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Several field experiments were sampled to determine the effect of previous treatments on the movement of Ca + Mg. Three to four years after application of gypsum, in ordinary superphosphate, subsoil pH and Ca + Mg status were increased, and Al saturation decreased at depths as great as 75 to 90 cm. *Zea mays* L. roots growing in the improved subsoil environment were able to take up water and withstand droughts.

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Calcium Leaching to Increase Rooting Depth in a Brazilian Savannah Oxisol[1]

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ABSTRACT

Root growth in subsoils of Oxisols is often precluded because the roots of many crops are sensitive to soil acidity. This increases plant stress during dry periods when available soil water in the limed surface layers is exhausted. The low soil CEC and high rainfall in Central Brazil suggest that soluble calcium salts might leach below the plow layer and reduce soil acidity. To test this possibility, soil columns, simulating field profiles, were constructed in the laboratory and various Ca salts were mixed in the 0 to 15-cm layer. Addition of 1,200 mm water to 2,000 kg/ha Ca added as $CaCl_2$, $CaSO_4$, and $CaCO_3$ caused Ca movement to 180, 75, and 25 cm, respectively. Calcium sulfate decreased Al saturation and increased soil pH at depth.

Several field experiments were sampled to determine the effect of previous treatments on the movement of Ca + Mg. Three to four years after application of gypsum, in ordinary superphosphate, subsoil pH and Ca + Mg status were increased, and Al saturation decreased at depths as great as 75 to 90 cm. *Zea mays* L. roots growing in the improved subsoil environment were able to take up water and withstand droughts.

Additional index words: Gypsum, Sulfate sorption, Soil water extraction, Subsoil pH, Ca + Mg, Aluminum saturation, Maize, Liming, Drought resistance.

EFFICIENT root growth in the subsoils of Oxisols and Ultisols is often precluded because the roots of many agronomic crops are sensitive to soil acidity. This presents a serious impediment to crop production, particularly during dry periods when the plants quickly exhaust the available soil water in the limed surface layers.

The tropical savannah region ("cerrado") of central Brazil occupies approximately 180 million ha, much of it level or gently rolling. Adequate light intensity, annual rainfall of about 1,500 mm, and generally excellent soil physical properties indicate a large potential for food production. The frequent occurrence of rainless periods of 1 to 3 weeks duration during the rainy summer season, however, is a serious problem to expanded agriculture.

One way of reducing the effects of the dry periods is through deeper root growth. Gonzalez (1976) showed that incorporation of lime to 30 cm allowed the roots to penetrate and use stored water throughout the limed layer. Increasing the depth of liming from 15 to 30 cm increased average yield of maize grain 1,300 kg/ha.

There is a great deal of interest in exploring ways for reducing the effects of subsoil acidity which do not necessitate the use of deep plowing or similar mechanical methods involving large expenditures of fossil fuel energy. Pearson et al. (1962) showed for Puerto Rico that heavy applications of ammonium sulfate in association with lime promoted movement of Ca to depths of 60 cm over a period of 2.5 years. Weir (1974) found that the use of residual-acid N fertilizers in association with surface applications of lime resulted in an appreciable downward movement of bases in a Red-Yellow Latosol. Reeve and Sumner (1972) found that although the leachate from the heavily limed surface soil of a South African Oxisol increased sub-surface Ca, a much greater increase occurred with equivalent applications of gypsum. In a medium-textured Red-Yellow Latosol near Brasilia, Brazil, Gonzalez (1976) found marked movement of Ca to 45 cm with applications of 218 kg/ha P as ordinary superphosphate (OSP). He suggested that the approximately 1,500 kg/ha gypsum ($CaSO_4 \cdot 2H_2O$) contained in the OSP might be responsible for the movement. Couto et al. (1979) showed that sulfate added to highly weathered tropical subsoils raised pH, probably by causing ligand exchange with hydroxyl groups.

In order to further investigate the practical aspects of Ca leaching, soil column experiments were initiated in the laboratory, and field experiments already in existence at the Cerrado Agricultural Research Center (CPAC) near Brasilia, Brazil, were sampled at depth to observe the effects of various applications of soil amendments on the chemical status and rooting conditions in the subsoil.

