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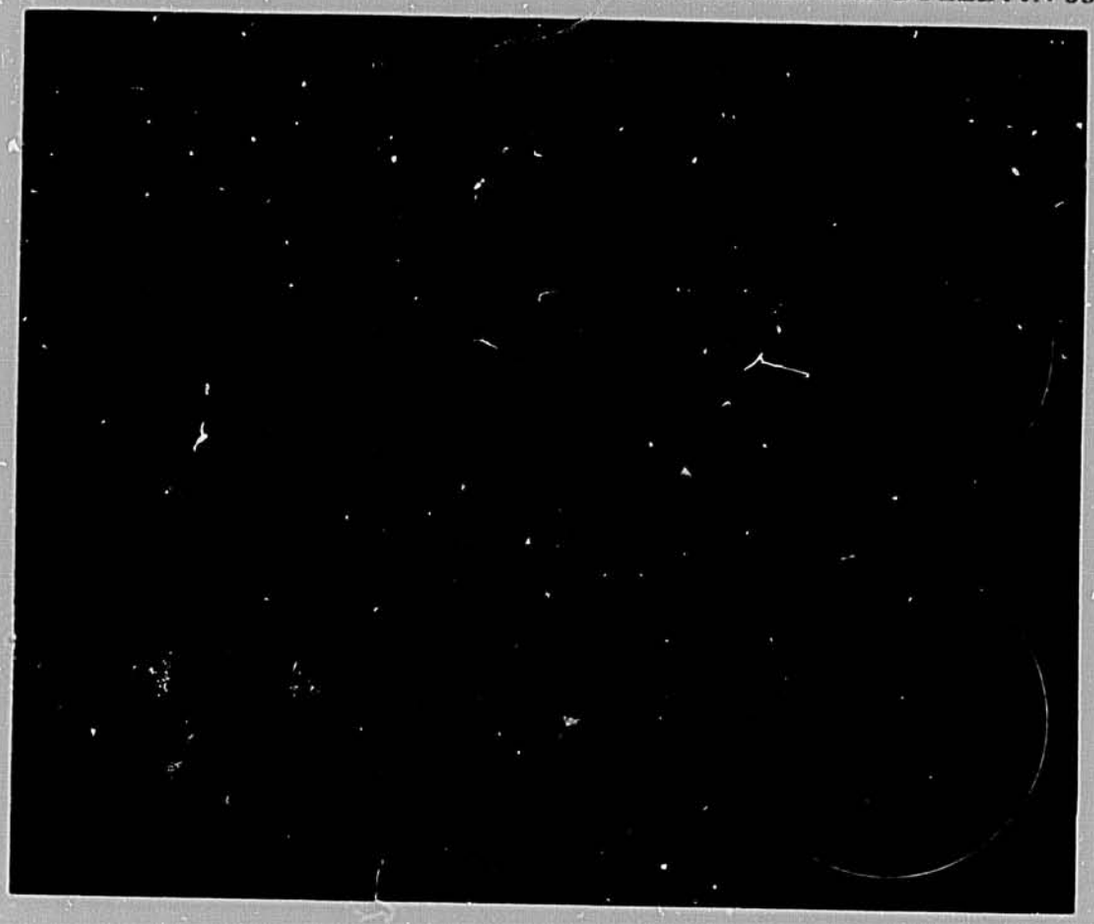

CROP RESPONSE TO LIMING OF ULTISOLS AND OXISOLS

A summary of cooperative projects carried out by
Centro de Pesquisa Agropecuaria dos Cerrados, Planaltina, Brazil
University of Puerto Rico, Rio Piedras, Puerto Rico
Soil Research Institute, Kumasi, Ghana
Yurimaguas Experiment Station, Ministerio de Agricultura, Yurimaguas, Peru
North Carolina State University, Raleigh, North Carolina
Cornell University, Ithaca, New York

NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
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Crop Response to Liming of Ultisols and Oxisols*

Edited by D. J. Lathwell†

ABSTRACT

Experiments were carried out on representative Ultisols and Oxisols of Puerto Rico, Brazil, Ghana, and Peru to define the lime requirement of these soils for optimum production of several food crops. These soils generally have a low cation exchange capacity. Since the soils are acid, the exchange complex is dominated by exchangeable Al. Crop response to lime has been common in these soils. Response to lime is attributed to neutralization of exchangeable Al and in some instances to elimination of Mn toxicity. The exchangeable Al content of these soils provides a reliable measure of their lime requirement. A few acid soils have a low cation exchange capacity and a low content of exchangeable Al. Their lime requirement is relatively low. On some soils, lime additions may enhance the availability of soil phosphorus. Weathering of minerals such as Al-chlorite and mineralization of organic matter provide sources of exchangeable Al in certain soils and increase their lime requirement.

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SUMMARY AND RECOMMENDATIONS

The Ultisols and Oxisols upon which the liming studies reported here have been made have a wide range of properties. Generally, they are highly weathered, and the crystalline clay fraction is dominated by kaolinite and/or gibbsite, with only minor amounts of the more active 2:1 clays such as Al chlorite. Most, if not all of them, contain substantial quantities of amorphous materials rich in Fe and Al.

The exchange complex of most of the soils we have studied is dominated by exchangeable Al, which varied from as little as 0.5 me to as much as 10 me/100 gm soil. Al saturation ranged from about 60 to 90 percent. A few of the soils are low in exchangeable Al, even though they are acid. Consequently, the effective CEC of these soils ranges from less than 1 me to 15 or more me/100 gm of soil. A substantial portion have effective CEC of less than 5 me/100 gm, and most of them have a great deal of pH-dependent charge.

On the Ultisols of Ghana, which have a low effective CEC and little exchangeable Al, response to liming has been modest. The influence of lime on phosphorus availability in these soils, however, is not clear, and it is possible that for short periods of time only one or the other need be used. Lime rates on these soils should be only enough to provide sufficient Ca and to neutralize the acid residues caused by adding nitrogen fertilizers. On these soils, rates of 1 to 2 tons/ha are more than adequate to meet the Ca demands and probably are sufficient to neutralize residual acidity of any fertilizer nitrogen that may be applied.

In Puerto Rico soil and crop responses to lime have been variable. Normally, the Oxisols are less responsive to lime than are the Ultisols at a comparable soil pH and percentage of Al saturation. Coffee, sweet potatoes, and stargrass are tolerant to exchangeable Al or Al in solution. Most other crops are sensitive to Al, and the exchangeable Al must be reduced to low values for optimum production. The Ultisols of Puerto Rico contain large amounts of exchangeable Al and still contain reserve Al in the form of Al-chlorite, for example. To reduce exchangeable Al to levels that do not interfere with crop growth, it is recommended that about 2 tons of lime/ha be applied per me of exchangeable Al. Thus, these soils have a high lime requirement — in many instances several tons per hectare. Where high rates of fertilizer nitrogen are used, the lime requirement is increased even further.

The soils of the Cerrado region of Brazil, and to a lesser extent those of the Yurimaguas area of Peru, appear to be more highly weathered than their counterparts in Puerto Rico, as evidenced by their effective CEC. The soils examined all had an effective CEC of less than 4 to 5 me/100 gm of soil, and most of them were less than 2 me/100 gm of soil. The large response to liming observed on these soils generally has been attributed to removal of exchangeable Al or Al from the soil solution, although direct response to Ca addition cannot be precluded. On the basis of the results to date for the Cerrado soils, liming recommendations have been developed

according to the following formulation:

$$t \text{ lime/ha} = (2 \times \text{exchangeable Al}) + [2 - \text{me (Ca + Mg)}].$$

Thus, for a soil containing 1 me of Al and 1 me Ca + Mg/100 gm soil, 3 t/ha of lime would be recommended. This formulation probably applies only to those soils with an effective CEC of less than 5 me/100 gm. It has been used successfully in the Cerrado region of Brazil.

Work still remains to be done in defining the range of soil conditions under which crops respond to additions of lime. On those acid soils where exchangeable Al dominates the exchange complex, the amount of exchangeable Al provides a reliable measure of the lime requirement. Procedures remain to be developed to provide an accurate estimate of the lime requirement of acid soils that have a low effective CEC and little exchangeable Al. The role of Mn in the deleterious effects of acid soils on plant growth needs to be clarified. Weathering of minerals such as Al-chlorite and mineralization of organic matters, which provide sources of exchangeable Al, may have important consequences in developing long-term liming programs. The factors that influence leaching of Ca in the profile need to be characterized and incorporated into the liming requirements before liming programs can be completely described. The continued development of the species and varieties of food crops tolerant to high concentrations of Al in the soil will likewise minimize the need for lime additions to acid Ultisols and Oxisols.

