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Aluminum and Calcium Constraints to Continuous Crop Production in a Brazilian Amazon Oxisol

T. J. Smyth* and M. S. Cravo

ABSTRACT

Acidity constraints in Oxisols of the Amazon may entail both Al toxicity and Ca deficiency. A field study was conducted in a Xanthic Hapludox near Manaus, Brazil, to evaluate lime and Ca requirements for corn (*Zea mays* L.), cowpea (*Vigna unguiculata* L.), soybean [*Glycine max* (L.) Merr.], and peanut (*Arachis hypogea* L.) during five consecutive years. Calcitic lime was applied once at rates of 0, 0.6, 1.2, 2.3, and 4.6 t of $CaCO_3$ equivalent per hectare. The effects of 1 t ha^{-1} of gypsum, applied to four crops, were evaluated with lime rates of 0, 1.2 and 2.3 t ha^{-1}. During the two initial years, maximum yields of corn and soybean occurred with 1.2 t of lime ha^{-1}. In subsequent years, maximum corn yields occurred to 4.6 t of lime ha^{-1}. Liming only increased cowpea yields in the third year. Peanut yields increased with liming to the highest lime rate in the fourth and fifth year. Gypsum increased yields for all crops to which it was applied. When averaged across time gypsum increased exchangeable Ca and reduced exchangeable Al by 0.41 and 0.20 cmol$_c$ kg^{-1}, respectively. Increased peanut shelling percent and peanut and cowpea leaf Ca concentrations with lime, gypsum, or both were indicative of improved soil Ca supply. Maximum corn and soybean yields occurred at 27% Al saturation, whereas the critical level for peanut was 54%. Regressions of relative yield for all lime and gypsum treatments on the exchangeable Ca:Al ratio gave R^2 values equal to those achieved with Al or Ca saturation. Critical Ca:Al ratio values would provide a useful index to ensure that lime recommendations based on Al saturation provide an adequate Ca supply.

SOIL ACIDITY is a major constraint for crop production in the Amazon Basin. Cochrane and Sanchez (1982) estimated that 81% of the land area under native vegetation had surface soil layers with pH <5.3, 75% had Al saturation >40%, and 46% had <0.4 cmol$_c$ kg^{-1} of exchangeable Ca. When slash-and-burn practices are used to clear the rainforest, surface soil acidity is temporarily decreased by the liming effect of the ash (Seubert et al., 1977; Smyth and Bastos, 1984). With subsequent cropping a progressive decline in exchangeable Ca and increase in exchangeable Al eventually leads either to correction of acidity constraints by liming or migration to new land.

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Although lime deposits have been identified and measured in the Brazilian Amazon (Moniz, 1983) information is lacking on both the effectiveness of these sources and the recommended levels which should be used for major crops grown in the region. In an extensive review of liming in the humid tropics, Pearson (1975) noted that near-maximum yields often occurred with the first increment of lime, often a rate as low as 0.5 t ha^{-1}. These observations raised the possibility that Ca deficiency was an important constraint, in addition to Al toxicity, for highly weathered soils. Under such conditions other Ca sources, such as gypsum, could be used. The objectives of this study were to evaluate lime requirements and the extent to which Ca is a limiting nutrient for corn, soybean, cowpea, and peanut on an Oxisol in the Brazilian Amazon.

MATERIALS AND METHODS

The experiment was conducted at the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) Experiment Station 30 km north of Manaus, Amazonas (3°8' S, 59°52' W, 50 m elevation). Average annual rainfall is 2420 mm with a maximum of 295 mm per month in March and April and a minimum of 105 mm during the months of August and September. Mean monthly maximum and minimum temperatures are 32 and 22 °C, respectively (EMBRAPA, 1984). The soil was classified as a Xanthic Hapludox (clayey, kaolinitic, isohyperthermic) (EMBRAPA, 1979). Primary forest vegetation was cut and burned in 1974. After two consecutive years of upland rice cultivation without lime or fertilizer inputs, the land was abandoned. Selected chemical

Table 1. Selected chemical properties for the Xanthic Hapludox prior to initiating the field experiment.

Depth	pH in H_2O	Exchangeable Ca	Mg	K	Al	Al Sat.	Organic C
m		cmol$_c$ kg^{-1}				%	g kg^{-1}
0–0.2	4.6	0.54	0.19	0.08	1.13	58	21.3
0.2–0.4	4.3	0.14	0.06	0.05	1.10	81	9.0
0.4–0.6	4.3	0.13	0.07	0.04	0.90	79	7.0

soil properties, prior to initiating the experiment, are shown in Table 1.

The lime source was a calcitic (80% $CaCO_3$ and 2.8% $MgCO_3$) deposit from Maués, Amazonas. Particle size distribution of the lime by dry sieving was as follows: 0.1% greater than 2.36 mm, 1.4% between 2.36 and 0.85 mm, 35.9% between 0.85 and 0.25 mm, and 62.6% finer than 0.25 mm. Lime was applied at rates of 0, 0.6, 1.2, 2.3, and 4.6 t ha^{-1} of $CaCO_3$ equivalent. Three additional treatments with 0, 1.2, and 2.3 t ha^{-1} of lime received 1 t ha^{-1} of broadcast-applied gypsum, providing a factorial arrangement among three lime rates and two gypsum rates. A randomized complete block design with four replications was used. Plot dimensions were 5 by 8 m. After lime was applied in August 1983, the entire area was plowed and disked. Gypsum was applied prior to planting corn in 1983 and 1985 and peanut in 1987 and 1988. Gypsum and broadcast fertilizers were incorporated with a rotovator to a 0.15-m depth in all crops.

