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9. ABSTRACT

This bulletin reviews the available results of liming trials conducted in humid tropical regions and determines from them information useful in synthesizing soil management systems for tropical areas. Differences in response to lime among acid soils of the humid tropics are as great as between soils of tropical and temperate regions. Although many tropical crops evolved under acid soil conditions and are probably tolerant of soil acidity, few, if any, are immune to all the factors of acid soil infertility. Relatively low rates of application are usually adequate for maximum crop production. Maximum cases lime seems to be effective chiefly as a source of Ca and Mg as nutrients. Maximum yield has usually been reached with the first increment of lime, even when it was very low. Overliming injury of crops on soils of the humid tropics seems to have been over-emphasized in the past for two reasons: The cost and availability of lime in most areas of the tropics prevent use of more than minimal rates, as a rule; and yield depression seems to be less frequent than was believed. Great differences exist among varieties of the same species in tolerance of soil acidity and this property offers a promising approach to effective land use in humid tropical areas far removed from sources of lime. Many tropical legumes can make maximum growth in extremely acid soils and strains of Rhizobium are highly acid-tolerant provided soil Mn is low. Lime requirements should be based on exchangeable Al rather than pH.

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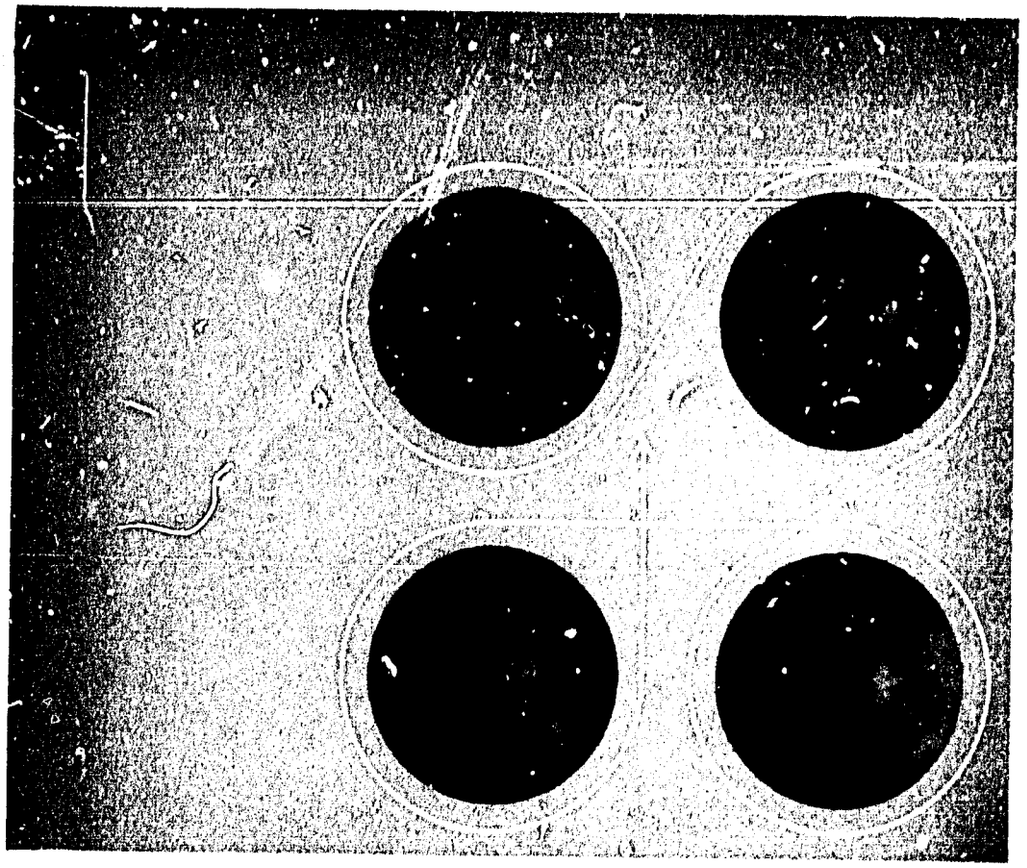

SOIL ACIDITY AND LIMING IN THE HUMID TROPICS

Robert W. Pearson

NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
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June 1975

Soil Acidity and Liming in The Humid Tropics*

Robert W. Pearson†

Introduction

The purpose of this bulletin is to review the available results of liming trials conducted in humid tropical regions and to determine from them the information that would be useful in synthesizing soil management systems for tropical areas.