INTRODUCTION

The Ultisols and Oxisols of the humid tropics are usually acid. Liming of acid soils is generally accepted as necessary for improving crop production. This report summarizes the results of field experiments made in Puerto Rico, Brazil, Peru, and Ghana to measure crop response to liming of acid Ultisols and Oxisols. The specific objectives of these experiments were to determine crop response to rate and depth of liming, to evaluate residual effects of liming, and to relate soil properties to lime requirements and crop response. The goal of this field research and supporting study of soil properties is to make liming recommendations that fit the specific soils and cropping situation of individual farmers.

Several recent reviews on soil acidity and liming of humid tropical soils are available, including Kamprath, 1967; Kamprath, 1972a; Kamprath, 1972b; and Pearson, 1975. When appropriate, reference will be made to the pertinent literature.

CROP RESPONSE TO LIMING

Puerto Rico experiments

Lime rate experiments. Experiments were established on three Ultisols and two Oxisols to study the influence of liming on yield of several important crops. The details of these experiments have been described by Abruña et al., 1974b, 1975. The Ultisols were the Los Guineos clay, Corozal clay, and Cialitos clay; the Oxisols were the Bayamon loamy sand and Catalina clay. A small amount of lime (0.45 t/ha) was applied to a plot of each soil to measure crop response to calcium addition. This low rate of $CaCO_3$ was insufficient to substantially alter the degree of base saturation, except possibly on the Bayamon loamy sand. Also, varying amounts of limestone were applied to plots of each soil type (tables 1 and 2). These amounts were based on an estimate of the lime requirement of the soils and applied with the goal of achieving soil pH values ranging from less than 5.0 to more than 6.5. All of the limestone treatments were applied before the first crop was planted, and a series of successive crops was grown without further additions of lime.

Table 1. Some chemical properties of lime-treated Puerto Rico Oxisols — Bayamon loamy sand and Catalina clay. (Samples taken 6 months after lime application)

Soil	*Lime rate*	*Sample depth*	*Soil pH*	*Exchangeable cations*		*Al saturation*
				Ca + Mg	*Al*	
	t/ha	*cm*		*me/100 gm*		*%*
Bayamon loamy sand	0.00	0–15	5.1	0.7	0.1	13
		15–30	5.1	0.6	0.2	25
	0.45	0–15	5.5	0.9	0.2	18
		15–30	5.0	0.8	0.2	20
	0.76	0–15	5.4	0.9	0	0
		15–30	5.1	0.8	0.2	20
	1.05	0–15	5.5	1.0	0	0
		15–30	5.2	0.9	0.1	10
	1.92	0–15	6.0	1.2	0	0
		15–30	5.5	1.0	0	0
Catalina clay	0.00	0–15	5.0	5.6	0	0
		15–30	5.1	5.3	0	0
	0.45	0–15	5.1	5.9	0	0
		15–30	5.1	5.2	0	0
	4.72	0–15	5.4	7.0	0	0
		15–30	5.2	5.4	0	0
	7.30	0–15	5.4	7.4	0	0
		15–30	5.2	5.4	0	0
	12.88	0–15	6.2	10.9	0	0
		15–30	5.3	6.5	0	0

The soil in all plots of each experiment was sampled 6 months after liming. Some chemical properties of the soils are given in tables 1 and 2. Generally the two Oxisols were not as acid as the Ultisols and were much lower in exchangeable Al. The coarse-textured Bayamon loamy sand, in addition, contained only very small quantities of exchangeable Ca and Mg. Because the cation exchange capacity of the Bayamon soil was extremely low, only small amounts of lime were added, and therefore the quantities of exchangeable bases increased only slightly. The Catalina clay, on the other hand, contained sizable quantities of exchangeable bases even without liming, and these increased significantly upon liming

Table 2. Some chemical properties of lime-treated Puerto Rico Ultisols – Los Guineos clay, Corozal clay, Cialitos clay. (Samples taken 6 months after lime application)

Soil	*Lime rate*	*Sample depth*	*Soil pH*	*Exchangeable cations*		*Al saturation*
				Ca + Mg	*Al*	
	t/ha	*cm*		*me/100 gm*		*%*
Los Guineos clay	0.00	0–15	4.6	5.7	2.8	33
		15–30	4.7	4.9	2.7	36
	0.45	0–15	4.6	5.3	2.8	35
		15–30	4.7	5.5	2.6	32
	5.65	0–15	4.8	6.7	1.8	21
		15–30	4.9	5.2	2.1	29
	8.78	0–15	5.4	8.4	0.2	2
		15–30	5.2	7.4	0.5	6
	13.77	0–15	5.4	9.3	0	0
		15–30	5.0	8.2	0.3	3
Corozal clay	0.00	0–15	4.7	12.3	4.1	25
		15–30	4.5	9.5	11.8	55
	0.45	0–15	4.7	13.4	2.3	15
		15–30	4.4	9.1	8.4	48
	1.22	0–15	4.9	15.0	1.7	10
		15–30	4.5	9.1	12.4	58
	4.52	0–15	4.9	18.6	0.9	5
		15–30	4.4	9.9	12.9	47
	9.81	0–15	5.5	20.5	0.3	1
		15–30	4.6	13.2	8.9	41
Cialitos clay	0.00	0–15	4.3	7.3	4.1	36
		15–30	4.3	5.5	6.6	55
	0.45	0–15	4.5	7.6	3.1	29
		15–30	4.4	6.1	4.3	41
	3.27	0–15	4.7	9.8	1.6	14
		15–30	4.5	6.8	4.4	39
	5.45	0–15	4.9	12.0	0.9	7
		15–30	4.4	6.1	4.7	44
	8.78	0–15	5.3	14.8	0	0
		15–30	4.5	6.7	4.6	41

because of the higher cation exchange capacity and greater lime requirement. Although the pH of the Catalina did not reach 7, it reached a pH above 6 after lime was added.

In the Ultisols, however, both the exchangeable Ca + Mg and the exchangeable Al were high. As the rates of liming increased, exchangeable Al and percentage of Al saturation declined. Soil pH values increased only slightly, but they declined to nearly the original values by the later sampling dates.

A response to liming was found on all soils included in the experiments (table 3). With the Bayamon loamy sand, the response (except for snapbeans) to the 0.45-t/ha application was about as great as to any of the higher rates. Such a response was not unexpected because this soil has a coarse texture and a low cation retention capacity. Likewise, the first two crops on the Catalina responded favorably to the 0.45-t/ha lime applica-

Table 3. Yield response to lime of a sequence of crops grown on several Ultisols and Oxisols of Puerto Rico (Yield is of marketable product)

Treatment		*Yield*					
Soil	*Lime rate*	*Maize*	*Snap beans*	*Maize*	*Sweet potato*	*Soybean*	*Plantain*
	t/ha	*kilograms per hectare*					
Bayamon loamy sand (Oxisol)	0	1,210	280	1,325	4,620	1,410	
	0.45	2,745	875	1,910	5,235	2,305	
	0.76	2,755	850	1,595	4,300	1,785	
	1.05	2,910	1,010	1,795	5,430	1,960	
	1.92	2,970	1,670	1,870	5,970	2,320	
Catalina clay (Oxisol)	0	2,795	6,945	4,435			
	0.45	3,900	8,290	4,200			
	4.72	4,395	10,640	4,905			
	7.31	4,145	6,160	5,070			
	12.88	3,580	9,185	4,825			
Los Guineos clay (Ultisol)	0		11,730	6,745	12,185	1,995	31,825
	0.45		10,530	6,760	11,950	1,750	33,700
	5.65		14,245	7,705	11,200	2,285	28,155
	8.75		14,345	9,810	13,915	2,335	32,925
	13.75		15,780	9,480	14,820	2,495	31,670
Coroza clay (Ultisol)	0		7,100	4,010	13,125		
	0.45		8,165	3,830	14,135		
	1.22		8,510	4,855	13,350		
	4.52		8,805	5,075	13,955		
	9.81		9,410	5,995	13,595		
Cialitos clay (Ultisol)	0		7,020	5,040			
	0.45		8,815	4,750			
	3.27		9,745	5,490			
	5.45		10,650	5,520			
	8.78		10,000	5,840			

tion. Abruña et al. (1975) have shown that the Oxisols of Puerto Rico, even when extremely acid, contain little exchangeable Al. However, they often do contain rather high contents of exchangeable and easily reducible Mn. Thus, it seems that both enhanced Ca supply and reduced Mn availability contribute to improved yields when these soils are limed.