Ten crops (four corn, three cowpea, two peanut, and one soybean) were planted during the period of November 1983 to April 1988. Crop sequence and varieties are shown in Table 2. Populations were approximately 50 000 plants ha^{-1} for corn, 200 000 for cowpea, 300 000 for peanut, and 250 000 for soybean. For the two final cowpea crops and both peanut crops, local varieties (IPEAN V-69 and Tatu Vermelho) were compared with varieties introduced from IITA for cowpea and the Peruvian Amazon for peanut in subplots of the lime and gypsum treatments.

Applications of fertilizers were based on results from nearby experiments designed to evaluate nutrient requirements for corn, cowpea and soybean in this soil (Smyth et al., 1987). Nitrogen for all corn crops was split into three applications of 27 kg N ha^{-1}, broadcast at planting as $(NH_4)_2SO_4$ and sidedressed at 25 and 55 d after planting as urea. Phosphorus (as triple superphosphate) was applied 110 and 44 kg ha^{-1} for corn in 1983 and 1985, 44 kg ha^{-1} for soybean, and 44 kg ha^{-1} for both peanut crops. All corn, soybean, and peanut crops received 50 kg K ha^{-1} as KCl. Corn crops in 1983 and 1986 received 30 kg Mg ha^{-1} as $MgSO_4$. Micronutrients were applied to corn crops in 1983 and 1986 at rates of 1 kg B ha^{-1} as borax, 2 kg Cu ha^{-1} as $CuSO_4$ and 5 kg Zn ha^{-1} as $ZnSO_4.7H_2O$. The soybean crop received 0.02 kg Mo ha^{-1} as $(NH_4)_2MoO_4$ and seeds were treated with a commercial *Bradyrhizobium japonicum* inoculum.

In all crops, soil samples (0-0.2 m) were taken from each plot at either corn silking or midflowering stage for cowpea, soybean, and peanut. Each sample contained 10 random subsamples from the central 3- by 6-m plot area. Soil pH was measured in a 1:2.5 soil-water suspension. Exchangeable Al, Ca, and Mg were extracted with 1*M* KCl, and exchangeable K was extracted with 0.05 *M* HCl + 0.0125 *M* H_2SO_4. Calcium and Mg were determined by atomic absorption spectrophotometry, K by flame photometry, and Al by titration with NaOH to the phenolphthalein endpoint. Aluminum and Ca saturation were estimated as the proportion of these cations in the effective cation exchange capacity (Al + Ca + Mg + K).

For the final cowpea crop and both peanut crops leaf samples were collected at the same time as soil samples from the central 1.5- by 6-m subplot area for each variety. Samples consisted of 20 fully expanded leaves at the top of the plant canopy. After wet ashing with H_2O_2 and H_2SO_4, Ca was determined by atomic absorption spectrophotometry.

Harvest measurements were taken from the central three rows of corn or five rows of soybean and the first cowpea crop, minus 1 m from each end of the plots. For the cowpea and peanut crops containing varietal comparisons harvest area was reduced to the central three rows in each subplot. Grain yields for all crops were adjusted to 130 g kg^{-1} moisture. Only soybean and peanut residues were removed from the field at harvest. Peanut shelling percentage was determined as the ratio of seed to seed plus shell weight.

Data were analyzed using analysis of variance and regression procedures in the Statistical Analysis System (SAS Institute, Inc., 1985). Homogeneity of variance was tested prior to combining sampling dates for evaluation of treatment, time (as subplots), and treatment by time effects on chemical soil data. Regression equations describing changes in soil Ca and Al with time were generated using significant components of the analysis of variance. Relationships between yield and applied lime were developed using either log functions or the Type III family of linear-plateau models as described by Anderson and Nelson (1987). Linear-plateau models were also used to describe the relations between yield and chemical soil data.

Table 2. Sequence, varieties, and dates of planting and harvest for all crops grown during the experiment.

Crop	Cultivar	Planting Date	Harvest Date
Corn	BR-5102	November 1983	March 1984
Cowpea	IPEAN V-69	June 1984	August 1984
Corn	BR-5102	November 1984	March 1985
Soybean	Tropical	March 1985	July 1985
Cowpea	IPEAN V-69 VITA-3	August 1985	November 1985
Corn	BR-5102	December 1985	April 1986
Cowpea	IPEAN V-69 VITA-3	June 1986	September 1986
Corn	BR-5102	December 1986	April 1987
Peanut	Blanco Tarapoto Tatu Vermelho	May 1987	September 1987
Peanut	Blanco Tarapoto Tatu Vermelho	April 1988	August 1988

RESULTS AND DISCUSSION

Effects of Lime on Yield and Soil Acidity

Corn, soybean, and peanut grain yields were significantly increased with liming. In the two initial corn crops, near maximum yields were obtained with 1.2 t lime ha^{-1} (Fig. 1). In subsequent years there was a progressive increase in corn yields to the highest rate

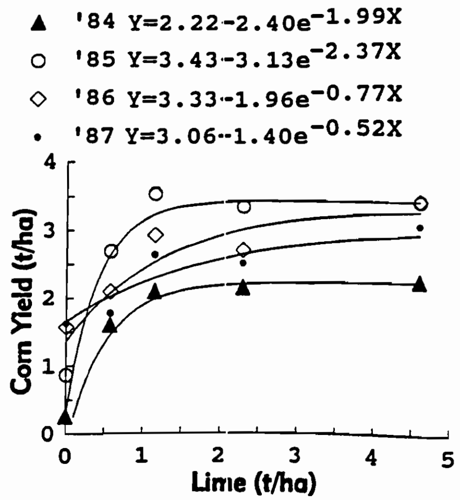

Fig. 1. Observed (symbols) and predicted (lines) corn grain yields during four consecutive years as a function of applied lime. Lime was applied prior to planting the initial corn crop.