Soils of humid tropical regions are usually acid, yet results of liming for improved crop production often have been contradictory. In earlier times, attempts to transfer liming practices directly from temperate regions to the tropics often gave poor results, owing to differences in the requirements of tropical and temperate crops and in soil reaction to lime additions (Richardson, 1951). Nevertheless, the judicious use of lime has continued to be accepted as an essential step to effective agricultural practice in large areas of the humid tropics (Ayres, 1961; Hardy, 1962; Laroche, 1966; Kamprath, 1972). Furthermore, the use of residually acid N fertilizers without an adequate liming program has intensified the problem (Neves, 1960; Pearson et al., 1961).

Wide differences, which have not been satisfactorily explained, occur in crop yield response to increasing pH, even among closely related soils (figure 1). Inconsistencies in the reports of liming trials in the tropics may be attributed to the fact that the measured soil properties commonly used in rationalizing observed plant behavior (soil pH and exchangeable cations) do not adequately define the root-soil environment. Displaced soil solution

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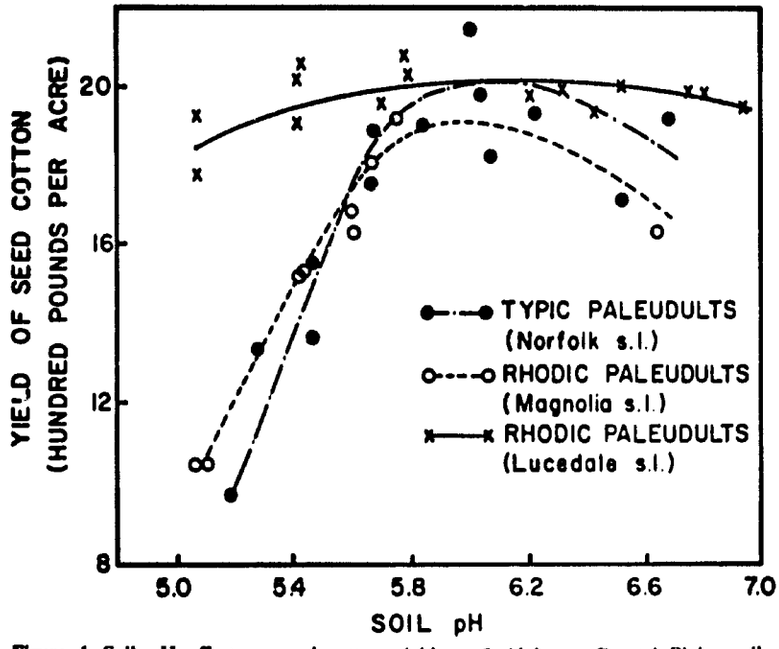

Figure 1. Soil pH effect on seed cotton yield on 3 Alabama Coastal Plains soils (Adams, 1968).

composition would probably go far toward explaining errant soil behavior (Pearson, 1971), but such information is seldom available because acquiring it involves rather tedious procedures.

Soils of the humid tropical regions differ widely in chemical, mineralogical, and physical properties; thus, any attempt to categorize them as "tropical soils" may be misleading unless done with full awareness of these differences. As pointed out by Zelazny and Calhoun (1971), Oxisols are the only order found exclusively in the tropics. An even more striking observation is that 9 of the 10 soil orders (U.S. Soil Taxonomy) occur in the small tropical island of Puerto Rico. Therefore, it would be unusual if inconsistencies did not occur among the reported observations of plant response to liming of soils in tropical regions. When organizing published liming research results to determine patterns of response, one is immediately confronted with the problem of lack of uniformity in soil classification. Soils information provided by authors from the various tropical areas ranges from none, through local soil type designation, to internationally recognized systems of classification. The problem cannot be resolved in this paper, but the research included is only that reported from humid-tropical climatic zones, and the authors' descriptive terminology has been used.

Effect of Lime on Soil Properties

Soil pH and exchangeable Ca

The conventional aim in liming acid soils of temperate regions is the alleviation of low pH and its attendant phytotoxicities. In acid soils of tropical regions, on the other hand, supplying Ca and Mg as nutrients may be the most important factor (Richardson, 1951). As a result, it is not uncommon to find large increases in crop yield reported for initial, minimal applications of lime in the tropics.

In temperate regions, liming causes immediately a fairly predictable soil pH change and subsequently, long-term gradual changes, but soils of tropical regions often respond differently. Grant (1970), working with strongly acid soils in Rhodesia, emphasized that many of the conditions governing lime reactions in soil, especially those influencing rate of reaction and loss by leaching, are not the same in tropical as in the temperate regions, where most of our ideas on liming originated. His results showed that, in general, losses of lime in field trials increased with increasing rate of application. This point is borne out by current research of Amedee and Peech (1976b), who defined Ca leaching losses as proportional to $\frac{\theta}{1-\theta}$, where θ is the degree of Ca^{++} saturation. However, their results also showed that Ca^{++} losses from a New York Inceptisol followed the same pattern and were as large as those from most of the Oxisols with which it was compared. In the experiments reported by Grant (1970), roughly one-third of the applied lime was lost by leaching during the first two seasons after liming, but the proportion varied from 10 to 60 percent, according to soil and ambient conditions. This was reflected in soil pH, which increased sharply during the first season after liming, then drifted downward, approaching the initial level by the end of the second season.

