 to 1996. The soil had water pH of 4.7, Al^{3+} of 33 $mmol_c$ kg^{-1}, O.M. of 45 g kg^{-1} and lime requirement to pH 6.0 of 9.0 t ha^{-1}. Dolomitic limestone at rates of 0, 4.5, 9.0, 13.5 and 18.0 t ha^{-1} (equivalent to pure $CaCO_3$) was incorporated into the soil down to 17 cm depth, in 1992. Liming increased linearly the values of soil pH (from 4.7 to 6.6) and Ca and Mg, eliminated Al^{3+} with rates of 9.0 t ha^{-1} or higher, decreased slightly Al-$CuCl_2$, Fe and Cu, and did not affect Zn and Mn. Maximum average corn yield for grain (7.9 t ha^{-1}) and for green matter for silage (GM) (59 t ha^{-1}) was obtained, respectively, at soil pH of 6.0 (12 t ha^{-1} of limestone) and of 6.1 (14 t ha^{-1} of limestone); maximum economic efficiency for grain was obtained at pH 5.6 (7.5 t ha^{-1} of limestone). Maximum yield increments due to liming were 17% for grain and 20% for GM.

Index terms: liming, corn, silage, acid soils, pH.

RESUMO: *AUMENTO DO RENDIMENTO DE GRÃOS E DE MASSA VERDE DE MILHO OCASIONADO PELA CALAGEM*

Apesar de a toxicidade do alumínio para os vegetais ser eliminada próximo a pH 5,5, recomenda-se o uso de calcário em muitas regiões para elevar o pH até 6,0 ou mesmo a valores mais altos. Para solos altamente tamponados, altas doses de calcário são necessárias para elevar o pH de 5,5 para 6,0, o que implica custos adicionais, nem sempre necessários. Este estudo objetivou avaliar o efeito do pH do solo no rendimento de milho num Latossolo Bruno distrófico (Hapludox). O experimento foi desenvolvido em Lages, SC, de 1992 a 1996. O solo apresentava pH = 4,7, Al^{3+} *= 33* $mmol_c$ kg^{-1}*, matéria orgânica = 45 g* kg^{-1}*, e requereu*

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(1) Received for publication in March of 1997 and approved in March of 1998.

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9 t ha^{-1} para elevar o pH até 6,0. Calcário dolomítico foi incorporado ao solo até 17 cm de profundidade, em 1992, nas doses de 0, 4,5, 9,0, 13,5 e 18,0 t ha^{-1} (PRNT 100%). A calagem aumentou linearmente os valores de pH (de 4,7 até 6,6) e de Ca e Mg, eliminou o Al^{3+} nas doses de 9,0 t ha^{-1} e maiores, diminuiu o Al-$CuCl_2$, Fe e Cu e não influiu no Zn e no Mn. As produções médias máximas para grãos (7,9 t ha^{-1}) e para massa verde (MV) para silagem (59 t ha^{-1}) foram obtidas, respectivamente, em pH 6,0 (12 t ha^{-1} de calcário) e pH 6,1 (14 t ha^{-1} de calcário); a máxima eficiência econômica para grãos foi obtida em pH 5,6 (7,5 t ha^{-1} de calcário). Os incrementos máximos no rendimento de milho ocasionados pela calagem foram de 17%, para grãos, e 20%, para MV.

Termos de indexação: pH, calagem, milho, silagem, solos ácidos.

INTRODUCTION

Aluminum toxicity is normally the most limiting chemical factor to increase crop production in natural tropical acid soils. This toxicity can be overcome by increasing soil pH.

In addition to the effect on Al chemistry, soil pH affects the availability of many nutrients. As the pH goes up, availability of P (Ernani et al., 1996), Mo (Lantmann, et al., 1989), Ca, Mg, S (Azevedo et al., 1996), and N normally increases in acid soils, and the opposite occurs for all other micronutrients (B, Fe, Cu, Zn and Mn)(Lindsay, 1972). Organic matter decay also increases with the increase on soil pH due to better conditions for microorganisms activity (Azevedo et al., 1996). The magnitude of all these reactions, however, varies with soil type and soil pH range.