With the three Ultisols, relatively little response was found to the 0.45-t/ha rate of lime, except for the snapbeans (which were the first crop) on the Corozal and Cialitos clays. With subsequent crops, however, the 0.45 t/ha had little effect on yield. In general, the greatest increase in yield was obtained with the first rate of lime above the constant 0.45-t/ha rate, although with several crops the highest yield was obtained at the higher rates of lime. On these soils, response to lime increased as the percentage of Al saturation declined. Maximum response to lime was obtained when the Al saturation fell below about 20 percent. Since adequate Ca and Mg were present in these soils, neutralization of extractable Al was essential for optimum growth (Abruña et al., 1974a, 1975; Perez-Escolar, 1977).

Response to lime tended to decline with successive crops in these soils, perhaps because of a gradual increase in percentage of Al saturation. Sweet potatoes were somewhat less responsive to lime than some of the other crops. Plantains grown on the Los Guineos clay did not respond to lime.

Depth of lime experiment. An experiment was established on a Humatas clay (Typic Palehumults) to measure the influence of depth of liming on crop response. The treatments included liming the 0–20-cm layer, the 0–40-cm layer, and the 0–60-cm layer, along with a control. In these treatments, irrespective of the depth of liming, the soil was disturbed to a depth of 60 cm to minimize soil disturbance as a factor in crop growth. Lime in the form of $Ca(OH)_2$ was applied at the rate of 3 me Ca for each me of Al found in the soil. The total quantities of lime applied and chemical data on samples taken after the first and fifth crops are given in table 4. Four consecutive crops of maize were grown on the experiment and grain yields measured on all except the second crop, where the above-ground dry matter was harvested (table 5). The maize crops were followed by two soybean crops, making a total of six (table 5). No additional lime was applied after the initial application, which was made before planting the first maize crop. Response to lime continued throughout the experiment on both the maize and soybean crops, illustrating a strong residual effect of lime. Generally, the deeper the lime application, the greater the response.

Exchangeable Al was lower where lime was applied. When lime was mixed through only the top 20 cm of soil, Al was inactivated in that zone only. When it was mixed to 40 cm, substantial portions of the Al were inactivated to a depth of 60 cm. Exchangeable Al was lower throughout the 0–60-cm zone when the lime was mixed to a depth of 60 cm. Sufficient lime was added to prevent a decline in pH or remobilization of Al

Table 4. Some chemical properties of a lime-treated Humatas clay as influenced by depth of liming. (Samples taken after first and fifth crops)

Lime treatment			*pH*		*Exchangeable Ca + Mg*		*Exchangeable Al*		*Al saturation*	
Quantity applied	*Depth of mix*	*Depth of sample*	*After crop 1 3/74*	*After crop 5 8/76*	*3/74*	*8/76*	*3/74*	*8/76*	*3/74*	*8/76*
t/ha	*cm*				*me/100 gm*				*percent*	
0		0 - 20	4.35	4.60	3.54	5.19	2.22	2.89	39	36
		20 - 40	4.30	4.75	2.38	3.01	2.60	2.58	52	46
		40 - 60	4.40	4.70	1.95	3.17	2.64	2.78	58	47
9.29	0 - 20	0 - 20	5.35	5.55	7.92	9.62	0.30	0.13	4	1
		20 - 40	4.30	4.80	3.13	7.02	1.97	1.92	39	21
		40 - 60	4.45	4.80	2.29	5.23	2.46	2.38	52	31
24.52	0 - 40	0 - 20	5.40	5.60	8.47	10.31	0.11	0.00	1	0
		20 - 40	6.30	6.95	11.18	13.26	0.00	0.00	0	0
		40 - 60	4.60	5.15	5.62	9.23	0.80	0.66	14	6
38.20	0 - 60	0 - 20	5.50	5.70	8.72	9.66	0.06	0.23	1	2
		20 - 40	6.30	6.80	12.77	12.43	0.00	0.00	0	0
		40 - 60	6.35	7.35	11.33	15.19	0.00	0.00	0	0

over the course of the experiment. The increased yields from the deeper liming were attributed to inactivation of Al in the deeper soil layers, allowing roots to penetrate deeper and plants to exploit water otherwise not available to them (Perez et al., 1978).

Table 5. Yield response of maize and soybean as influenced by depth of liming of Humataz clay

Lime treatment		*Maize grain yields**					*Soybean grain yields*		
Quantity applied	*Depth of mix*	*Crop 1 10/73*	*Crop 2** *5/74*	*Crop 3 10/74*	*Crop 4 6/75*	*Avg*	*Crop 5*	*Crop 6*	*Avg.*
t/ha	*cm*	*kilograms per hectare*							
0		5,585	4,375	4,280	4,290	4,635	3,325	1,390	1,360
9.29	0 – 20	6,420	5,145	6,200	6,010	5,945	1,880	1,690	1,740
24.32	0 – 40	6,620	4,965	7,005	6,005	6,150	1,975	1,845	1,910
38.20	0 – 60	7,980	5,780	6,855	6,585	6,805	2,520	1,625	2,075

*Crop 2 was total dry-matter yields, all others were grain yields

Brazil experiments

Rate and placement experiment. An experiment involving rate and placement of lime was laid out at the CPAC on a soil classified in the Brazilian system as a dystrophic, clayey-textured, *cerradão*-phase Dark Red Latosol. In the United States taxonomy (Cline and Buol, 1973), this soil probably is classified as a Typic Haplustox — fine, isohyperthermic, kaolinitic. An area that had uniform exchange acidity and soil pH was selected for this experiment. The total cation content of the soil was very low (<1.5 me/100 gm soil), and about 75 percent of the cations on the exchange complex were Al (table 6). The experiment was laid out in freshly broken savanna that was cleared from shrubs and grasses. Limestone was applied at rates of 0, 1, 2, 4, and 8 tons/ha at two depths, 0 – 15 cm and 0 – 30 cm (Gonzalez, 1976). Of the six crops grown on the experiment, the first three were maize, the fourth was sorghum, and the fifth and sixth were maize. Two varieties of sorghum were grown, Taylor Evans Y-101, which was Al tolerant, and RS-610, which was Al sensitive (Salinas, 1978).

The yields given in table 7 show that maize responded markedly to lime on this soil. At low rates of lime, yields of the Al-tolerant variety of sorghum were higher than the Al-sensitive sorghum, but the two varieties responded equally at the highest lime rate. The response to lime continued throughout the six crops grown, with no evidence that the lower application rates were becoming less effective than the higher rates. Thus, even at the lowest lime rates, the residual effects remained significant throughout the course of the experiment. Those treatments in which lime was applied to a depth of 30 cm consistently yielded more than those where lime was applied to a depth of only 15 cm. Over the course of the experiment, the response to 1 and 2 tons of lime mixed in 30 cm of soil equalled the response to 2 and 4 tons of lime mixed in 0 – 15 cm of soil.