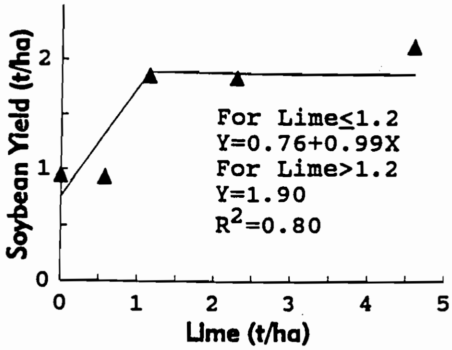

Fig. 2. Observed (symbols) and predicted (line) soybean grain yield in 1985 as a function of lime applied in 1983.

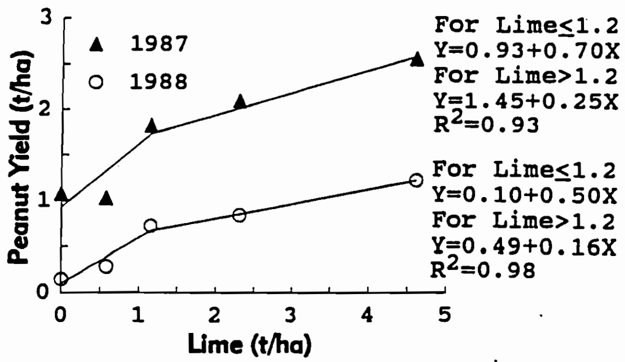

Fig. 3. Mean yield for Blanco Tarapoto and Tatu Vermelho peanut cultivars in 1987 and 1988 as a function of lime applied in 1983.

of lime. Increased corn yields for the unlimed plots in 1986 and 1987 may be associated with a reduced phytotoxicity of solution Al through complexation with dissolved organic compounds (Hue et al., 1986; Lu and Hue, 1990). Residues from all crops, except soybean and peanut, were incorporated prior to planting subsequent crops. In a Haplorthox from Indonesia, Wade et al. (1988) attributed the positive effects of green manures on a subsequent rice crop to reduced Al toxicity but detected no changes in the exchangeable cations for soil samples taken at rice harvest.

For the soybean crop, grown during the second year after liming, a yield plateau of 1.9 t ha^{-1} was achieved with 1.2 t lime ha^{-1} (Fig. 2). Yield response to residual lime in both peanut crops were described by two linear segments with different slopes (Fig. 3). For lime rates $\leq$ 1.2 t ha^{-1}, shelled peanut yields in 1987 were increased by 0.7 t ha^{-1} for each t of lime. At higher lime rates, each additional t of lime increased yields by 0.25 t ha^{-1}. Despite a reduction in yields by heavy infestation of *Cercospera*, a similar yield response pattern was observed for peanut in 1988.

In both peanut crops there was a significant yield difference between varieties but lime–by–variety interactions were not significant. Mean yields across lime rates for Blanco Tarapoto were 1.9 and 0.8 t ha^{-1} in 1987 and 1988, respectively. For peanut variety Tatu Vermelho mean yields in 1987 and 1988 were 1.6 and 0.6 t ha^{-1}, respectively. Liming increased shelling percent and leaf Ca concentration for both

Table 3. Shelling percentage and leaf Ca content for Blanco Tarapoto (BT) and Tatu Vermelho (TV) peanut varieties during two crop cycles as a function of lime and gypsum treatments.

		1987						1988					
		Shelling			Leaf Ca			Shelling			Leaf Ca		
Lime	Gypsum†	BT	TV	Mean	BT	TV	Mean	BT	TV	Mean	BT	TV	Mean
– t ha^{-1} –		%			g kg^{-1}			%			g kg^{-1}		
0	0	27	64	50	5.8	6.8	6.3	34	56	45	6.7	5.0	5.8
0.6	0	42	62	52	6.8	11.6	9.2	41	54	48	7.3	5.3	6.3
1.2	0	56	69	63	8.8	11.0	9.9	52	68	60	10.3	10.0	10.1
2.3	0	60	73	66	9.3	11.5	10.4	59	68	63	12.8	10.6	11.7
4.6	0	71	73	72	11.6	13.6	12.6	69	74	71	14.6	15.8	15.2
0	1	71	74	73	10.0	13.3	11.6	70	74	72	13.0	13.4	13.2
1.2	1	69	74	72	10.3	12.3	11.3	69	74	72	13.9	15.6	14.8
2.3	1	72	74	73	12.3	12.0	12.2	71	74	72	16.2	17.5	16.8
Mean		60	70		9.4	11.5		58	68		11.8	11.7	
						— LSD (0.05) —							
Treatment			11			2.0			12			3.5	
Variety			4			0.9			2			NS‡	
Tmt. × Var.			11			NS			7			NS	

† Gypsum (1 t ha^{-1}) was applied at planting to each peanut crop and to corn crops harvested in 1984 and 1986.
‡ NS = *F* value for effect not significant at $p \leq 0.05$.