These observations are consistent with reports from various humid tropical regions. Foster (1970), for example, reported results of liming experiments at a number of locations in Uganda on ferrallitic and related soils whose initial pH values ranged from 4.3 to 5.9, and CEC's by Σ cations varied from 4 to 23 meq/100 g. The first 5 t/ha of lime increased soil pH about 0.6 unit, regardless of initial pH, but the second increment of 10 tons had a varied effect (table 1). In general, the soils were highly resistant to pH change induced by liming and seldom exceeded pH 5.5 to 6.0, although two of them had initial pH's in this range and responded sharply to the first increment of lime. In a similar vein, Rixon and Sherman (1962) reported that lime applications of up to 46,000 lb./acre on three Humic Latosols and a Hydrol Humic Latosol (Andepts suborder of the Soil Taxonomy System) did not reduce extractable Al (NH_4OAc-$BaCl_2$) more than about 40 percent. Presumably, this peculiar behavior was at least partly due to the very high pH-dependent charge exhibited by these soils. Uehara and Keng (1974) point out that this type of behavior is caused by the development of high surface-charge densities on the oxides and hydroxides of Si, Fe, and Al, particularly in Oxisols and Ultisols. Rixon and Sherman's

Table 1. **Effect of lime on pH of several "ferrallitic" and related soils included in field trials reported by Foster (1970)**

Location	Exchangeable Al	Initial	Soil reaction	
			1 yr after 5 t/ha lime	2½ yr after 15 t/ha
	meq/100g	pH	pH	pH
Rubare I	0.38	4.53	5.16	5.95
Kachwekano II	0.14	5.02	5.38	6.14
Kawanda II	0.13	5.06	5.62	5.86
Kachwekano I	0.14	5.20	5.76	6.42
Namulonge I	0.08	5.25	6.36	6.53
Balindi II	--	5.64	6.20	6.37
Bukalasa II	--	5.77	6.40	6.67

data show that theoretically some 30 tons of $CaCO_3$/acre would be required to satisfy the difference in CEC between that indicated by Σ cations and that measured by NH OAc at pH 7.0. They used an agricultural grade of crushed stone, which probably contained at least 50 percent relatively unreactive material because of the particle size distribution. Using this approach to rationalize their observations, maximum effective rate applied would have been only about 12 tons/acre, thus explaining failure to approach neutrality in these soils. In Colombia, Medina and Luna (1971) found that on strongly acid soils from volcanic ash, even 60 t/ha of $CaCO_3$ did not raise pH above about 6.5, whereas in red soils of the area, only 5 to 10 t/ha were required to raise pH to this level. These results are in agreement with those reported on somewhat similar soils in Hawaii (Rixon and Sherman, 1962).

In other instances, increments of applied lime have had rather consistent effects on pH. Soares et al. (1974) reported that the first 5 tons of limestone increased pH in three medium- and fine-textured Latosols of central Brazil from around 4.5 to about 6.0, and the second 5-ton increment raised pH an additional 0.5-unit average. Our experience with a variety of Ultisols and Oxisols in Puerto Rico has shown that lime is much more effective in shifting pH around 4.5 and 5.5 than it is in raising it to a higher level, even though there is only a small pH-dependent CEC component in these soils. Similar results have been reported by Martini et al., (1974).

Pratt and Alvahydo (1966), in an extensive study of the cation exchange properties of soils of São Paulo State in Brazil, observed three different patterns of pH change with lime application. The curves of figure 2 show that the pH of the Red-Yellow Podsolic soil increased regularly in straight-line fashion from about 4.2 to above 7, whereas that in the Latosol increased rapidly at first, and then progressively more slowly. In the B-horizon material of the Red-Yellow Podsolic soil, pH changed little, if any, through the first 5-ton application, then more rapidly with each increment up to about pH 7. Among the twenty soils included in Pratt