Table 6. Some chemical properties of Dark Red Latosol (Typic Haplustox) as influenced by several rates of liming applied at 2 depths. (Samples taken 3 weeks after lime application and after 5th crop)

Lime rate	*Depth of sample*	*Soil pH*		*Exchangeable Ca + Mg*		*Exchangeable Al*		*Al saturation*	
		12/72	*4/76*	*12/72*	*4/76*	*12/72*	*4/76*	*12/72*	*4/76*
t/ha	*cm*			*me/100 gm*				*percent*	
0	0 – 15	4.9	4.2	0.40	0.42	0.95	1.48	70	78
	15 – 30	4.7	4.1	0.35	0.51	0.90	1.25	72	71
Shallow									
1	0 – 15	5.0	4.4	0.92	1.13	0.60	0.68	39	44
	15 – 30	4.7	4.4	0.40	0.86	0.75	0.90	65	51
2	0 – 15	5.5	4.8	1.95	1.92	0.45	0.64	19	25
	15 – 30	4.7	4.6	0.35	1.02	0.90	0.80	72	44
4	0 – 15	6.4	4.9	2.65	2.41	0.10	0.36	4	13
	15 – 30	4.8	4.7	0.35	1.40	0.85	0.69	71	33
8	0 – 15	7.0	5.7	2.90	1.98	0.00	0.02	0	1
	15 – 30	4.7	4.9	0.40	2.04	0.80	0.36	67	15
Deep									
1	0 – 15	5.1	4.4	0.80	0.73	0.80	1.25	50	63
	15 – 30	4.7	4.4	0.60	0.66	0.90	1.07	60	62
2	0 – 15	5.5	4.6	1.85	1.62	0.35	0.73	16	31
	15 – 30	5.2	4.6	1.40	1.30	0.45	0.66	24	33
4	0 – 15	6.0	5.2	3.15	2.82	0.15	0.18	5	6
	15 – 30	5.5	4.8	1.70	1.83	0.30	0.43	15	19
8	0 – 15	6.4	5.7	4.10	4.95	0.10	0.[illegible]	2	1
	15 – 30	5.8	5.2	2.10	2.85	0.30	0.15	13	5

With 4 tons mixed in 0 – 30 cm of soil, the response was superior to 8 tons mixed in 0 – 15 cm of soil. Consistently higher yields were obtained with 8 t/ha of lime mixed in 0 – 30 cm of soil than with any other treatment.

With shallow liming, the addition of lime produced two notable general results in the chemical properties of the soil (table 6): Ca + Mg content increased, and Al saturation declined. Thus, although the yield responses undoubtedly were due in part to reduced Al saturation, increased Ca availability also probably contributed to plant growth. Furthermore, the percentage of Al saturation in the 0 – 15 cm zone has tended not to

increase over time, even at the low lime rates. This stability probably accounts for the long-lasting residual effects of lime over the course of the experiment.

With deep liming, the percentage of Al saturation in the 15–30-cm zone dropped to low values with 2 tons or more of lime. Al saturation changed little with time in either the 0–15-cm zone or the 15–30-cm zone. Soil pH in the limed zone, however, has gradually fallen with both the deep and the shallow liming. In the shallow liming treatment, the pH has not increased over time in the 15–30-cm zone at the higher lime rates,

Table 7. Grain yields of maize and sorghum on a Dark Red Latosol (Typic Haplustox) as influenced by several rates of liming applied at 2 depths

Lime rate and depth	*Maize*			*Sorghum (crop 4)*			*Maize*		*Avg.*
	Crop 1 '72–73	*Crop 2* '73	*Crop 3* '73–74	*Y-101* '74–75	*RS-610*	*Avg.*	*Crop 5* '75–76	*Crop 6* '76–77	
t/ha	*kilograms per hectare*								
0	2,115	4,570	880	2,335	610	1,475	2,360	1,175	2,220
0–15 cm									
1	3,425	5,280	1,475	5,105	1,945	3,525	4,280	1,940	3,280
2	3,530	5,690	1,865	6,030	5,135	5,585	4,320	2,005	3,480
4	4,005	5,905	2,265	6,550	5,900	6,225	4,620	2,705	3,900
8	3,725	5,960	2,050	6,895	6,855	6,875	5,410	2,455	3,920
0–30 cm									
1	4,020	5,685	2,085	5,810	3,325	4,570	4,430	1,380	3,520
2	4,340	5,860	2,575	6,135	5,580	5,860	4,600	2,125	3,900
4	4,800	6,680	3,060	6,760	6,085	6,425	4,810	2,350	4,340
8	4,790	7,265	3,600	7,020	7,090	7,055	5,970	2,775	4,880

even though the content of Ca + Mg has increased and percentage of Al saturation has decreased. In spite of these effects, the differences between deep and shallow liming have persisted. Enhanced root growth in the 15–30-cm zone and water extraction from a greater volume of soil were associated with the greater yields from the deep liming treatments (Gonzalez, 1976). Improved Ca nutrition could also have been involved in the responses observed.

Extrapolation experiment, Red-Yellow Latosol. To determine whether the results from the lime study on the Dark Red Latosol could be extrapolated to other soils, an experiment was carried out on a Red-Yellow Latosol (Haplustox – Acrustox intergrade) at the CPAC. As shown in table 8, the percentage of Al saturation was high in the untreated soil. The absolute amounts of Al and Ca + Mg, however, were low (0.15 me/100 gm soil). The crops responded to lime, both in the control plot, which received ordinary superphosphate, and even more significantly in the plots that received 4 tons of lime mixed in 30 cm of soil. The control-plot yields in this experiment were substantially higher than those on the Dark Red Latosol reported in the previous section, possibly because gypsum in the ordinary superphosphate supplied Ca to the soil; the P_2O_5 that was applied to the soil contained about 450 kg of Ca/ha, which probably counteracted some of the adverse effects of soil acidity. Exchangeable Ca showed a marked increase after ordinary superphosphate was added, and the percentage of Al saturation was lower. Furthermore, Al saturation was low enough at the end of the first crop that it was not a significant factor in the crop growth, except possibly for Al-sensitive crops such as sorghum.

Residual effect of liming in a Dark Red Latosol. Although the effect of liming on acid soils usually is expected to last for several years, it is also expected to be of shorter duration in tropical than in temperate regions

Table 8. Yields of maize and sorghum as influenced by liming a Red-Yellow Latosol (Haplustox – Acrustox intergrade)

*Lime treatment**	*Al saturation*		*Yield*				
	Untreated	*After crop 1*	*Crop 1*	*Crop 2*		*Crop 3*	
			Maize	*Maize*	*Sorghum*	*Maize*	*Sorghum*
t/ha	*percent*		*kg/ha*				
0	75	35	4,510	5,850	3,560	7,650	5,630
4	75	3	5,500	7,140	8,080	8,350	7,960

*Lime applied to a 0–30-cm zone, and ordinary superphosphate used as P source.

because of higher rainfall and higher temperature. In this experiment, two varieties of soybean, were grown in the 1973 – 74 season on an acid Dark Red Latosol where lime had been applied in November 1970 and on which *Stylosanthes* had been grown since that time (Gonzalez, 1976).

As shown in table 9, yields increased significantly for both varieties with the first increment of lime. At rates greater than 1 ton/ha, responses were important only at the 6-ton level with the Viçoja variety. The strong response to the first increment of lime occurred even though the soil remained very acid (pH 4.8) and the Al saturation was high. This condition may indicate that these two varieties are relatively tolerant to Al and respond well to small additions of lime (Gonzalez, 1976). Because the Ca + Mg content in the untreated soil (0.57 me/100 gm) was very low, the crops may have responded directly to Ca, also.

After 3 years of cropping, noticeable residual effect of liming remained in this soil and most of the exchangeable Al was still neutralized at the higher lime rates.

Ghana experiments

Lime rate experiment. An experiment was established on the Kumasi (Typic Paleudult) series of the Soil Research Institute station at Kwadaso to measure response of maize to lime. Lime in the form of $Ca(OH)_2$ was applied at rates of 0, ½, 1, 2, and 4 t/ha in April 1975. Maize was planted in April at the beginning of the rainy season and harvested in August. A second maize crop was planted in October 1975 and harvested in January 1976. The experiment was laid out in an area that recently had been cleared from forest. Soil pH and Ca + Mg contents of the soil are given in table 10. Only in the subsoil was any appreciable quantity of extractable Al found, and even there the amount was not great compared with many soils. The pH and the Ca + Mg content both increased upon liming.

Yield increased slightly with the first increment of lime applied for both crops (table 10), and a slight reduction occurred at the 4-ton rate. Unfor-

Table 9. Residual effect of various lime levels on grain yields of 2 soybean varieties on a Dark Red Latosol (Haplustox)

Amounts of lime applied, 11/71	*Al saturation*		*Soybean yield 1973–74*	
	12/70	*3/74*	*Viçoja*	*IAC-2*
t/ha	*percent*		*kg/ha*	
0	85	70	1,095	1,060
1	61	49	1,900	1,870
2	56	29	2,135	1,920
4	34	20	2,140	2,295
6	12	7	2,695	2,405
8	3	4	2,730	2,260

tunately, the experiment was lost after the minor season crop, so that longer-term results could not be obtained. On a similar soil, Ofori (1973) reported increases in maize yields from liming, which he attributed to counteracting the effect of $(NH_4)_2SO_4$ in acidifying these poorly buffered soils. In this experiment, extractable Al played no significant role in growth of maize.