Therefore, raising soil pH has direct and indirect effects on nutrient availability and crop growth that are difficult to quantify. In acid soils correctly fertilized, Al is certainly the most limiting factor to increase crop yield. Since Al toxicity is completely eliminated near water pH of 5.5, plants should grow well in soils containing pH close to or above this value if nutrient availability is in the sufficiency range. Addition of lime to raise soil pH to 6.0 or 6.5 rather than to 5.5 is, however, a decision that depends on gains in the efficiency of nutrient utilization by crops and additional cost of liming, an important factor to consider for highly buffered soils.

The objective of this study was to evaluate the effect of liming on corn yield in a highly buffered, acid soil.

MATERIAL AND METHODS

The experiment was conducted from 1992 to 1996 in Lages, Southern Brazil, on an Oxisol (Hapludox) that had not been previously cropped. The experimental site had original pH of 4.7 (1:1 soil:water), P-Mehlich-1 of 1 mg kg^{-1}, exchangeable K of 120 mg kg^{-1}, organic matter of 45 g kg^{-1}, exchangeable Al of 33 $mmol_c$ kg^{-1}, Al saturation on cation exchange capacity (CEC) of 56%, and lime requirement to increase the soil pH to 6.0, based on SMP method, of 9.0 t ha^{-1}.

Treatments consisted of increasing rates of dolomitic limestone, equivalent to 0, 4.5, 9.0, 13.5 and 18 t ha^{-1} with acid neutralizing capacity of 100%. The limestone was incorporated into a 17 cm soil depth layer, using moldboard plowing (twice) and disking (twice), in 1992, two months before the first corn planting. Treatments were set up in a randomized complete block design, under the split plot arrangement, with four replicates. Corn destination (grain or silage) was allocated in the main plots, and limestone rates were allocated in the splitplots. The splitplot size was 5.0 by 6.0 m and only the central 20 m^2 were used for sampling and measurements.

Corn (Pionner 3230) was always sown in the second half of November, in row spacing of 1.0 m for grain and 0.7 m for silage, providing a final population, after thinning, of 5 x 10^4 and 7 x 10^4 plants per hectare, respectively.

Urea, triple superphosphate, and potassium chloride were added each year at rates of 90 kg ha^{-1} of N, 100 kg ha^{-1} of P_2O_5, and 100 or 150 kg ha^{-1} of K_2O, respectively, on plots for grain and for silage. Urea application was split: 30 kg ha^{-1} was applied at planting time and 60 kg ha^{-1} 45 days afterward; P and K were totally applied at planting time. Corn grain yield was expressed with 13% moisture, and green matter for silage was harvested at the dough stage.

Composite soil samples of six cores were collected in each splitplot after each corn harvest, within a soil layer ranging from 0-17 cm. Soil pH, P, Al and K were determined on samples collected in all years; Al-$CuCl_2$, Ca, Mg, Fe, Cu, Zn, and Mn were determined only on the samples collected after the last corn growing season. All samples were oven-dried at 65°C and passed through a 2 mm sieve. Soil pH was determined using water as solvent, in a ratio of 1:1 (v/v). The following solutions were used to extract the elements from the soil solid phase: double acid (Mehlich-1) for P and K; 1.0 mol L^{-1} pH 7.0 Ammonium Acetate for Al, Ca and Mg; 0.5 mol L^{-1} $CuCl_2$ for Al-$CuCl_2$; and 0.1 mol L^{-1} HCl for Fe, Cu, Zn and Mn. Shaking time of one hour and soil:extracting solution ratio of 1:10 were used for all extractions. Exchangeable Al was determined by titrimetry; P by colorimetry; K by flame emission; and Fe, Cu, Zn, Mn, Ca, Mg and Al-$CuCl_2$ by spectroscopy using an inductive coupled plasma (ICP).

The data were analyzed by polynomial regression techniques.

RESULTS AND DISCUSSION

Soil buffer capacity for H^+ was high and linear over the entire range evaluated. Addition of increasing rates of dolomitic limestone (4.5, 9.0, 13.5 and 18.0 t ha^{-1}) raised linearly the soil water pH from 4.7 to 5.4, 5.7, 6.3 and 6.6 respectively, in the average of four growing seasons (Table 1). There was a need of 1.1 t ha^{-1} of pure dolomitic lime to increase 0.1 pH unit (Table 3). Soil pH did not change significantly during the experimental period due to the high soil buffer capacity. The small variations verified among sampling dates did not have any specific trend and were probably caused by differences on salt concentration at sampling time or by sampling variation.