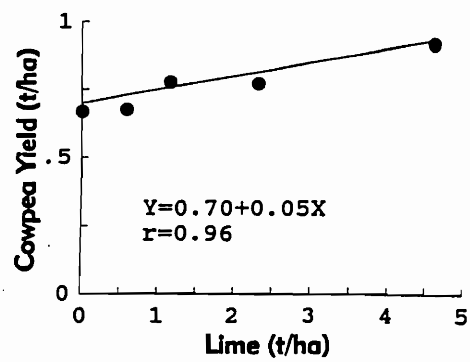

Fig. 4. Mean yield for IPEAN V-69 and VITA 3 cowpea cultivars in 1986 as a function of lime applied in 1983.

varieties (Table 3), but there was a greater response with the large-seeded Blanco Tarapoto than with the small-seeded Tatu Vermelho. Although large-seeded cultivars often require a higher level of ambient soil Ca for pod fill than small-seeded cultivars, seed size per se is not considered the controlling factor (Cox et al., 1982). Foliar Ca concentration has not served as an effective index of Ca deficient conditions for peanut yield (Cox et al., 1982). Consistent increases in leaf Ca content with liming, in the present study, may have resulted from the low Ca levels initially present in the soil profile (Table 1).

There was a significant difference in yields between cowpea varieties in both 1985 and 1986. Mean yields for IPEAN V-69 were 0.76 and 0.78 t ha^{-1} compared with 0.69 and 0.75 t ha^{-1} for VITA 3 in 1985 and 1986, respectively. There was no significant (p = 0.05) yield response to liming in the two initial cowpea crops. Mean yields across lime treatments in 1984 and 1985 were 1.3 and 0.7 t ha^{-1}, respectively. In 1986 there was a significant linear increase in yield of 0.05 t ha^{-1} for each ton of applied lime across both cowpea varieties with no lime-by-variety interaction (Fig. 4). The absence of a response to liming by cowpea until the third year of continuous cropping is consistent with previous findings that cowpea exhibited greater tolerance to Al than other crop species (Nicholaides and Piha, 1987; Munns and Fox, 1977; Spain et al., 1975; Wade et al., 1988).

Exchangeable Ca and Al, and Al saturation of the surface soil layer (0-0.20 m) were influenced by both lime rates and time after liming (Fig. 5). All coefficients in the regressions were significant ($p \leq 0.05$) except for the linear term for time in the Al saturation model. Whereas exchangeable Ca increased with lime rates and decreased with time in a linear form, the same factors influenced exchangeable Al in a curvilinear pattern. In the absence of lime, exchangeable Ca decreased from 0.54 to 0.19 $cmol_c\ kg^{-1}$ between 0.26 and 4.78 yr after liming, and Al increased from 1.13 to 2.03 $cmol_c\ kg^{-1}$. With 4.6 t ha^{-1} of lime the reduction in exchangeable Ca and increase in exchangeable Al between the same sampling dates were 3.00 to 1.23 and 0.18 to 0.73 $cmol_c\ kg^{-1}$, respectively. Changes in Al saturation reflect the combined effects of lime and time on both soil Ca and Al. At the initial sampling date (0.26 yr) liming (4.6 t ha^{-1}) reduced Al saturation from 59 to 5% and raised pH from 4.6 to 5.6. At 4.78 yr after liming, Al saturation and pH values between 0 and 4.6 t lime ha^{-1} ranged from 84 to 34% and 4.4 to 4.9, respectively. Crop response to residual effects of lime, therefore, occurred under conditions of continuous change in exchangeable Ca, Al, and Al saturation.

There was a significant ($R = 0.84$) curvilinear relationship between soil pH and Al saturation across all sampling dates and lime treatments. The regression equation, based on 55 observations and with coefficients significant at the 0.0001 probability level, was as follows

$$\text{pH in water} = 5.47\exp^{-0.003(\text{Al saturation }\%)} \quad [1]$$

Calcium levels for the treatment without lime remained below the value of 0.87 $cmol_c\ kg^{-1}$ which Andrew and Norris (1961) found was needed for maximum growth of legume species in a sandy soil of pH 5.5. In an extensive review of lime studies on soils in the tropics, Kamprath (1984) recommended 1.0 $cmol_c$