MATERIALS AND METHODS

Laboratory Column Experiments

Duplicate columns 218 cm tall were set up with sections of 9.7-cm-inside-diameter PVC irrigation tubing 5 or 15 cm long. The columns were carefully filled section by section with air-dried soil screened through a 2-mm sieve to obtain a bulk density of 1.08 g/cm^3, approximately that of soil in the field. The 0 to 15-cm sections consisted of surface soil collected from an experiment carried out on a clayey Dark Red Latosol, Cerradão phase (Typic Haplustox, fine, kaolinitic, isohyperthermic, in the U.S. Taxonomy). Ordinary superphosphate fertilizer, equivalent to 873 kg/ha P, was mixed in the 0 to 15-cm sections. This supplied about 600 kg/ha Ca as $Ca(H_2PO_4)_2$ and about 1,400 kg/ha Ca as $CaSO_4 \cdot 2H_2O$. During the 2 years that this soil was cultivated, it received 314 kg/ha P as OSP, 3,000 kg/ha lime, and 208 kg/ha K as KCl. The remainder (15 to 210 cm) of the columns consisted of virgin soil from the 30 to 45-cm layer of a profile excavated near the experiment. Chemical properties of the soils are shown in Table 1.

Each day for 15 days 100 mm of distilled water (slightly more than the maximum daily rainfall observed in 1976) was dripped slowly onto the surface of the columns. After flow from the columns nearly ceased, the soil from each section was thoroughly mixed, sampled for water content, dried, and chemically analyzed.

Extractable Al was measured by mixing the soil with 1 *N* KCl (1:10 soil solution ratio) and titrating the extract with 0.10 *N* NaOH to the bromthymol blue endpoint. Exchange-

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able Ca and Mg were similarly extracted and measured by atomic absorption spectrophotometry or by titration with 0.01 *N* EDTA with Eriochrome Black T. as indicator (Vettori, 1969). Potassium was determined by flame photometer on a 1:10 soil:solution extract of 0.05 *N* HCl + 0.025 *N* H_2SO_4 stirred for 5 minutes. Sulfate was extracted with monobasic Ca phosphate and determined turbidometrically (Hunter, 1977). The pH was measured in a 1:1 soil:water suspension after equilibrating 1 hour. Soil moisture was measured by oven-drying at 105 C for 48 hours.

The agreement between the duplicate columns was considered sufficient to proceed without replication.

The second column experiment was carried out on a reconstructed 0 to 135-cm profile removed in 15-cm increments from the same excavation. The initial values of extractable Ca in the test soil before leaching are shown in Fig. 1. The initial pH was 4.5 at the 15 to 30-cm depth and 4.1 between 30 and 60 cm, and rose gradually to 5.0 at 135 cm. Extractable Al was 0.9 meq/100 g at 15 cm, and gradually decreased to zero at the 105-cm depth. The virgin 0 to 15-cm soil that received the treatments shown in Table 2 was incubated for 3 weeks, and then air-dried. The columns were constructed as before except that total height was increased, and the 135 to 233-cm sections were uniformly filled with a very low CEC subsoil. Before addition of the air-dry 0 to 15-cm section, the remainder of each column was pre-moistened by daily additions of 40 or 80 mm water until dripping commenced. After the top section was in place, water was slowly added to the column at 40 mm/day until a total of 1,200 mm water had been applied. The columns were dismounted as before, except that a layer of soil 1 to 2 cm thick was removed from the top and bottom of each section in order to avoid contamination from the soil in the adjacent section.

Table 1. Leaching influences on chemical properties of an Oxisol that had received heavy applications of ordinary superphosphate.