Lime × phosphorus experiments. Two experiments were carried out in Ghana to study the effects of various combinations of lime and phosphorus on yield and response of food crops. One was at Kwadaso on Asuansi soil, and the other was at Aiyinasi on Basachia soil. The site at Kwadaso had been cropped for a number of years, whereas the site at Aiyinasi was cleared just before the experiment was established, from secondary forest vegetation that had grown up after previous cropping. Crops were grown at both sites—maize during the major rainy season and cowpeas during the minor rainy season of the 1976 and '77 cropping years. Yield data for cowpeas was obtained only at the Aiyinasi site for the 1977 minor season crop. The lime treatments shown in tables 11 and 12 were applied and worked into the soil with a hoe before the first crop was planted. No further lime applications were made.

At Aiyinasi, maize grain yields for the 1976 major season were increased by both lime and phosphorus. The response to lime was less at Kwadaso, although the response to phosphorus was significant (tables 11 and 12). Drought in 1976 limited the grain yields at Kwadaso and may also have restricted response to lime. In general, the largest reponse to lime at both sites occurred without added fertilizer phosphorus, and the least response to lime occurred at the higher rates of applied fertilizer phosphorus.

In 1977, grain yields were increased significantly by both lime and phosphorus at both sites. Although grain yields at Aiyinasi were limited by drought and by damage from birds and insects, yield tended to increase as

Table 10. Influence of liming on yield of maize grain grown in the 1975 major rainy season and total dry matter grown in the 1975 minor rainy season on a Kumasi soil (Paleudult)

Lime applied	*Soil pH*	*Exchangeable cations*	*Maize grain yields*	*Dry-matter yield*
		Ca + Mg	*Major season*	*Minor season*
t/ha		*me/100 g*	*kg/ha*	
0	5.6	5.86	4,990	5,120
½	5.9	6.97	5,470	5,650
1	6.1	7.32	5,220	5,670
2	6.1	7.16	5,450	5,580
4	6.6	10.82	4,900	5,310

Table 11. Influence of various combinations of lime and phosphorus on maize grain yields grown in 1976 and 1977 major rainy seasons on an Asuansi soil (Paleudult)

P_2O_5 rate	Lime rate, t/ha				
	0	1	2	4	Avg.
kg/ha	Yield, kg/ha				
1976 major season					
0	1,070	1,430	1,340	1,960	1,450
25	890	1,430	1,430	1,610	1,340
50	1,430	1,610	1,250	1,780	1,520
75	1,610	2,140	1,610	2,320	1,920
100	2,500	1,960	1,610	2,500	2,140
Avg.	1,500	1,715	1,450	2,035	
1977 major season					
0	1,040	1,860	2,550	2,370	1,955
25	2,110	2,270	2,560	2,780	2,430
50	2,150	2,820	2,780	3,350	2,775
75	2,590	2,910	3,160	3,240	2,915
100	3,190	2,760	2,970	3,460	3,095
Avg.	2,165	2,525	2,805	3,080	

Table 12. Influence of various combinations of lime and phosphorus on yield of maize grain grown in 1976 and 1977 major rainy seasons on a Basachia soil (Oxisol)

P_2O_5 rate	Lime rate, t/ha				
	0	1	2	4	Avg.
kg/ha	Yield, kg/ha				
1976 major season					
0	1,050	1,380	2,230	3,080	1,935
25	2,630	2,790	2,700	3,010	2,780
50	2,920	3,100	2,990	3,420	3,010
75	2,900	3,130	3,200	3,060	3,070
100	2,830	3,440	3,610	3,330	3,300
Avg.	2,470	2,770	2,950	3,180	
1977 major season					
0	715	910	1,525	1,635	1,195
25	1,515	1,965	1,735	1,610	1,705
50	1,550	1,915	1,880	2,555	1,975
75	2,160	1,415	1,855	2,740	2,045
100	1,430	1,780	2,165	2,330	1,845
Avg.	1,340	1,600	1,830	2,175	

the rate of applied lime increased. As in the previous year, the largest response to lime occurred where no fertilizer phosphorus was applied. The yields of the zero-lime plots increased much more with added phosphorus than did the plots that received both lime and phosphorus. Thus, the response to lime was reduced by the application of fertilizer phosphorus. Cowpea yields, however, were not affected by lime at Aivinasi in the minor cropping season.

After analyzing Kumasi soil samples from a nearby location, Mughogho (1977) concluded that levels of extractable Mn were sufficiently low to preclude it from being a substantive factor in lime response on these particular Ultisols.

The chemical data on the Asuansi soil given in table 13 show definitely that exchangeable Al was not a factor in response to lime. Both soil pH and exchangeable Ca increased with liming. Because yields continued to increase up to the highest rate of liming except at the highest rate of

Table 13. Some chemical properties of the Asuansi soil as affected by liming (Samples taken at end of first cropping season)

Lime treatment	*Soil pH*		*Exchangeable cations*			*Al saturation*
	H_2O	*$CaCl_2$*	*Ca*	*Mg*	*Al*	
t/ha			*me/100 gm*			*percent*
0	5.4	4.9	1.56	0.29	0.09	4
1	6.4	5.9	3.22	0.36	–	
2	6.6	6.2	3.79	0.19	–	
4	7.4	7.0	8.21	0.33	–	

Table 14. Some chemical properties of the Basachia soil as affected by liming (Samples taken at end of first cropping season)

Treatment	*Sample depth*	*Soil pH*		*Exchangeable cations*		*Al saturation*
		H_2O	*$CaCl_2$*	*Ca + Mg*	*Al*	
t/ha	*cm*			*me/100 gm*		*percent*
0	0–15	4.5	4.2	0.98	0.41	29
	15–30	4.2	3.9	0.47	0.90	66
1	0–15	5.0	4.5	1.96	0.13	6
	15–30	4.6	4.1	1.03	0.55	35
2	0–15	5.7	5.3	3.02	0.03	1
	15–30	4.7	4.3	1.10	0.45	29
4	0–15	6.0	5.6	3.62	0.03	1
	15–30	4.8	4.3	1.15	0.45	28

applied fertilizer phosphorus, it is doubtful that the response can be attributed to Ca alone. Rather it seems to be related to an increase in available phosphorus which probably occurs because applied lime enhances mineralization of organic phosphorus.

As shown in table 14, the Besachia soil from Aiyinasi contained more exchangeable Al than did the Asuansi soil, especially in the subsoil. The degree of Al saturation in the subsoil probably was high enough to restrict root growth. The content of Ca + Mg was also low in the untreated soils, again especially in the 15–30-cm zone. Adding lime had several effects: both soil pH and exchangeable Ca + Mg increased; exchangeable Al declined to very low values; and Al saturation declined in the subsoil to about half the original value. In addition, there was evidence of movement of Ca + Mg into the 15–30-cm zone.

Peru experiments at Yurimaguas

Continuous cropping experiment. The objective of the Yurimaguas research program is the development of viable alternatives to shifting cultivation on the Ultisols of the Amazon jungle region. The research has been directed at evaluating the effects of land-clearing methods on soil properties and crop yields and selecting the most practical cropping sequences and fertilizer requirements for sustained crop production. Although experiments aimed at developing specific lime and fertilizer practices were not made, selected treatments were available to measure crop response to lime. These soils are strongly acid and very low in Ca + Mg content, especially in the subsoil (table 15). The percentage of Al saturation is high.

Data used were derived from a continuous cropping experiment in which several cropping sequences were introduced on land that had been cleared either by traditional methods of slash and burn or by bulldozing

Table 15. Selected chemical properties of a Yurimaguas soil of Peru

Sample depth	*Soil pH*	*Exchangeable cations*		*Al saturation*
		*Ca + Mg**	*Al*	
cm		*me/100 gm*		*percent*
0–5	3.8	1.44	1.17	45
5–15	3.7	0.13	2.14	94
15–45	3.9	0.13	2.82	96
45–77	4.0	0.08	2.73	97
77–140	4.1	0.10	4.19	98
140–200	4.9	0.14	3.51	96

Source: Tyler, 1975.
*Includes K & Na, which in lower horizons constitute 30% to 40% bases.