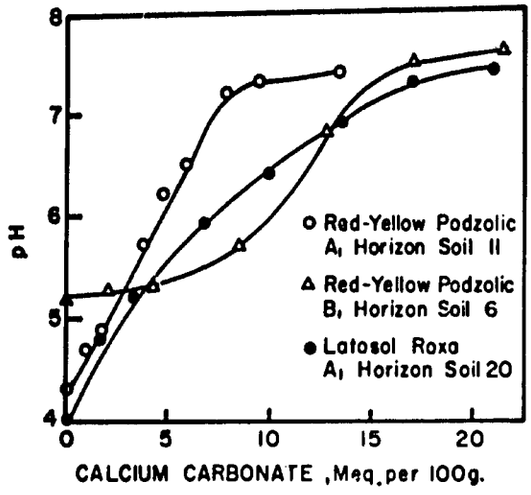

Figure 2. Types of pH response patterns to liming observed on soils in central Brazil (Pratt and Alvahydo, 1966).

and Alvahydo's study, the Red-Yellow Podsolic soils contained the lowest ratio of pH-dependent:permanent CEC, which probably accounts at least in part for the difference in slope of the two A_1 horizon curves of figure 2. The relationship of pH to base saturation was consistent among these widely different soils, and similar to that found by Adams and Evans (1962) for Red-Yellow Podsolic soils of the southeastern United States.

In general, it seems that soil pH changes induced by liming tend to be more transient in tropical soils than in those of temperate regions. We found that exchangeable Al practically disappears from both Ultisols and Oxisols in Puerto Rico at pH values around 5.5 and that it is difficult to maintain levels that high, regardless of the rate of lime used. This is clearly shown in figure 3 for an Oxisol and an Ultisol in field experiments in Puerto Rico. The initial application of lime, calculated to essentially neutralize exchangeable Al, raised pH in both soils to approximately the level anticipated within about a year. During the next 18 months, however, pH in the Oxisol dropped to 4.65, near the original value, while that of the Ultisol held constant. Application of an additional rate calculated to raise pH to about 6 resulted in pH of only 5.5 in the Oxisol, and during the following 4 years it fell to 4.7. In this same period, pH of the Ultisol dropped from 6.3 to 5.1. The fact that residually acid N fertilizer applied during this 7-year period would have offset no more than 3 tons of the lime removes fertilization as a determining factor in the rapid pH shifts observed. Also, inasmuch as in both experiments the lime was incorporated into the plowed layer, erosion losses should have been relatively small. Of course, if seasonal variations in salt concentration caused some of this fluctuation, that would support the concept of standardizing pH measurements in a salt solution such as 0.01 M $CaCl_2$ (Peech, 1965). Figure 3 records be-

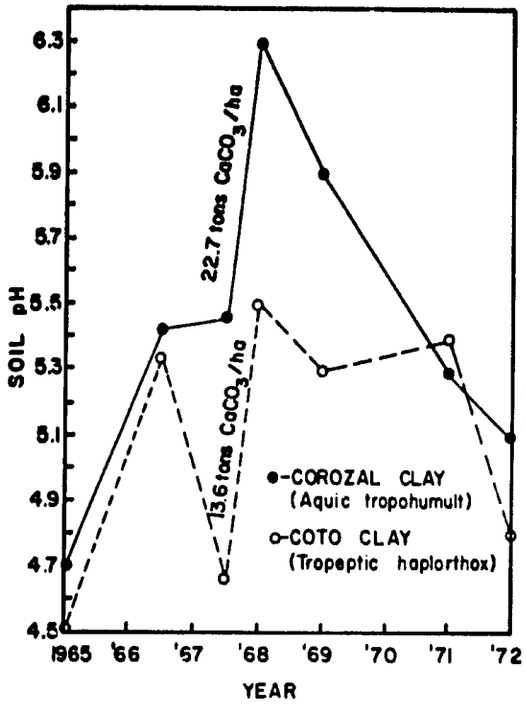

Figure 3. Changes in pH over time after lime is applied to a Puerto Rican Ultisol and an Oxisol (personal communication, Fernando Abruña, 1974).

havior that contrasts sharply with pH changes observed in a Florida Spodosol after lime applications (Gammon and Blue, 1968). Soil reaction was completed in about 2 years, after which pH declined steadily over the ensuing 8 years. At the lowest rate (2.2 t/ha), pH had returned to its original level in 8 years.

Mikami and Kimura (1964) pointed out that Ca added to tropical soils as lime often is not recovered even in the absence of leaching or erosion losses, and suggested a fixation reaction of undetermined nature. In laboratory studies using Hawaiian soils, they found up to 15 percent of applied Ca fixed within 5 months. Amedee and Peech (1976b), however, found no indication of Ca fixation by six Oxisols and one Ultisol included in their study. Rios et al. (1968) noted that soil pH decreased in the absence of leaching or use of residually acid fertilizer during the 6 months after lime application and suggested a possible reaction of Ca with P released from an Fe and Al combination as the reason for the soil pH decrease.