Depth in column	pH	Ca	Al	Mg	K	Al saturation	Water content
cm		meq/100 g			ppm	%	
			Before treatment and before leaching				
0 to 15	5.2	1.80	0.04	0.48	108	2	-
15 to 218	4.0	0.03	0.6	0.03	8	87	-
			After leaching				
0 to 15	5.4	2.89	0.0	0.18	19	0	26
15 to 20	5.0	1.10	0.2	0.04	19	13	29
20 to 25	4.7	0.58	0.5	0.03	16	42	29
25 to 30	4.7	0.63	0.4	0.03	16	39	29
30 to 45	4.7	0.67	0.4	0.04	15	36	30
45 to 60	4.7	0.74	0.4	0.07	20	31	31
60 to 75	4.7	0.71	0.4	0.14	22	33	31
75 to 90	4.8	0.26	0.5	0.18	13	49	31
90 to 105	4.8	0.02	0.6	0.02	5	91	32
105 to 120	4.5	0.03	0.5	0.02	6	90	32
120 to 135	4.4	0.03	0.5	0.02	6	90	33
135 to 150	4.4	0.04	0.5	0.02	7	87	34
150 to 165	4.3	0.04	0.6	0.02	7	87	37
165 to 180	4.2	0.05	0.6	0.03	8	85	41
180 to 195	4.3	0.05	0.5	0.03	8	84	45
195 to 210	4.4	0.05	0.5	0.03	8	84	49

Field Experiments

To observe the effects of Ca and Mg leaching under field conditions, soil samples were collected from two experiments at CPAC. The experiments were located on the same soil used in the columns, about 400 m from the excavated profile mentioned earlier.

The first experiment sampled was a P rate study initiated in November, 1972 (Yost, 1976). Varying broadcast rates of OSP were applied and incorporated to 20-cm depth after 4,000 kg/ha calcitic lime were plowed in. The 873 kg/ha P treatment, however, received 35 kg/ha P banded initially and 838 kg/ha 8 months later. The five replications in the experiment were sampled after the fifth and sixth maize harvests, using composites of three and five subsamples per plot respectively. Composites of samples from five locations 2 m outside the experiment (where no lime or fertilizer had been applied) were also collected.

The influence of three levels of lime on Ca and Mg movement were analyzed by sampling a P sources × lime factorial experiment planted with *Brachiaria decumbens* pasture grass in December, 1973 (R. S. Yost et al. 1974. Phosphorus sources and rates for forage crops. p. 92-102. *In* Soil Science Dep. Agronomic-economic research on tropical soils. Annual Report for 1974. North Carolina State Univ., Raleigh.). Large plots treated with 0, 3,000, and 4,500 kg/ha of limestone were divided into 15 subplots each. The subplots received broadcast applications of various rates of several P fertilizers which were incorporated to 20 cm. In June, 1977, treatments of interest were sampled by compositing three soil subsamples from each subplot of the three replicates in the experiment.