Table 16. Yield of several crops as influenced by liming and land-clearing methods on the Yurimaguas soil (Yields from the first crop after treatment, 1973)

Crop*	Slash & Burn		Bulldozed clearing	
	Complete	Complete + 4 t lime	Complete	Complete + 4 t lime
	Kilograms per hectare			
Rice	2,560	3,210	1,060	2,525
Cassava	29,100	34,200	22,000	32,000
Maize	195	700	85	375
Guinea grass	14,980	24,100	12,860	18,380
Soybeans (system 6)	845	2,340	275	1,315
Soybeans (system 3)	905	1,480	75	400
Field beans (system 6)	60	280	30	325

Source: Seubert, 1975
*All grain yields except Guinea grass where yields are 4 cuttings of forage.

Table 17. Some chemical properties of Yurimaguas soil as influenced by land-clearing method (Sampled after first crop, which received no treatment, and after first crop which received lime application)

Sample depth	Burned				Bulldozed			
	pH	Exchangeable cations		Al saturation	pH	Exchangeable cations		Al saturation
		Ca + Mg	Al			Ca + Mg	Al	
cm		me/100 gm		percent		me/100 gm		percent
Sample after first untreated crop								
0–10	4.4	1.40	1.50	52	4.4	0.67	2.17	76
10–30	4.3	0.43	2.61	86	4.3	0.26	2.78	91
Sample after first lime-treated crop								
0–10								
–Lime	4.3	1.90	1.70	47	4.4	1.50	1.20	56
+Lime	6.2	6.00	0.10	2	6.1	5.40	0.10	2
10–30								
–Lime	4.2	0.70	2.50	78	4.3	0.50	3.00	86
+Lime	4.4	1.60	2.20	58	4.5	1.20	2.40	67

Source: Seubert, 1975

(Seubert, 1975). A first crop was grown on these plots without any further treatment. Several treatments were imposed after the first crop was harvested and before the second was planted, including a lime control treatment and one receiving 4 t/ha of lime. With both clearing systems, all crops showed a greater response to lime than those that received only the complete fertilizer (table 16). The yields on the traditionally cleared plots were, on the whole, higher than those from the bulldozed plots. The response to lime, however, was not greatly different on the two groups of plots.

Some chemical properties of the soils taken at the end of the first crop, which received no treatment, and after the second crop (treated) are given in table 17. Compared with the original samples (table 15), soil pH increased slightly at the end of the first crop (6 months). Ca + Mg were definitely higher in the samples from burned plots, and the percentage of Al saturation was reduced in the surface layer. At the 10-month sampling on both the burned and bulldozed areas, however, the Al saturation was reduced to low levels as a result of lime application in the surface horizons. The effect of lime at the lower depths was minimal. In both the burned and bulldozed soils, response to lime was associated with a reduction of Al saturation.

Lime rate experiments. To study the effect of rate of liming on crop response, an experiment was established in July 1974 on a field that had been cleared and burned in August 1972, planted in rice once, and thereafter maintained in Guinea grass without lime or fertilizer additions (Wade, 1978). The chemical properties of the soil without the additions of lime show that the soil was very acid and high in exchangeable Al (table 18). Lime was applied in one initial treatment at rates of 1, 2, 3, and 4 t/ha and thoroughly mixed into the soil in the 0–10-cm zone. Four plantings of various crops were grown without additional lime treatments. Crops grown and yields obtained are given in table 19. No maize crop was obtained in crop 3 because the weather was unfavorable. Without lime, crop yields were a failure. A substantial increase in yield was obtained at the 1-ton rate of lime, and yields of most crops in the sequence continued to increase throughout the four plantings. Wade showed that these crops had maximum yields when the Al saturation was reduced to values of 30 to 40 percent or when the Ca + Mg content was raised to 2 me/100 gm of soil or more. He concluded that liming to reduce Al toxicity was fundamental in these soils but that the crops may be responding to increased Ca supply as well.

In addition to the treatments where the lime was thoroughly mixed into the 0–10-cm zone, two application methods — mixing with a hoe and applying to the surface — at the 3-ton rate were used. Yields from these two methods were somewhat lower than those from the thoroughly mixed 3-ton treatment, but still a significant response to lime was obtained. In another treatment, only 0.6 ton of lime per hectare was spread on the surface before each crop was planted, and surprisingly good yields were

Table 18. Some chemical properties of Yurimaguas soil as influenced by lime rate and method of application. (Samples taken at end of first and fourth harvests)

Lime treatment		*Soil pH*		*Exchangeable Ca + Mg*		*Exchangeable Al*		*Al saturation*	
Rate	*Depth*	*10/74*	*11/75*	*10/74*	*11/75*	*10/74*	*11/75*	*10/74*	*11/75*
t/ha	*cm*			*me/100 gm*				*percent*	
0	0–10	4.6	4.2	1.1	1.5	1.2	2.7	52	64
Thoroughly mixed:									
1	0–10	4.6	4.2	2.0	1.6	1.0	2.7	33	63
2	0–10	5.0	4.4	2.4	2.0	0.5	1.9	18	48
3	0–10	4.9	4.5	2.1	2.2	0.3	2.4	11	52
4	0–10	5.0	4.6	3.3	2.5	0.3	1.4	8	38
Mixed with hoe:									
3	0–10	4.8	4.4	2.9	1.9	0.4	2.4	12	56
Applied to surface:									
3		4.9	4.4	2.6	1.9	0.8	2.5	24	56
0.6		4.8	4.4	1.6	1.6	0.9	2.8	37	61

Source: Wade, 1978.

obtained. If resources are limited, this may be a method of getting the necessary lime applied, albeit over a longer period of time.

The soil pH (table 18) was only slightly altered by the lime additions. As the lime rate increased, exchangeable Ca + Mg increased and exchangeable Al decreased. Thus, the percentage of Al saturation was reduced from more than 70 percent in the initial sample to less than 10 percent in

samples taken at the end of the first harvest. Both exchangeable Al and percentage of Al saturation increased at subsequent sampling dates. Exchangeable Ca + Mg decreased somewhat over the same period. Surface applications of lime did not reduce the exchangeable Al to as low levels as the mixed treatment, and the exchangeable Al increased rather rapidly in subsequent samplings. Thus, the percentage of Al saturation was quite high from the second crop on.

Table 19. Grain yields of several crops as influenced by lime rate and method of application on Yurimaguas soil

Lime treatment		*Crop 1 (9/74)*		*Crop 2 (2/75)*		*Crop 3 (7/75)*	*Crop 4 (12/75)*	
Rate	*Depth*	*Maize*	*Cowpea*	*Maize*	*Peanuts*	*Maize*	*Maize*	*Soybean*
t/ha	*cm*	*kilograms per hectare*						
0		200	360	190	440	650	0	0
Thoroughly mixed:								
1	0–10	1,260	1,070	1,850	1,520	1,830	910	520
2	0–10	2,240	1,200	2,710	2,000	2,510	2,410	1,400
3	0–10	1,990	1,160	2,540	2,030	2,500	2,200	2,190
4	0–10	2,410	1,400	2,740	2,300	2,130	3,360	3,270
Mixed with hoe:								
3	0–10	1,530	1,120	2,150	1,640	2,440	1,510	3,030
Applied to surface:								
3		1,410	850	1,510	1,320	2,190	1,750	1,610
0.6		630	670	1,280	1,080	1,670	1,660	820

Source: Wade, 1978.

Included in another experiment were lime rates of 0, 2, and 4 t/ha (Villachica, 1978). As shown in table 20, response to 2 t/ha was substantial, but above that amount it was insignificant, except for the maize crop in the SAM (soybeans – rice – maize) series.

Adding lime to this soil increased the soil pH and the content of exchangeable Ca + Mg (table 21). It drastically reduced the content of

Table 20. Effects of lime rates on yields of several crops grown in 2 cropping sequences on Yurimaguas soil

Cropping series and lime rate	*Grain yields*		
	6/75	*10/75*	*8/76*
t/ha	*kilograms per hectare*		
*MAS series**	*Maize*	*Rice*	*Soybeans*
0	2,150	3,235	Crop failure
2	3,380	3,670	
4	3,340	3,725	
*SAM series**	*Soybeans*	*Rice*	*Maize*
0	420	2,160	140
2	2,380	3,660	3,280
4	2,540	3,795	5,275

Source: Villachica, 1978.
*M = maize, A = rice, S = soybeans.