Brams (1971) also noted that pH in two West African Oxisols used in field liming experiments tended to decline rather quickly after liming. In this instance, an average initial soil pH of 4.4 was increased to 5.4 by liming, but one year later was back to 4.5 again. Similarly, Mahilum et al. (1970) found that Ca moved downward at a relatively rapid rate in a Typic

Hydrandept in Hawaii and reported recovery figures as low as 5 percent 7 years after lime application. Exchangeable Ca determinations showed movement throughout the 4-foot profile at the sites examined. Rapid downward movement of bases was shown to occur in two Puerto Rican soils where high rates of residually acid N fertilizer were used (Pearson et al., 1961). Amounts of Ca and Mg equivalent to about 13 tons of $CaCO_3$/ha moved out of the 0- to 15-cm layer into the 15- to 50-cm zone from surface-applied limestone.

Brauner and Catani (1967) measured pH and exchangeable Al changes with time after liming and incubation of 11 soils from various parts of Brazil. They found that both pH and exchangeable Al tended to return to the initial levels much more rapidly in the Latosols than in the Red-Yellow Podsolic soils (table 2). In this study, there was no loss of Ca from the system, and the amount of $CaCO_3$ added was roughly equivalent to the exchangeable Al in the Latosol, and half that in the Red-Yellow Podsol. Yet, after 60 days of incubation, Al was only 20 percent less than the initial level in the former. In the latter soil, Al seemed to have become essentially stabilized at about the level expected. In the case of pH, the effect of the lime had completely disappeared from the Latosol after 60 days, but was holding constant in the Red-Yellow Podsol. Mascarenhas et al. (1969) reported similar results for a strongly acid Latosol in São Paulo State of Brazil. Initial pH was 4.36 unlimed and 5.03 limed. After 1 1/2 years, these figures were 4.53 and 4.85, respectively. However, the difference in exchangeable Al between limed and unlimed soil remained essentially constant, even though soil pH difference had narrowed from about 0.7 unit to only 0.3 unit.

Acid tropical soils do not always respond to pH and Ca levels as unpredictably as previously described. Rodríguez and Correa (1966) found that pH in three acid "red soils" of Colombia increased in a predictable manner within 30 days after $CaCO_3$ applications, but changed very little during the next 120 days of incubation. One of these soils was very acid (pH 4.8) and had only a trace of exchangeable bases, indicating extreme weath-

Table 2. Changes in soil pH and exchangeable Al in 2 soils of Brazil after incubation following addition of 1000 ppm $CaCO_3$*

Soil	Initial	10 days	30 days	60 days
		pH		
Latosol	4.55	5.20	4.90	4.45
Red-Yellow Podsol	4.70	5.50	5.30	5.25
		Exchangeable Al, meq/100g		
Latosol	2.29	0.83	1.20	1.71
Red-Yellow Podsol	4.26	1.45	2.08	1.79

* Brauner and Catoni, 1967.

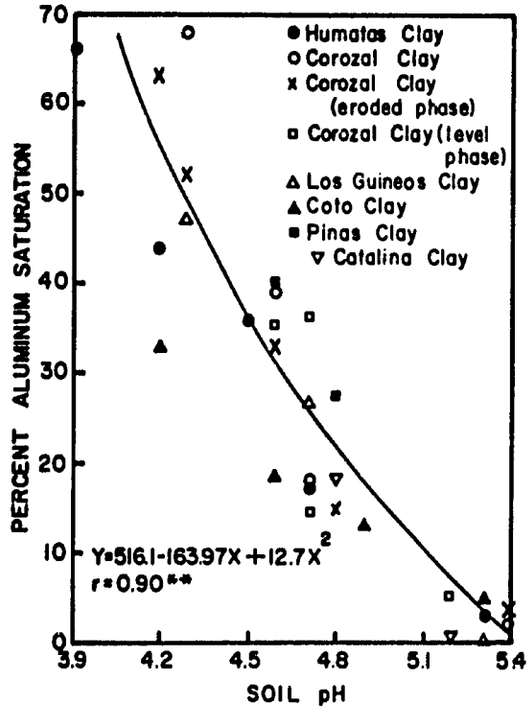

Figure 4. Changes in Al saturation percentage with pH in several Puerto Rican Ultisols and Oxisols (Abruña et al., 1974).

ering and leaching. Yet only 5 t $CaCO_3$/ha raised pH to above 6, where it remained unchanged for the 150-day period of observation. Also, Bornemisza et al. (1967) reported that pH of a Costa Rican Latosol did not change during the interval between 15 and 195 days following the incorporation of $CaCO_3$ into the potted soil. Rates up to nine times exchangeable Al equivalent were required to raise pH to near 7. At a rate three times exchangeable Al equivalent, soil pH was 5.5, which agrees generally with our experience in Puerto Rico.