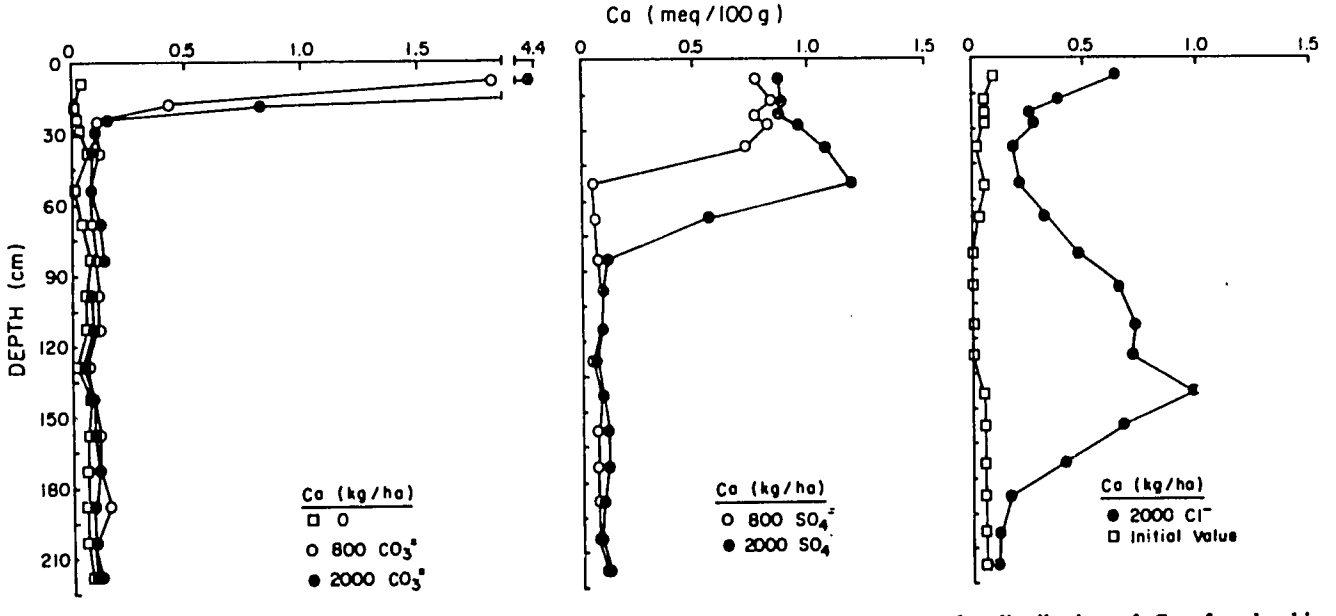

Fig. 1. Results of the second column experiment showing the effects of various anions on the distribution of Ca after leaching with the equivalent of 1,200 mm rainfall in a reconstructed virgin Dark Red Latosol profile 0 to 135 cm. Calcium as carbonate, sulfate, or chloride was added to the 0 to 15-cm layer and incubated 3 weeks before leaching began.

RESULTS AND DISCUSSION

Laboratory Column Experiments

Selected chemical properties of the soil columns in the first experiment before and after leaching are listed in Table 1. Calcium, K, and Mg all moved as a pulse. The movement of Mg^{2+} was greater than that of K^+ which was greater than that of Ca^{2+}. In the zone of increased base status (15 to 90 cm), pH increased and KCl-extractable Al tended to decrease.

The equivalent of 800 mm precipitation drained from the column after the last addition of water with the resulting distribution of water content as shown (Table 1). Field capacity for these soils is approximately 29%. The water content was less than 115% of field capacity in the top 135 cm of the column.

The results of the first column experiment with OSP showed that the leaching observed by Gonzalez (1976) could be reproduced in the laboratory. The substitution of $CaSO_4$ for OSP in the second experiment gave similar results (Fig. 1), confirming the supposition of Gonzalez that gypsum in the OSP was responsible for the leaching he observed.

In the second column experiment the Ca chloride treatment produced pulse movement of Ca^{2+} to as deep as 150 cm; the sulfate produced a Ca^{2+} peak at 60 cm; but the Ca^{2+} pulse from $CaCO_3$ reached only 25 cm into the soil (Fig. 1).

Increasing the Ca sulfate rate from 800 kg/ha Ca to 2,000 kg/ha Ca increased the depth of important Ca peneration from 45 cm to 75 cm. The extractable Al content decreased in the subsurface sections where Ca and sulfate contents were high, and there was a tendency towards increased pH (data not shown), but the effects were somewhat less marked than in the first column experiment.

Differences in the rate of descent of Ca observed in the second experiment can be partially explained by the nature of the accompanying anion, which must be present to maintain electroneutrality. The carbonate of the limed treatments is neutralized by reaction with the acidity present in the surface soil and so no anion is available to accompany the Ca, most of which is absorbed on the exchange complex (Reeve and Sumner, 1972). The Ca added as $CaCl_2$ leached the most rapidly. Chloride does not readily react with the soil, and Ca chloride is quite soluble: the 2,000 kg/ha Ca level dissolves in the equivalent of 1 mm of rain. Calcium sulfate is less soluble: 226 mm of precipitation are required to dissolve the same amount of Ca. Moreover, the rate of descent of sulfate is slower because of reactions of sulfate with the soil.

Table 2. Chemical properties of the 0 to 15-cm layer of an Oxisol following application of Ca^{2+} carriers and incubation for 3 weeks at 83% field capacity.

Calcium† source	Calcium rate	pH	Al	Ca	Ca + Mg
	kg/ha		meq/100 g		
			Before incubation		
–	–	4.4	1.1	0.1	0.3
			After incubation		
Check	0	4.1	1.2	0.1	0.4
$CaCO_3$	800	5.0	0.1	2.4	2.7
$CaCO_3$	2,000	5.9	0.0	5.1	5.4
$CaSO_4 \cdot 2H_2O$	800	4.3	0.8	2.6	2.7
$CaSO_4 \cdot 2H_2O$	2,000	4.3	0.6	6.1	6.1
$CaCl_2$	2,000	3.7	0.7	5.9	6.2

† All but the check treatment also received monocalcium orthophosphate equivalent to 131 kg/ha P.