Both forms of Al^{3+} and Al-$CuCl_2$ decreased linearly with the increase on liming rate. At a pH of 5.4, Al^{3+} was 5 mmol$_c$ kg^{-1} on the two initial years and 8 mmol$_c$ kg^{-1} on the two final years (Table 1). These values may be slightly overestimated by the presence of some exchangeable H which is also quantified by the titrimetric method used. At the treatments with pH values above 5.4, Al^{3+} was completely precipitated (Table 1), which is in agreement with the results of Ernani & Almeida (1986) for 49 soils of Santa Catarina State, in that Al^{3+} was eliminated at pH values between 5.3 and 5.5. Aluminum extracted by 0.5 mol L^{-1} $CuCl_2$ (Al-$CuCl_2$), that represents Al bonded to soil organic matter plus exchangeable Al (Hargrove and Thomas, 1981), was much higher than Al^{3+} (Table 2). Nonexchangeable Al (Al-$CuCl_2$ - Al^{3+}) was about 3-fold higher than Al^{3+} in the treatment without liming (Table 2). This ratio is similar to that found for the average of 26 soils of Santa Catarina State (Figueiredo & Almeida, 1991). Even in the soil treatment where there was no Al^{3+}, Al-$CuCl_2$ was still between 90 and 100 mmol$_c$ kg^{-1}. Thus, there is a significant amount of Al bonded to other sites in the soil, especially to the organic matter, in addition to that bonded in the negative charges. Consequently, organic matter should be preserved as much as possible in this kind of soil, otherwise it may release active forms of Al to the soil solution whenever the soil pH drops to values below 5.5. The relationship between Al-$CuCl_2$ (Y) and soil pH (X), was Y = 27.4 -3.05X (R^2 = 0.97).

Table 1. Values of soil pH, P, K, and exchangeable Al in the soil samples collected in plots with grain corn after each corn growing season, as affected by addition of increasing rates of dolomitic limestone in an acid Oxisol, in Lages, Southern Brazil. Average of four replicates

Lime rate	92/93	93/94	94/95	95/96	Average
t ha^{-1}			**pH**		
0	4.9	4.7	4.7	4.7	4.7
4.5	5.4	5.5	5.3	5.5	5.4
9.0	5.6	5.9	5.7	5.7	5.7
13.5	6.4	6.4	6.1	6.3	6.3
18.0	6.6	6.7	6.4	6.6	6.6
			Phosphorus$^{(1)}$ (mg kg^{-1})		
0	4.0	1.5	5.0	4.4	3.8
4.5	4.4	2.9	4.9	4.5	4.2
9.0	5.6	3.6	4.2	3.6	5.7
13.5	4.6	3.7	4.4	4.6	4.3
18.0	6.7	3.9	6.2	5.6	5.6
			Potassium$^{(1, 2)}$ (mg kg^{-1})		
0	141	149	149	110	137
4.5	129	132	115	136	128
9.0	162	130	131	109	133
13.5	124	100	125	109	114
18.0	120	158	118	105	125
			Potassium$^{(1, 3)}$ (mg kg^{-1})		
0	126	104	132	130	123
4.5	104	103	116	109	108
9.0	110	98	109	103	105
13.5	90	81	93	103	92
18.0	101	96	105	105	102
			Aluminum$^{(4)}$ (mmol$_c$ kg^{-1})		
0	33	29	31	33	32
4.5	05	05	08	08	06
9.0	0	0	0	0	0
13.5	0	0	0	0	0
18.0	0	0	0	0	0

(1) Extracted with HCl 0.05 mol L^{-1} + H_2SO_4 0.025 mol L^{-1}. (2) Plots for grain. (3) Plots for silage. (4) Extracted with KCl 1.0 mol L^{-1} and determined by titrimetry.

Soil pH and Al^{3+} values remained almost constant during all experimental period, showing that residual effect of liming did not decline and it is longer than what was previously thought for this soil (four to five years). This high buffering capacity is a consequence of high organic matter (45 g kg^{-1}) and clay values (550 g kg^{-1}). Azevedo et al. (1996), working with a similar soil, also found a high liming residual effect, evaluated by soil chemical analysis, even after 23 years of 20 and 40 t ha^{-1} of limestone application.