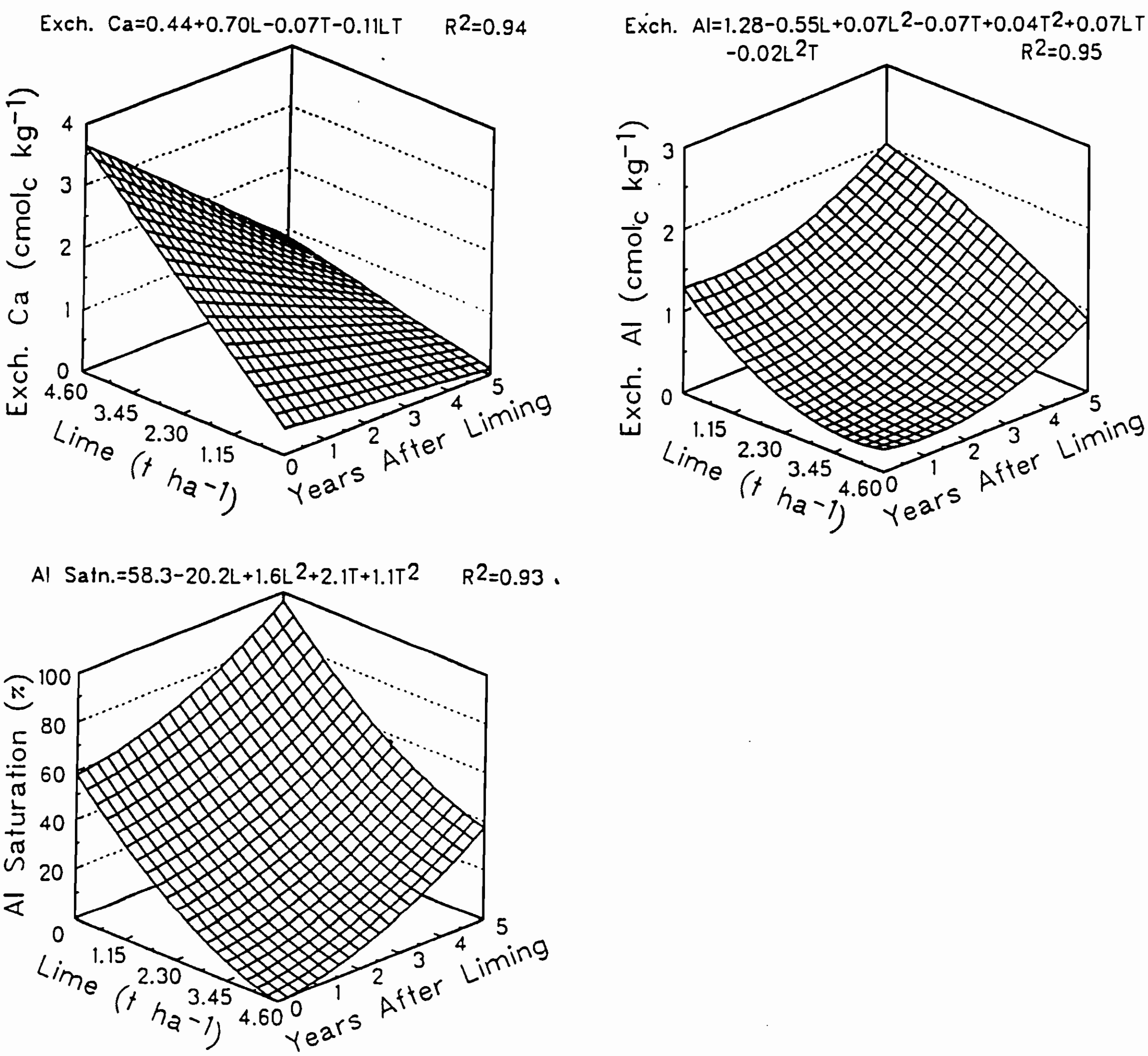

Fig. 5. Surface response functions for effects of lime rates (L) and time after liming (T) on exchangeable Ca, Al and Al saturation in the surface 0.20m of soil. Regression equations were generated using significant components of the analysis of variance.

Table 4. Corn, soybean, cowpea, and peanut yields as a function of applied lime and gypsum.

Applied		Corn				Soybean	Cowpea			Peanut	
Lime	Gypsum†	1984	1985	1986	1987	1985	1984	1985	1986	1987	1988
		t ha^{-1}									
0	0	0.27	0.87	1.57	1.63	0.95	1.11	0.52	0.67	1.08	0.15
1.2		2.09	3.53	2.92	2.63	1.87	1.38	0.80	0.78	1.83	0.73
2.3		2.15	3.33	2.70	2.50	1.86	1.31	0.76	0.77	2.10	0.85
	Mean	1.51	2.58	2.40	2.25	1.56	1.27	0.69	0.74	1.67	0.58
0	1	1.58	1.97	1.95	2.06	1.38	1.19	0.73	0.70	2.64	1.20
1.2		2.12	3.59	3.30	2.68	1.63	1.41	0.74	0.84	2.62	1.28
2.3		2.63	3.24	3.64	3.44	2.12	1.47	0.88	0.92	2.91	1.35
	Mean	2.11	2.93	2.97	2.72	1.71	1.36	0.78	0.82	2.72	1.28
					Lime Means						
0		0.93	1.42	1.76	1.84	1.16	1.16	0.63	0.68	1.86	0.67
1.2		2.11	3.56	3.11	2.65	1.75	1.39	0.77	0.81	2.22	1.01
2.3		2.39	3.28	3.17	2.97	1.99	1.39	0.82	0.84	2.51	1.10
					Probability > F						
Source	df										
Lime	2	<0.001	<0.001	<0.001	0.003	0.045	0.103	0.064	0.003	0.064	<0.001
Gypsum	1	0.006	0.167	0.030	0.056	0.557	0.379	0.164	0.029	<0.001	<0.001
L × G	2	0.044	0.130	0.560	0.309	0.537	0.863	0.240	0.432	0.264	0.010
LSD (0.05)											
Lime		0.48	0.62	0.60	0.58	0.63	NS‡	NS	0.13	NS	0.27
Lime × Gypsum		0.68	NS	NS	NS	NS	NS	NS	NS	NS	0.38

† Gypsum (1 t ha^{-1}) was applied at planting to each peanut crop and to corn crops harvested in 1984 and 1986.
‡ NS = F value for effect not significant at $p \leq 0.05$.

kg^{-1} of Ca as a minimum value for good plant growth. The low native soil Ca levels may explain why a greater response in peanut shelling percent and leaf Ca concentration in peanut and cowpea was observed with lime in this soil than in the Ultisols used by Nicholaides and Piha (1987). In their treatments that were not limed but received 35 to 40 kg P ha^{-1} as ordinary superphosphate, soil Ca + Mg ranged from 1.0 to 1.5 $cmol_c$ L^{-1} (Piha and Nicholaides, 1983).