Field Observations

The distribution of Ca + Mg with depth as a function of rates of P as OSP applied in the field is shown in Fig. 2 and Table 3. Analysis of the 70 and 873 kg/ha P treatments for phosphate-extractable sulfate indicated that the layers below 30 cm with high values of Ca + Mg also had high sufate contents (results not shown). The pH of the subsoil was significantly increased by OSP additions. Decreases in Al saturation were brought about by decreases in Al as well as by increases in the Ca + Mg status.

The agronomic significance of the reduction in subsurface acidity was demonstrated by comparing the water uptake on a plot receiving 559 kg/ha P as OSP with that occurring in a nearby maize experiment fertilized with 148 kg/ha P as triple superphosphate (TSP), after 2 weeks of severe drought. In the TSP treatment, no roots were found below 45 cm, where the Al saturation was over 60% (Table 4). The wilting maize plants on the TSP plot had extracted more water from the 0 to 45-cm layer than those in the other plot, but the deep roots of the OSP treatment had better utilized water from 45 cm to the lowest depth measured (120 cm).

The effect of increasing liming rates on Ca + Mg movement for several P sources is shown in Fig. 3. At each rate of lime ordinary superphosphate produced more Ca + Mg movement than the other P sources. The movement observed in the limed no-P treatments

Table 3. Soil properties at selected depths as a function of rates of OSP applied in 1972 (838 kg/ha P of the 873 kg/ha treatment was applied in 1973).

Depth	P added	pH	Ca + Mg	Al
cm	kg/ha		meq/100 g	
			Sampled June, 1977	
30 to 45	70	4.54	0.84	0.51
	140	4.70	0.74	0.46
	279	4.82	1.03	0.38
	559	4.84	1.48	0.31
	873	4.86	1.38	0.26
	$S_{\bar{x}}$ (24 df)	0.083	0.097	0.043
45 to 60	70	4.34	0.54	0.42
	140	4.46	0.68	0.34
	279	4.64	0.79	0.28
	559	4.92	1.42	0.17
	873	4.86	1.42	0.20
	$S_{\bar{x}}$ (24 df)	0.060	0.077	0.030
			Sampled Aug. 1976	
45 to 60	Virgin	3.97	0.02	0.56
	70	4.09	0.20	0.46
	140	4.26	0.40	0.34
	873	4.72	1.11	0.23
	$S_{\bar{x}}$ (12 df)	0.083	0.067	0.043
75 to 90	Virgin	3.98	0.09	0.20
	70	3.98	0.18	0.29
	140	4.07	0.25	0.19
	873	4.74	1.00	0.10
	$S_{\bar{x}}$ (12 df)	0.050	0.090	0.020

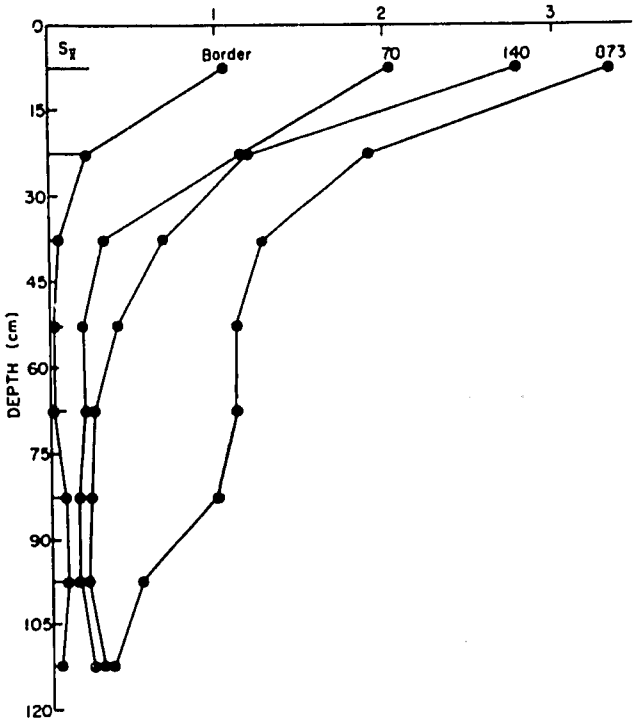

Fig. 2. Effect of varying rates of P (kg/ha) as OSP on Ca + Mg in the soil profile as sampled August, 1976. Standard error of the mean is based on 12 df.

is presumably made possible by the anions associated with blanket applications of KCl, urea, and sulfates. Plant growth and associated nutrient uptake on these treatments were very small. Calcium might also have been transported by diffusion and animal activity.