Exchangeable and soil solution Al

Around 1920, soil scientists began to focus their attention on the role of Al in acid soils, and a great deal of excellent research was reported during the next decade. Magistad (1925), for example, related pH to the level of Al in soil solution and in culture solutions. His results showed that as pH is increased in the soil, in a culture solution, or in a simple solution of $Al_2(SO_4)_3$ in H_2O, the level of Al in solution decreases rapidly to < 1 ppm at around pH 5 and above. Since soil solution composition directly reflects the soil chemical environment governing plant growth (Pearson, 1971), and Al toxicity is known to be a major cause of acid soil infertility (Kamprath, 1972b), little response to liming would be expected in many soils at soil

solution pH values above 5. The fact that observed plant response usually does extend above a soil pH of 5 is at least partly a reflection of the difference in soil suspension- and true soil solution-pH, which is usually around 0.5 unit, being lower in the soil solution. Also, exchangeable Al does persist in appreciable proportions well above a soil suspension pH of 5.0. This is shown clearly in figure 4, which presents data for both Oxisols and Ultisols.

This relationship between soil pH and Al saturation is consistent with observations reported from various tropical areas of the world. By extrapolation of Bram's (1971) results, exchangeable Al in two soils from West Africa (a Plinthic Haplustox and a Typic Haplustox) would reach very low levels by pH 5.2. Similarly, Fox et al. (1962) found $BaCl_2$ extractable Al in Hawaiian Latosols reached minimal levels at 5.5 to 6.0. Further confirmation of the soil pH-exchangeable Al relationship in soils of tropical regions is provided by observations of Popenoe (1960) of a number of soils in Central America, and by Soares et al. (1974) for three Latosols in Brazil. However, the exact significance of exchangeable Al, as determined by extraction with neutral salts such as KCl, has been recently questioned by Amedee and Peech (1976a). Although the research cited has been with soils of humid tropical regions, there is evidence that the soil pH-Al saturation relationship described is essentially the same for temperate region soils (Brenes and Pearson, 1972).

While soil pH is closely related to Al saturation and solubility of Al,

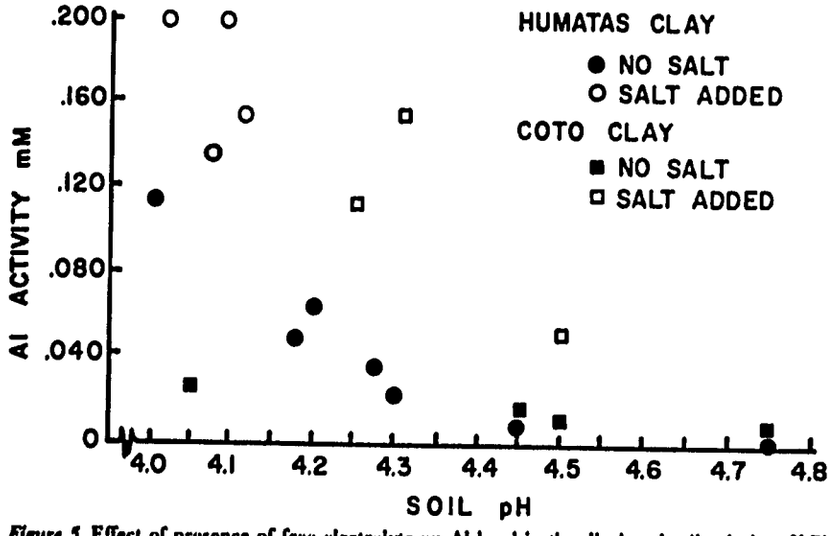

Figure 5. Effect of presence of free electrolyte on Al level in the displaced soil solution. KCl added at 0.5 meq/100 g average to 2 Puerto Rican soils and equilibrated before displacement (Brenes and Pearson, 1972).