Table 2. Values of Ca, Mg, Al-$CuCl_2$, Fe, Cu, Zn, and Mn in soil samples collected in plots with grain corn after the last corn growing season (1995/1996), as affected by addition of increasing rates of dolomitic limestone, in an acid Oxisol, in Lages, Southern Brazil. Average of four replicates

Lime rate	Ca(1)	Mg(1)	Al-$CuCl_2$(2)	Fe(3)	Cu(3)	Zn(3)	Mn(3)
t ha^{-1}	—— $mmol_c\ kg^{-1}$ ——			—— mg kg^{-1} ——			
0	13.7	9.0	127	28	6.8	1.5	17
4.5	33.1	27.2	108	20	5.7	1.5	12
9.0	39.0	33.9	93	16	5.4	1.5	13
13.5	53.6	49.0	80	12	4.3	1.4	12
18.0	66.0	61.6	70	11	4.3	1.4	15

(1) Extracted with KCl 1.0 mol L^{-1} and determined by ICP. (2) Extracted with $CuCl_2$ 0.5 mol L^{-1} and determined by ICP. (3) Extracted with HCl 0.1 mol L^{-1} and determined by ICP.

Table 3. Regression equations(1) and coefficients of determination between some soil characteristics(2) (Y) and liming rate (X, in t ha^{-1}) in an Oxisol of Lages, Southern Brazil.

Y	Unit	Equation	R^2
pH	unitless	Y = 4.87 + 0.092X	0.95
Al^{3+}	$mmol_c\ kg^{-1}$	Y = 29.6 - 5.04X	0.99
Al-$CuCl_2$	$mmol_c\ kg^{-1}$	Y = 124 - 3.73X	0.97
Ca	$mmol_c\ kg^{-1}$	Y = 16.1 + 2.78X	0.98
Mg	$mmol_c\ kg^{-1}$	Y = 10.7 + 2.82X	0.99
Fe	mg kg^{-1}	Y = 25.2 - 0.870X	0.97
Cu	mg kg^{-1}	Y = 6.7 - 0.151X	0.94

(1) Coefficients for Mn and Zn equations were not statistically significant at 5% probability level. (2) For Ca, Mg, Fe and Cu the data are only from soil samples collected after the last corn growing season (1995/96); for the others, the data represent the average of all four years.

Exchangeable Ca and Mg increased linearly with increases on liming rate (Tables 2 and 3) because they are components of the limestone. Since a dolomitic lime with an high content of Mg was used, Mg increased proportionally more in the soil than Ca (Tables 2 and 3). Exchangeable K always remained above the sufficiency range in the soil, which demonstrates that the current recommendations for K (COMISSÃO DE FERTILIDADE DO SOLO, 1995) are correct for grain as well as for silage.

Extractable micronutrients were not adversely affected by increasing soil pH. Values of Zn and Mn extracted by 0.1 mol L^{-1} HCl were not affected by changes on soil pH; values of Cu and especially of Fe decreased with increases on soil pH (Tables 2 and 3). Changes in soil pH should affect the amount extracted only for those micronutrients where precipitation plays an important role in controlling soil values, like Fe, regardless of the extractor used. For those micronutrients where inner sphere complexes is the dominant reaction, variation in soil pH should not cause a significant change on extractable values because it only modifies the solid phase-soil solution equilibrium, which affects availability to crops, but keeps the total amount extracted about the same. Similar relationships between soil pH and acid extractable micronutrients were found for Mn (Muraoka et al., 1983a; Abreu et al., 1994), for Zn (Muraoka et al., 1983b; Buzetti, 1992) and for Fe (Camargo et al., 1982). Values for all these micronutrients, however, remained above the soil critical levels in all liming treatments (COMISSÃO DE FERTILIDADE DO SOLO, 1995).

Corn yield increased quadratically with liming (Figure 1). Corn grain yield varied from 5.4 to 8.8 t ha^{-1} and GM yield from 42 to 70 t ha^{-1}. These values are considered reasonable and are similar to those obtained by other authors in the same region (Sangoi, 1990; Ernani et al., 1996). Maximum average yield for grain (7.9 t ha^{-1}) and for green matter (GM) for silage (59 t ha^{-1}) were obtained at soil pH of 6.0 and 6.1, respectively, which agree with the present recommendation for this soil (COMISSÃO DE FERTILIDADE DO SOLO, 1995). It would be necessary to apply, respectively, 12 and 14 t ha^{-1} of pure limestone to raise soil pH up to these values.