CONCLUSIONS

The persistence of $CaSO_4$ in the soil depends on the rate of dissolution of added gypsum, the degree of sorption, and the rate of subsequent desorption. Couto et al. (1979) found that the B_2 horizons of two Brazilian Oxisols and an Alfisol sorbed from 0.4 meq to about 1.1 meq $SO_4^{=}$/100 g soil from solution, while the Ap horizon sorbed much less. After the sulfate sorption capacity of the soil is reached, additional soluble sulfate is present only temporarily, and as water moves through the soil it leaches to lower portions of the profile. Once all the $CaSO_4$ incorporated in the surface layer has dissolved, continued addition of water causes desorption of some of the sulfate (Couto et al., 1979). The extent of the desorption determines how greatly the soil will be permanently changed as a result of one application of Ca sulfate. The process is not rapid; in the experiments reported here, significant concentrations of Ca + Mg are still evident at depths of interest 6 years after application.

Movement of Ca sulfate into the subsoil improves the conditions for root growth in several ways. Additional Ca is needed to meet the nutritional requirements for crop root growth because some native Cerrado soil solution levels of Ca are as low as 1.2 ppm

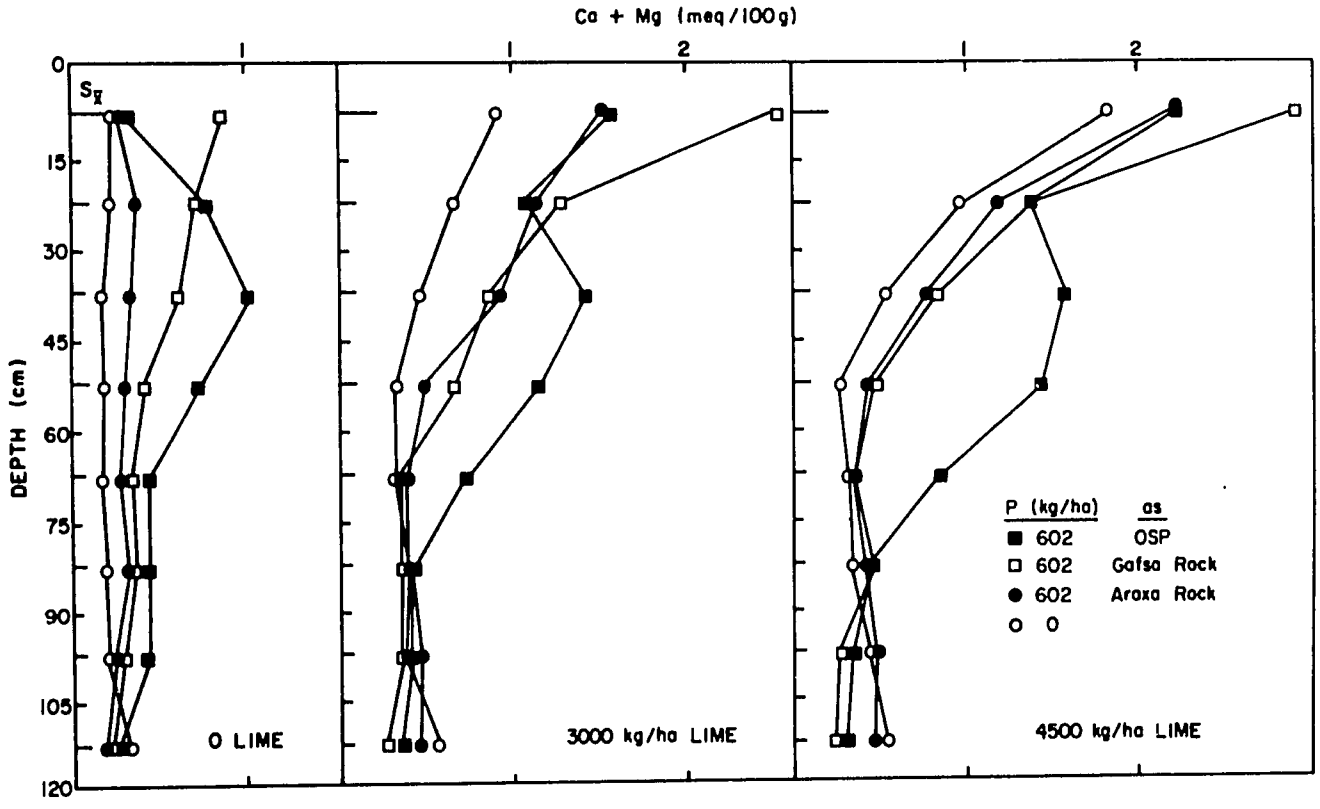

Fig. 3. The distribution of Ca + Mg in the P sources × lime experiment for three P sources. Gafsa rock ("hiperfosfato") is a treated Moroccan rock phosphate with high citrate solubility. Araxa Rock is a Brazilian rock phosphate of low citrate solubility. Standard error of the mean is based on 24 df.

Table 4. Compared effect of ordinary superphosphate versus triple superphosphate on depth distribution of soluble Ca + Mg, pH, Al saturation, maize rooting, and moisture content in an Oxisol. The soil moisture values are significantly different at 90% or 95% in all but the 30 to 45-cm and 75 to 90-cm layers.

	Ca + Mg		pH		Al saturation		Roots		Soil moisture	
Depth	TSP	OSP	TSP	OSP	TSP	OSP	TSP	OSP	TSP	OSP
cm	meq/100 g				— % —				— % —	
0 to 15	3.4	1.9	5.4	5.1	1	14	yes	yes	13.6	16.6
15 to 30	2.1	1.3	5.0	4.7	12	30	yes	yes	18.1	19.9
30 to 45	0.8	1.4	4.6	4.7	47	21	yes	yes	20.2	21.7
45 to 60	0.5	1.5	4.1	4.8	61	12	no	yes	22.7	20.6
60 to 75	0.4	1.1	4.0	4.5	62	17	no	yes	23.6	20.8