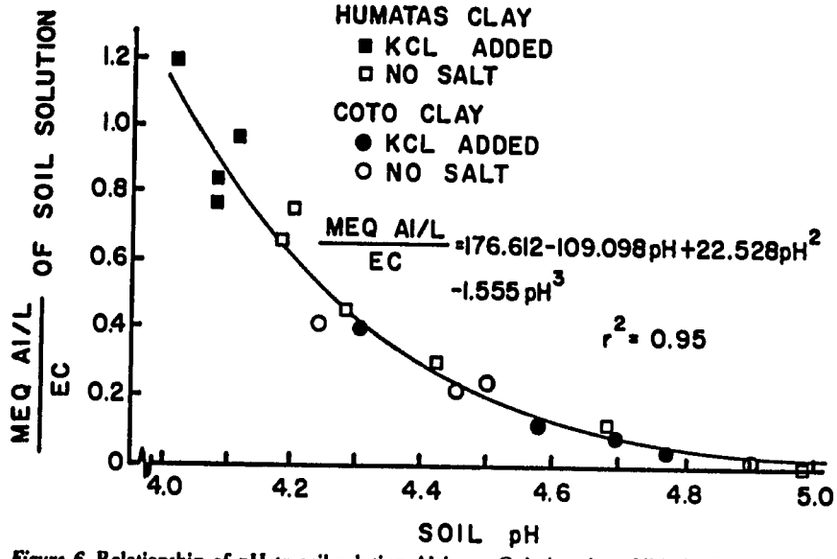

Figure 6. Relationship of pH to soil solution Al in an Oxisol and an Ultisol when free salt content as reflected in electrical conductivity (EC) of soil solution is considered (Brenes and Pearson, 1972).

both the concentration and the chemical activity of Al in the soil solution are drastically influenced by electrolyte level in the soil. This phenomenon was early noted by Fried and Peech (1946), who found Al concentration in a water extract of an acid soil treated with gypsum to be increased more than 100 percent; and later by Cate and Sukhai (1964), who recommended that salt content of acid rice soils be kept below 1000 ppm to prevent Al toxicity. This salt effect on the activity of Al^{3+} in the soil solution itself is shown in figure 5 for an Ultisol and an Oxisol in Puerto Rico. What appears to be an anomaly in this instance, in that Al^{3+} activity should take electrolyte content into account, is probably due to the use of soil suspension pH rather than soil solution pH in the correlation. Thus, soil solution pH would have been lower than soil suspension pH for any soil with pH above zero point of charge, but higher for those with pH's below that point (Van Raij and Peech, 1972). When the salt effect was taken into account by including electrical conductivity of the soil solution in the expression of Al level, the variations at a given soil pH value were essentially eliminated (figure 6).

Available manganese

Manganese toxicity is one of the hazards to plants growing in acid soils and, like Al toxicity, can be avoided by proper use of lime (Adams and Pearson, 1967). In Puerto Rico, intensively managed coffee on strongly acid soils high in Mn responded to liming but did not respond on soils

low in Mn, though exchangeable Al was high (Vicente-Chandler et al., 1969). Manganese uptake depends upon the activity of divalent Mn in the soil solution, which is dependent upon the presence of easily reducible Mn in the soil. Generally, a few ppm Mn in the soil solution is enough to induce Mn toxicity (Bortner, 1935; Adams and Wear, 1957; Morris and Pierre, 1949). In Puerto Rico, dangerous levels of either easily reducible or exchangeable Mn appear to be limited to specific soils at low pH. Ultisols seldom present a Mn problem, whereas the Oxisols frequently do (Vicente-Chandler et al., 1969; Abruña et al., 1974)(see table 3). In one case, a Tropeptic Haplorthox had 3.3 meq Mn/liter soil solution, while a Typic Tropohumult at the same pH had essentially none (Brenes and Pearson, 1972). Manganese concentration decreased to a very low level where liming raised the soil pH from 4.05 to 4.75. In other experiments, Mn uptake of various crops decreased progressively as soil pH was increased by lime application (Abruña et al., 1964, 1974), indicating that soil solution levels of Mn decreased as soil pH increased.

Ayres (1961) stated that some Hawaiian soils, notably the Low Humic Latosols, are high in Mn oxides, and when they become strongly acid they have high levels of soluble Mn. In other soils, such as Hydrol Humic Latosols, Mn is so low as to cause deficiency in sugarcane. Liming was shown to reduce exchangeable Mn to 10 ppm in some cases. Similarly, extractable Mn was reduced to near 0 in eight Natal Oxisols by the first increment of lime (Reeve and Sumner, 1970a).

Table 3 Some characteristics of the soils at 8 liming experiment sites in Puerto Rico*

Soil type	Classification	Easily reducible Mn	Exchangeable Al	Soil reaction
		ppm	meq/100g	pH
Humatas clay	Typic Tropohumult	120	6.3	3.9
Corozal clay	Aquic Tropodult	210	9.9	4.3
Corozal clay	(level phase)	---†	5.5	4.6
Corozal clay	(eroded phase)	---†	6.9	4.2
Los Guineos clay. . . .	Epiaquic Tropohumult	40	4.5	4.3
Coto clay	Tropeptic Haplorthox	700	1.1	4.2
Catalina clay	Typic Haplorthox	638	0.9	4.8
Pinas sand	Typic Haplorthox	144	0.4	4.6

* Abruna et al., 1974.