Effects of Gypsum on Yield and Soil Acidity

Yields of all crops receiving 1 t of gypsum ha^{-1} at planting were increased significantly (Table 4). In the initial corn crop and the final peanut crop, yield response to lime was markedly reduced when gypsum was applied. Significant residual effects from gypsum applications to a subsequent crop were only observed in the 1986 cowpea crop. In all corn, soybean and peanut crops, yield with gypsum plus 2.3 t ha^{-1} of lime were equal to or greater than yields with 4.6 t ha^{-1} of lime. Peanut shelling percent and peanut and cowpea leaf Ca concentrations with gypsum alone were consistently higher to all treatments with <2.3 t ha^{-1} of lime Tables 3 and 5). In the presence of gypsum, lime had no effect on these plant variables. Previous studies have shown that the relative effectiveness of lime and gypsum on peanut yield is primarily dependent on the level of available soil Ca in the pegging zone during pod filling stage (Cox et al., 1982). Results for peanut in our experiment would suggest that Ca availability from the treatment with 1 t ha^{-1} of gypsum was comparable to 2.3 t ha^{-1} of lime.

The influence of gypsum on exchangeable soil Ca and Al, and Al saturation during the successive years of cultivation are shown in Fig. 6. Main effects and interactions between gypsum and time were significant ($p \leq 0.05$) for all these variables. Lime-by-gypsum and lime-by-gypsum-by-time interactions,

Table 5. Effect of lime and gypsum on mean foliar Ca concentration at midflowering stage of two varieties in the 1986 cowpea crop.

Lime	Gypsum†	Ca
t ha^{-1}		g kg^{-1}
0	0	11.8
0.6		14.2
1.2		17.0
2.3		20.6
4.6		20.9
0	1	20.7
1.2		19.7
2.3		20.7
LSD 0.05:		5.0

† Gypsum (1 t ha^{-1}) was applied at planting to corn crops harvested in 1984 and 1986.

however, were not significant. Although there was a progressive decline across time in both treatments, soil Ca was higher with gypsum by an average of 0.41 $cmol_c$ kg^{-1}. The rapid decline in Ca after each gypsum application suggests a limited residual effect for this Ca source. Gypsum delayed the increase in exchangeable Al with time of cultivation and the magnitude of this effect increased with each successive application. The mean reduction in Al by gypsum across all sampling dates was 0.20 $cmol_c$ kg^{-1}. Differences in Ca and Al between gypsum treatments resulted in lower Al saturation values when gypsum was applied. By the second year of the study Al saturation values with applied gypsum were reduced by more than 10% relative to similar lime treatments without gypsum. Mean difference in pH between gypsum treatments was <0.1.

Ritchey et al. (1980) reported similar effects on chemical soil properties for gypsum applied to an Oxisol in the Cerrado of Brazil. Several investigators have reported that reductions in exchangeable Al, following gypsum applications to Oxisols and Ultisols, were accompanied by increased solution Al, but in-

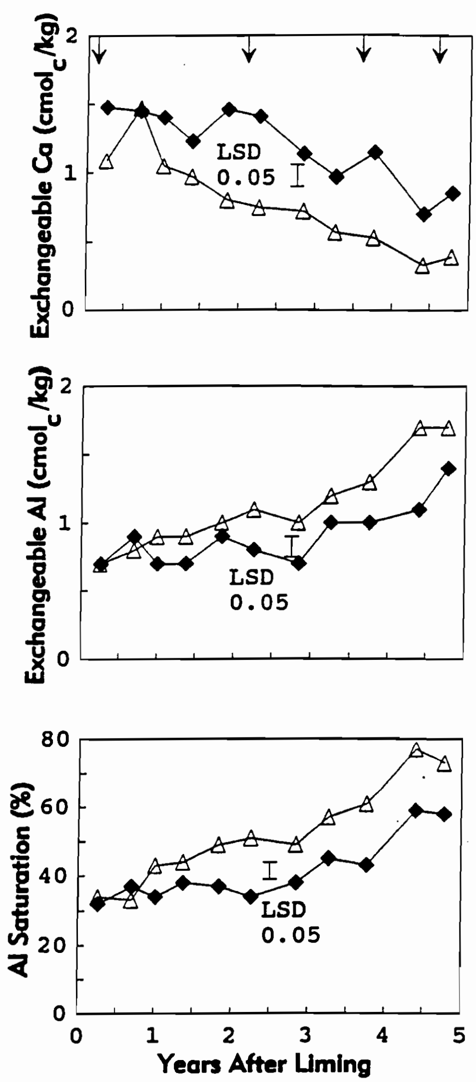

Fig. 6. Mean values for exchangeable Ca, Al, and Al saturation for three lime rates, with (closed symbol) and without (open symbol) applied gypsum (1 t ha^{-1}), as a function of time after lime was applied. Arrows in the top panel indicate the times when gypsum was applied.