75 to 90	0.2	0.8	4.2	4.6	73	18	no	yes	24.3	23.3
90 to 105	0.1	0.5	4.2	4.3	80	22	no	yes	26.0	23.2
105 to 120	0.1	0.5	4.2	4.4	74	8	no	yes	25.3	24.1

(Gonzalez 1976). Increasing the level of Ca in the soil solution also reduces the ratio of Al to bases. This decreases the toxicity of Al (Zanstra, 1972). As shown in Tables 1 and 3, the absolute amount of extractable Al also decreases with Ca sulfate additions, possibly because of increases in pH arising from sorption of sulfate. Rajan (1978) showed that OH^- was released when $SO_4^=$ was sorbed by Fe oxides, and Parfitt (1978) showed the same for Al oxides. Couto et al. (1979) showed pH increases of up to 0.5 units when Brazilian soils were treated with sulfate solutions. The changes in pH observed in our column and field experiments were variable, but an increase of from 0.1 to 0.8 units was almost always observed where the Ca status of the soil was increased due to Ca sulfate additions. In contrast, the soil layers to which Ca chloride had leached tended to show a decrease in pH when compared with the check column (data not shown).

Significant reductions in Al toxicity can be obtained with relatively small additions of Ca sulfate because of the low CEC of the soils. For example, in the P sources × lime experiment at the 60 to 75-cm depth in the 4,500 kg/ha lime treatment, the Ca + Mg increase due to OSP was 0.52 meq/100 g. The pH increased 0.75 units and the exchangeable Al decreased by 0.31 meq/100 g. The combined result was a marked decrease in Al saturation: from 64 to 24%, which is sufficient to allow maize root growth (Table 4).

Couto et al. (1979) verified the observations of other authors that sulfate sorption decreases as the pH increases. As shown in Fig. 3, increasing the rate of liming greatly increased the amount of Ca which leached below the 30-cm layer. Although the location of the Ca peak remained the same, the application of 4,500 kg/ha of lime reduced the Al saturation to about half or less of the value where no surface lime had been applied, down to a depth of 75 cm (data not shown).

The marked leaching of K and Mg associated with the addition of gypsum indicates that special attention should be paid to maintaining adequate levels of these nutrients in the surface soil (Table 1).

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