Maximum economic efficiency for grain yield during the entire period (four growing seasons) was obtained with addition of 7.5 t ha^{-1} of lime, which increased soil pH to 5.6. To obtain this result, we used local market prices (March of 1997) which were R$100,00 t^{-1} (1.0 US$ = 1.10 R$) for corn grain and R$30,00 t^{-1} for limestone. Thus, considering this economic parameter, pH in this soil does not need to be increased above 5.6 for corn.

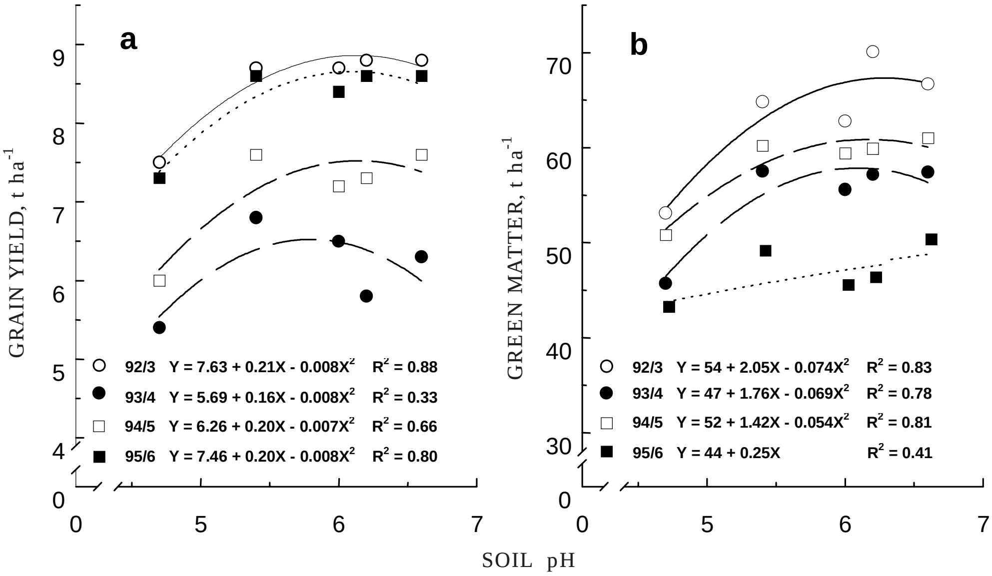

Figure 1. Corn grain yield (a) and corn green matter yield for silage (b)in four consecutive growing seasons, as affected by addition of dolomitic limestone rates in an Oxisol, in Lages, Southern Brazil. Average of four replicates.

Yield increments due to liming were not large. The average increment for all four years was 17% for grain and 20% for GM for silage. In the absence of liming (pH of 4.7, Al^{3+} of 33 mmol$_c$ kg^{-1}, and 56% of Al saturation on CEC), corn yield was always higher than 5.0 t ha^{-1} for grain and higher than 40 t ha^{-1} for GM for silage; in two of the four growing seasons, the yield without liming was higher than 7.0 and 50 t ha^{-1} for grain and GM respectively. A possible explanation for the reason that Al did not restrict corn yield substantially is its association with soil organic matter (45 mg kg^{-1} in this soil). Organic matter has the ability to bond Al (Hoyt and Turner, 1975; Ernani & Gianello, 1982; Miyazawa et al., 1993), decreasing Al activity in the soil solution (Bloom et al., 1979) and its toxicity to crops (Miyazawa et al., 1992). Cation competition (Ca, Mg, K and even H) with Al by the exchange sites on the roots membranes is also a factor which can alleviate Al phytotoxicity (Grauer and Horst, 1992).

The association between grain yield and GM for silage was not significant. Grain yield for the 95/96 growing season was one of the highest, whereas GM for silage in this season was the lowest (Figure 1). Annual yield variations can be explained by differences in climatic conditions.

CONCLUSIONS

1. Corn yield increased with liming up to pH 6.0 for grain and up to pH 6.1 for GM for silage, requiring 12 and 14 t ha^{-1} of limestone, respectively;

2. Liming promoted yield increments of 17 and 20% for grain and GM, respectively. With reference to yields obtained at pH of 5.4 (4.5 t ha^{-1} of limestone), these increments were 5 and 10%, respectively;

3. Maximum economic efficiency for grain yield was obtained at a pH of 5.6 by the addition of 7.5 t ha^{-1} of lime;

4. Cationic micronutrients (Fe, Cu, Zn, and Mn) were kept above the soil critical levels in all liming treatments, and only Cu and Fe decreased with increases in soil pH.

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