Table 21. Some chemical properties of lime-treated Yurimaguas soil as influenced by lime rate in 2 cropping sequences. (Samples taken at first and third harvests)

Lime rate	*Soil pH*		*Exchangeable Ca + Mg*		*Exchangeable Al*		*Al saturation*	
	6/75	*8/76*	*6/75*	*8/76*	*6/75*	*8/76*	*6/75*	*8/76*
t/ha			*me/100 gm*				*percent*	
Maize-rice-soybean series (MAS)								
0	4.8	4.1	1.8	0.88	1.50	2.43	58	73
2	5.2	4.5	2.52	2.11	0.42	1.23	14	37
4	6.1	5.2	4.40	3.32	0.15	0.17	3	5
Soybean-rice-maize series (SAM)								
0	4.5	4.4	1.00	0.74	1.50	1.90	60	72
2	5.8	5.0	2.41	1.77	0.30	0.62	11	26
4	6.4	5.3	4.24	3.08	0.10	0.30	2	9

Source: Villachica, 1978.

exchangeable Al, and the percentage of Al saturation consequently was reduced to very low values. At the later sampling, exchangeable Al increased slightly and exchangeable Ca + Mg decreased, with a resultant increase in Al saturation.

Lime × phosphorus experiment. An experiment to determine the optimum rates of lime and phosphorus for Guinea grass was carried out (Lopez, unpublished data). The first experiment was designed to determine the best combination rates of phosphorus and lime for optimum forage production. The chemical properties of the soil used and of other soils at the experimental site are similar. The area had been cleared a year before establishing the Guinea grass in October 1973 and had grown a crop of rice and a crop of beans without fertilization. Lime and phosphorus were applied before the establishment of the Guinea grass only. The grass was harvested on an 8-week schedule and a total of 14 cuttings were made.

As shown in table 22, a modest response to lime was observed in the lime and phosphorus rate experiment and only at the 2-ton rate. No further gain was observed for the 3.5-t/ha rate. In addition, response to lime was higher at the two lowest rates of fertilizer phosphorus, suggesting that lime was enhancing the availability of phosphorus through mineralization of organic phosphorus. Given that Guinea grass seems to be tolerant of relatively acid soil conditions, only modest responses to lime are found.

Table 22. Yield of Guinea grass forage as influenced by various combinations of lime and phosphorus on Yurimaguas soils. (Average of 14 cuttings)

P_2O_5 rate	Lime rate, t/ha			
	0	2	3.5	Avg.
kg/ha	Yield in t/ha			
0	1.99	2.86	2.73	2.52
57.5	2.64	3.47	3.48	3.20
115	3.16	2.99	3.09	3.08
230	3.03	3.38	3.52	3.31
460	3.60	3.33	3.28	3.40
Avg.	2.83	3.21	3.22	

Source: Lopez, unpublished data.

PREDICTION OF LIME REQUIREMENT

Soil properties

Soils of the humid tropical regions vary widely in their chemical, mineralogical, and physical properties. These soils are usually acid by conventional measures, and lime additions are often recommended to correct this condition. In spite of the great deal of work done on soils of the humid tropics, universal agreement does not exist as to the nature of the acidity measured, the causes of poor growth of plants on these acid soils, and the criteria needed to determine the quantities of lime required to ameliorate the acidity. Pearson et al. (1977), in their study of comparative response of three plant species in soils of the southeastern United States and of Puerto Rico, found different response patterns, which were not clearly related to either crop species or soil category. Their results supported the view that satisfactory plant growth can be made on the acid soils of tropical regions at somewhat lower pH levels than on the soils of temperate regions. They also concluded that liming experience gained in temperate regions should be used with caution for acid soils of tropical regions.

The Ultisols and Oxisols with which we have worked are characterized by a low effective cation retention capacity, a low content of exchangeable Ca and Mg, and a low degree of base saturation of the exchange complex. In addition, many of them are dominated by KCl-extractable Al. Some Oxisols, such as the Coto and Catalina clays of Puerto Rico, contain only small amounts of Al but can have rather high contents of exchangeable and easily reducible Mn.

All of the soils with which we have worked are highly weathered, and the crystalline clay fraction is dominated by kaolinite with smaller amounts of gibbsite, Al-chlorite, and crystalline iron oxides (goethite or hematite). Also, 2:1-layer silicates are often present in the clay fraction. The mica, vermiculite, and Al-chlorite are not separate species but instead are randomly interstratified mixtures. In addition to the crystalline fraction, all of the soils contain a sizable clay fraction consisting of amorphous materials of Si, Al, and Fe. These amorphous materials, along with organic matter, contribute to a substantial pH-dependent charge in many of these soils. The clay fraction of the Ultisols usually is dominated by kaolinite and still contains 2:1 minerals along with Al-chlorite. The clay fraction of the Oxisols, on the other hand, is dominated by iron oxides, gibbsite, and amorphous materials, with only traces of the 2:1 minerals (Cornell University Annual Report, 1971; Weaver, 1974; Tyler, 1975).

It is likely that the weathering of the Al-chlorite and the 2:1 minerals provided the main source of neutral salt-extractable Al found on the exchange complex of these soils. Mengel and Kamprath (1978) have also shown that organic matter can contain large quantities of Al, which is extractable with $CuCl_2$ but not by KCl. This large reserve of Al probably contributes to the acidity of soils as the organic matter decomposes and

the Al is released to the soil solution. Thus, in many of the Ultisols, as the exchangeable Al is being neutralized by liming, additional exchangeable Al is generated by weathering of Al-bearing minerals or by decomposition of organic matter (Juo and Kamprath, 1978). This generation of exchangeable Al may well explain the short-term liming effect or poor residual effect of lime noted by Pearson (1975) and reflected in the Puerto Rican studies (Abruña et al., 1975). It likewise explains why Wade (1978), while on the experiments in Yurimaguas, found a decrease in soil pH and an increase in exchangeable Al only a few months after lime additions. Exchangeable Ca + Mg had changed little over the course of his experiment, indicating that the leaching of bases was not a significant factor in increasing acidity.

On the other hand, in the Oxisols, which have a much smaller or no reserve of Al, exchangeable Al is not likely to be replenished. In these soils, the liming effect should be much longer lived, a conclusion that is borne out in the substantial residual effects of lime found at CPAC in Brazil. The Oxisols, thus, should require less frequent maintenance applications of lime and at lower rates than should the Ultisols.

Soil pH. The soils reported here all have pH values between 4 and 5 before treatment, except for certain ones from Ghana where the surface soil pH was in the low 5 range. The subsoils usually had pH values in the 4 range. The relationship between soil pH and lime application was very erratic, however. In many soils, there was enough pH-dependent charge that large lime application brought about only modest and, in some instances, rather transitory pH changes (see table 1 and 2). After the Ultisols and Oxisols of Puerto Rico were limed to about pH 5.2, no further increase in yield was obtained (Abruña et al., 1974a). Their analysis suggests that when these soils have a pH of 5 to 5.5 and Ca is in adequate supply, no response to further additions of lime will be obtained because there is no Al in solution at pH 5.2 or higher.

Aluminum saturation. In addition to being extremely acid, the Ultisols and Oxisols contain appreciable quantities of Al, which is extracted by a neutral, unbuffered salt solution. The effective cation exchange capacity of these soils is considered to be the sum of the exchangeable bases (Ca + Mg) plus the unbuffered, neutral, salt-extractable Al at the pH of the soil. In highly acid soils, most of the effective exchange sites are occupied by exchangeable Al. The percentage of Al saturation in the acid soils we have worked with has ranged from very low in the Catalina soil (Oxisol) of Puerto Rico and the Kumasi soil (Ultisol) of Ghana to as high as 90 percent in some of the other soils. The Al saturation was in range of 60 to 80 percent in most of them, and the actual amounts of exchangeable Al varied from as little as 0.7 – 1.0 me/100 gm to as high as 9.9 me/100 gm in one of the Ultisols of Puerto Rico.