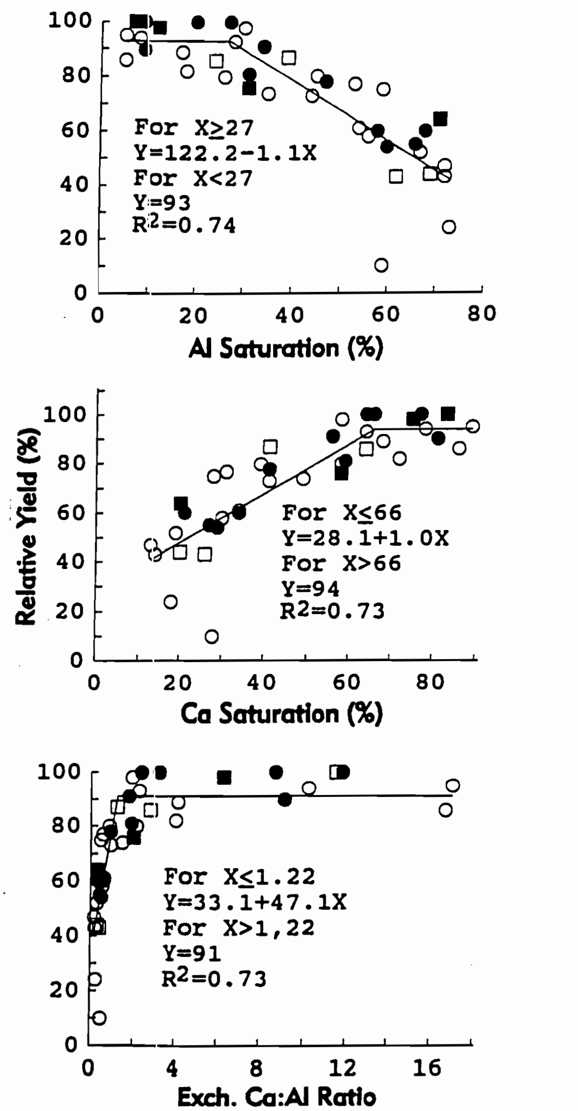

Fig. 7. Observed (symbols) and predicted (lines) relationships between yields of corn (circles) and soybean (squares) and Al saturation, Ca saturation, and exchangeable Ca:Al ratio. Open symbols denote treatments with only lime and solid symbols denote treatments with gypsum.

creased levels of Ca and the $AlSO_4^+$ion pair in solution reduced Al phytotoxicity to plant roots (Pavan and Bingham, 1982; Sumner et al., 1986). Furthermore, the absence of an increase in exchangeable Al at depths greater than that of the leading edge of gypsum movement through the soil profiles in their experiments would suggest the formation of relatively insoluble Al compounds.

Yield Relationships with Soil Acidity Parameters

Relative yield for lime and gypsum treatments were based on the highest yielding treatment in each crop. Relationships between yield and soil acidity parameters for corn and soybean (Fig. 7) differed from those for peanut (Fig. 8). Critical levels of Al and Ca saturation for corn and soybean were 27 and 66%, respectively. Yield plateaus for peanut, in contrast, occurred at Al and Ca saturation values of 54 and 31%, respectively. Regression coefficients for the yield relationships with Al and Ca saturation also indicate a greater yield response for peanut relative to corn and soybean at high Al or low Ca saturation levels.

Results for corn and soybean are similar to previous reports that 90% of maximum yield in soils of the tropics occurred at Al saturation levels of <20% (Kamprath, 1980; Sousa et al., 1986; Pearson, 1975). In liming experiments on Oxisols and Ultisols in Indonesia Wade et al. (1988) established critical Al saturation values of 29% for corn and 15% for soybean. The higher critical value for Al saturation with peanut in the present study is consistent with a higher Al-tolerance relative to corn and soybean (Kamprath, 1984; Pearson, 1975; Wade et al., 1988). However, sensitivity of peanut to low Ca conditions and the unique Ca requirements of the developing fruit (Table 3; Cox et al., 1982; Pearson, 1975) would support the greater yield response obtained with this species than with soybean and corn at low Ca saturation levels.

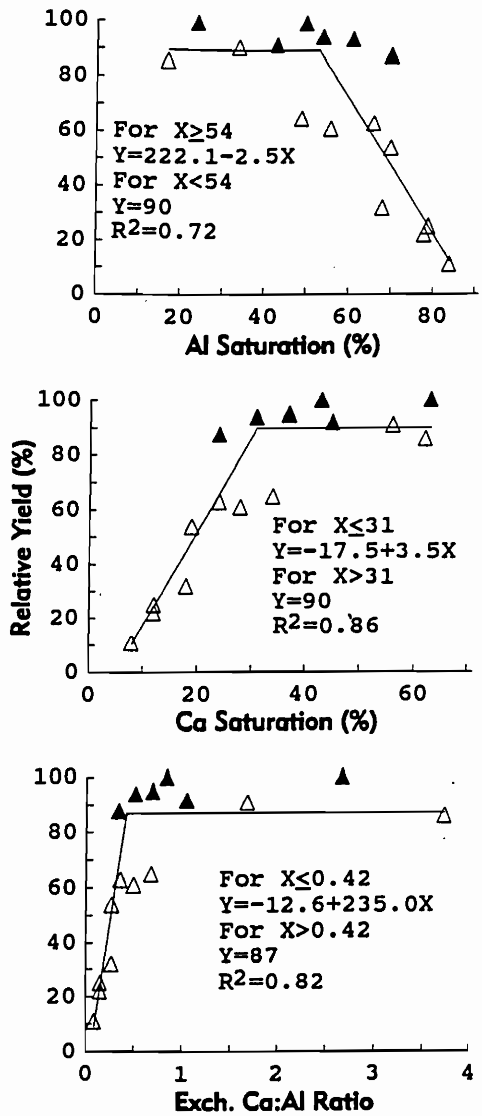

Fig. 8. Observed (symbols) and predicted (lines) relationships between peanut yields and Al saturation, Ca saturation, and exchangeable Ca:Al ratio. Open symbols denote treatments with only lime and solid symbols denote treatments with gypsum.

The reciprocal relationships between yield and Al or Ca saturation suggested a high correlation between Al and Ca levels on the exchange complex. There was a strong linear correlation ($r^2 = 0.98$) between Al and Ca saturation across all sampling dates, and lime and/or gypsum treatments. The regression equation, based on 80 observations and with coefficients significant at the 0.0001 probability level, was as follows

$$\text{Al saturation \%} = 87.6 - 0.99 \text{ (Ca saturation \%)}. \quad [2]$$

There was essentially a 1:1 relationship between changes in Al and Ca on the exchange complex. The value for the intercept also indicated that a constant fraction of the effective CEC (12.4%) was occupied by other cations (K and Mg). Exclusion of background levels of exchangeable K and Mg, when relating yield to the soil Ca:Al ratio, may explain why this soil index provided R^2 values equal to those for Ca or Al saturation (Fig. 7 and 8).

Activity ratios of Ca:Al in nutrient solution cultures (Alva et al., 1986; Noble and Sumner, 1988; Cameron et al., 1986) and soil solutions (Wright and Wright, 1987) have provided a useful index of Al phytotoxicity to root growth for several species. Alva and coworkers (1986) attributed the enhanced root growth with increased additions of Ca to solutions with Al on the correction of an Al-induced Ca deficiency. Similar effects may explain the increased yields obtained in this study with applications of gypsum or 0.6 t ha^{-1} of lime which caused little changes in pH and exchangeable Al. Since both Ca and Al would change simultaneously with liming, it is unlikely that such a cation ratio could replace Al saturation in determining lime recommendations. Critical values for Ca:Al ratios would, however, offer an additional safeguard towards ensuring that lime recommendations for soils with low Ca and effective CEC provided adequate amounts of Ca for good plant growth.

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Comparison of Methods for Determining Critical Concentrations of Soil Test Phosphorus for Corn

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ABSTRACT

Critical concentrations of soil-test P (STP) are used to identify soils where response to P fertilization should be expected. There is, however, little agreement concerning the methods that should be used to identify critical STP concentrations. This study compares the efficacy of critical STP concentrations generated by using various methods. Twenty-five P fertilization trials with corn (*Zea mays* L.) were established in Iowa. Available soil P at each site was estimated by the Bray-P_1, Mehlich-3, and Olsen extractants. Corn yield response was expressed in both absolute and relative terms and then related to STP values by using various statistical models (Cate-Nelson split, linear-plateau and quadratic-plateau segmented polynomials, the quadratic polynomial, an exponential Mitscherlich-type equation, and a multivariate polynomial). The use of various combinations of the extractants, expressions of yield response, and models resulted in a wide variety of critical STP concentrations. Comparisons of the ability of each critical concentration to generate economic returns when used to guide fertilization across the 25 sites showed that selection of the model was much more important than selection of the extractant or the expression of yield response. The best model was the Cate-Nelson, which identified critical concentrations of 13 mg kg^{-1} for the Bray-P_1, 12 mg kg^{-1} for the Mehlich-3, and 5 mg kg^{-1} for the Olsen extractants. Overall, the results of this study demonstrate that selection of the most appropriate critical STP concentration can be a major factor affecting the profitability of fertilization in areas having an abundance of soils testing high in P.

CRITICAL CONCENTRATIONS of STP are generally considered the soil test values below which crop responses to P fertilization should be expected and above which crop responses should not be expected. Critical concentrations of STP are known to vary with plant species, major differences in soil or climatic factors, and the analytical extractants used. The determination of an appropriate critical concentration of STP for a specific extractant and soil-plant category is a fundamental step required for use of soil testing in making fertilizer recommendations. Errors in determination of critical concentrations result in incorrect decisions relating to fertilizer applications.

Numerous models have been proposed for determining appropriate critical STP concentrations. These models describe an observed relationship between amounts of STP and some measurement of plant response to added P. Most commonly used models relate STP values to relative yields (i.e., yields without fertilizer expressed as percentages of maximum yield with fertilizer under otherwise similar conditions) or absolute yield increases (Nelson and Anderson, 1977; Evans, 1987). These relationships are usually described and analyzed by fitting continuous models (Nelson and Anderson, 1977; Peaslee, 1978), segmented polynomial models (Waugh et al., 1973), or by data-splitting models (Cate and Nelson, 1971). Other techniques involve incorporation of STP values into fertilizer response models (Bray, 1936; Colwell, 1967; Mombiela et al., 1981) or the use of multivariate polynomial models that include various controlled and uncontrolled variables in addition to STP values and fertilization treatments (Nelson, 1987).

The use relative yields as an expression of yield response in continuous models relating crop response with soil test values has been criticized for statistical reasons (Nelson and Anderson, 1977; Colwell et al., 1988). Also, it has been shown (Mombiela et al.,

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Abbreviation: STP, soil-test P.