Liming experiments carried out in Puerto Rico have been summarized in a series of papers (Abruña et al., 1974a, 1974b, 1975; Perez-Escolar,

1977; Perez-Escolar et al., 1978a, 1978b). With maize and snapbeans, a close relationship between yield and percentage of Al saturation existed. The degree of Al saturation of the Oxisols was much less, and maize yield showed little response to lime, except on the Bayamon loamy sand where Al saturation reached 40 percent and yields were lower than on soils with a higher pH and a lower percentage of Al saturation. Yields of snapbeans, however, increased progressively as Al saturation approached zero on all soils. The yield of sweet potatoes, a crop quite tolerant of soil acidity, showed no significant response to liming. Soybeans were intermediate in their response and, in general, yields were reduced by high amounts of exchangeable Al.

Abruña et al. (1975) have shown also that the Oxisols with which they worked had a higher content of easily reducible Mn and that Mn toxicity at low pH values may be involved in poor plant growth. Thus, they concluded that both Al and Mn were yield-limiting factors for snapbeans on soils below pH 5.0 and that a Ca:Mn ratio in the leaf of about 225 would be required for maximum yield. They also suggested that a high level of available Ca in itself is effective in overcoming the deleterious effects of excess Mn in plants.

Brenes and Pearson (1973) measured the sensitivity of sorghum, maize, and stargrass roots to Al in the soil solution of an acid Humatas clay (an Ultisol) and a Coto clay (an Oxisol). They found that Al in solution restricted root growth of maize and sorghum but that it did not detrimentally affect stargrass roots. Maize root growth was reduced only when the saturation was above 30 percent. Sorghum root growth was sharply reduced by any level of exchangeable Al above the lowest level they tested. Aluminum activity in the soil solutions ranged from 0.113 mM at the lowest pH to only 0.0009 mM at the highest pH in the Humatas clay. Sorghum root growth dropped sharply with the first increment of soil-solution Al. Maize root growth was also restricted, but about twice as much Al was required to cause the same reduction in root growth of both maize and sorghum. Brenes and Pearson (1973) also noted that root growth did not differ among various species grown in either the Ultisol or the Oxisol when the soil-solution Al level was the same. Thus, they concluded that root inhibition in acid humid-tropical soils is primarily a result of soil-solution Al toxicity. They also concluded from their analyses of the soil solution that Ca should be adequate for plant growth even in the most acid soils.

Kamprath (1970) concluded that realistic lime application rates for Ultisols and Oxisols can be based on exchangeable Al extracted with neutral, unbuffered salt. A quantity of lime equivalent to exchangeable Al reduced Al saturation to less than 30 percent. He showed that below pH 5.4 the buffer capacity of these soils was determined primarily by exchangeable Al. On the other hand, Amedee and Peech (1976a, 1976b) showed that the amount of extractable Al removed from several highly weathered tropical soils and one New York soil greatly underestimated the amount of $CaCO_3$ that would react with a soil upon equilibration with

an excess of $CaCO_3$. Even so, the exchangeable Al content of these soils provides the most useful measure of their lime requirement

Gonzalez (1976), in his study of the liming of the Dark Red Latosol of Brazil, found that Al saturation of 50 to 60 percent was critical: below this range, the concentration of Al in soil solution was reduced to low values; above it, soil-solution Al increased substantially. The activity of Al in solution is generally controlled by the solubility of poorly organized hydroxy-Al compounds or, in some instances, by gibbsite. Gonzalez's observations suggest that the addition of small quantities of lime (1 to 2 tons/ha in the top 15 cm) results in a rapid decrease in the soil-solution Al concentration. This marked decline undoubtedly accounts for the striking response of maize to the low rates of lime found in the Brazil experiment (see table 7), even though the degree of Al saturation of the effective CEC varied from 30 to 50 percent after liming.

On the other hand, Zandstra (1971) concluded that no single value measure of soil acidity was sufficiently reliable to explain variation in maize or sorghum root growth. He concluded that the soil-solution parameters pH − ½ pCa and ⅓ pAl − ½ pCa were superior to either pH or pAl in explaining the variation in root growth observed. Predicting the solution ratio of Ca and Al on the exchange complex should effectively explain how Al toxicity in various soils affects root growth. Thus, Zandstra concluded that exchangeable Ca and Al in the relation

$$\frac{[Ca]^{1/2}}{[Al]^{1/3}\,C^{1/6}}$$

, where C is the sum of exchangeable cations in me/100 gm soil, gave a useful index of Al toxicity in soils that have more than 80 percent of their exchange complex saturated with Ca plus Al.

The use of organic matter to alleviate Al toxicity has shown promise in certain situations. Evans and Kamprath (1970) have shown that soils with increasing organic-matter content had a lower soil-solution Al content at a given pH. Santiago (1972) found that organic matter rich in Ca was as effective in neutralizing exchangeable Al as was $Ca(OH)_2$. Wahab and Lugo-Lopez (1978) have shown that adding decomposed coffee leaves to soils resulted in decreased soil acidity and exchangeable Al. Coffee leaves were more effective than Pangola grass in inhibiting Al toxicity. They indicated that organic matter may well complex soluble Al and thereby reduce its toxicity to plants. Thus, soil organic matter and organic-matter additions to the soil may help alleviate Al toxicity.

Lime — phosphorus interactions. The evidence from the experiments in Ghana and Peru indicate that a strong interaction occurs between lime and phosphorus. The addition of lime in these experiments apparently enhances the availability of native soil phosphorus — a change which may derive from increased mineralization of organic phosphorus. Phosphate fertilizers supply Ca to the soil and thereby may reduce Al and Mn toxicities, much as adding lime does. Little is known about these reactions,

although Woodruff and Kamprath (1965) found that liming increased the efficiency of fertilizer phosphorus on acid soils that contained an appreciable amount of exchangeable Al. Mendez and Kamprath (1978) found on some Latosols of Panama that liming to neutralize Al, when combined with low levels of added phosphorus, increased plant growth. When Al saturation was below 60 percent and large amounts of phosphorus were added, there was no benefit from liming; and when Al saturation was above 60 percent, not even large phosphorus applications could completely overcome the detrimental effects of Al on plant growth. Much work remains for clarifying lime – fertilizer interactions to improve assessments of the need for lime on Ultisols and Oxisols.

Calcium leaching. Although it has been suggested that Ca leaches more readily from tropical soils than from soils of temperate regions, Amedee and Peech (1967a) found that smaller cumulative amounts of Ca were removed by successive extractions with water from highly weathered, humid tropical soils than from a New York Fragiochrept. The concentration of Ca in solution was proportional to the degree of Ca saturation of the soil. Juo and Ballaux (1977) likewise found that Ca losses through leaching were relatively small in an Ultisol from Nigeria. Only 1 percent of the added Ca was found in the leachate or had moved beyond the 30-cm depth during 10 weeks of cropping. These data indicate that Ca leaching from the highly weathered tropical soils is not greatly different from that in humid temperate-region soils.

Plant tolerance to acid soil stress. An alternative approach to modifying the soil environment to provide a suitable medium for optimum plant growth is to select or adapt plants that thrive in the presence of adverse conditions. The selection of various food crop plants tolerant of acid soil conditions is usually accomplished by screening presently available cultivars for their tolerance to various levels of Al in solution. The long-term goal, however, should be to develop varieties more tolerant of specific stress conditions than those presently available. Such an approach requires extensive genetic studies to identify the germ plasm responsible for the tolerant condition. The current status of our knowledge in this area has been well developed in a series of papers edited by Wright (1976).

As part of these projects, and as a follow-up to the earlier work of da Silva (1976), Salinas (1978) carried out an extensive greenhouse and field program to identify varietal tolerance to Al stress in important crops of the Cerrado region of Brazil. One of the striking observations was that Brazilian wheat varieties developed under acid soil conditions were much more tolerant of Al stress than Mexican wheat varieties developed under calcareous soil conditions. He also showed that rice, beans, sorghum, and maize, in addition to wheat, have wide ranges in tolerance to Al stress. He likewise found that greenhouse conditions for ranking varieties were similar to field conditions.

In other aspects of the studies, Rhue and Gregan (1976, 1977) de-

v-loped screening procedures which allowed reliable ranking of inbred maize lines with respect to Al tolerance. They also showed that Ca and Mg can protect maize roots from the toxic effects of Al. A wide range of tolerance to Al was observed in screening solutions: the toxicity of Al was reduc d by increasing the Ca concentration in solution.

These studies show the potential for developing and using Al-tolerant cultivars. They will be most useful in enhancing root growth in otherwise hostile root environments so that the plant can exploit subsoil water.

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