† Not determined.

Phosphorus availability

One of the primary reasons commonly given for liming acid soils is to improve P availability. Although there has been controversy over the validity of this assumption with regard to P present in the soil before liming, the beneficial effect on P applied after soil acidity is corrected in temperate regions has been widely accepted. It was natural, perhaps, that these concepts gained even wider acceptance in attempts to synthesize soil management practices for the acid, highly weathered soils of the humid tropics. However, as pointed out by Kamprath (1972), published results show that the effect of lime on P availability can vary from beneficial to detrimental.

Sherman (1952) stated that the effect of lime on chemical activities of gels containing Al, Fe, Si, and Ti, such as are encountered in many tropical soils, would be small, and that such amorphous materials have large P-fixing capacities. Numerous studies have failed to show either reduction in P fixation after liming or improvement in solubility in various extractants. Soil P solubility in an Oxisol from Colombia decreased sharply as pH was increased by $CaCO_3$ application up to about pH 6.5, and the limed soil had a higher maximum P adsorption capacity than the unlimed soil (Amarasiri and Olsen, 1973). The authors suggested that the freshly precipitated Fe and Al hydroxides were responsible for the increased inactivation of added P as lime rate increased. Pot-grown rye and millet were given a wide range of lime and P applications. Essentially no growth of either crop occurred at P_0, but yield was near maximum at the highest rate. Phosphorus uptake was higher around pH 5.5 than at either higher or lower values, as is shown for rye in figure 7. Percent P in the plants increased with liming at the lower levels, but remained constant after reaching a maximum at the third lime level, indicating that the yield decrease at the upper lime rates caused the drop in P uptake and was due to some factor other than depressed P availability. Similarly, Reeve and Sumner (1970) found that liming did not reduce P fixation in eight Natal Oxisols. They also reported that P retention was not related to exchangeable Al levels in these soils. Again, lime applied to ferrallitic soils of West Africa with pH levels of around 5.3 and exchangeable Al ranging from 6 to 26 percent did not influence availability of P applied to maize or groundnuts (Brams, 1971). P extracted by various methods and P fixation were unaffected when a number of soils of the cacao region of Bahia, Brazil were limed (Cabala and Fassbender, 1971). This was also the case with a Costa Rican Andosol (Fassbender, 1969). Perhaps the most extensive laboratory study reported of lime×P relationships was made by Anastacio (1968), using 55 soils from different regions of Brazil, including a number of Latosols and Terra Roxa soils. His data do not indicate any relationship between recoverable P (dilute-acid extraction) from P applications or from either soil pH or exchangeable Al.

The pattern of P uptake by plants as influenced by liming acid tropical soils is by no means as consistent as the chemical characterization of liming

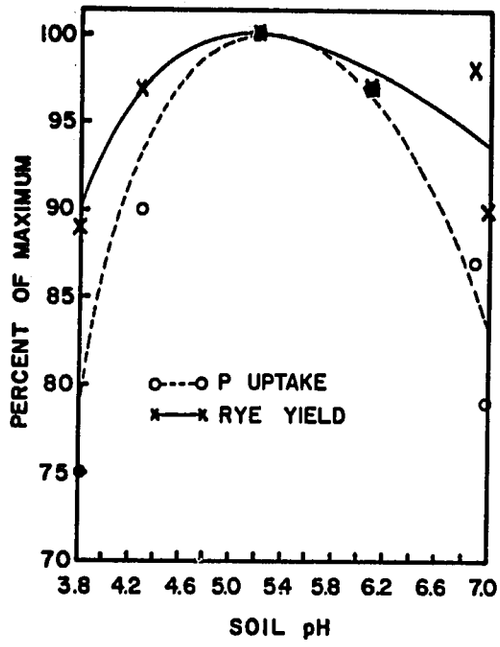

Figure 7. Soil pH effect on rye yield and P uptake from an Oxisol (Amarasiri and Olsen, 1973).

effects on P availability. Fox et al. (1962), for example, concluded that optimum P availability in Hawaiian soils occurred at pH values between 5 and 6. In a later experiment using P_{32}-tagged fertilizer, Fox and Plucknett (1964) showed a much higher recovery of applied P by sudangrass and Desmodium sp. at pH 5.0 than at higher pH levels in a Hydrol Humic Latosol. In a Humic Ferruginous Latosol there was no depression in P uptake even above pH 7.

Experiments by McClung et al. (1961) on three Terra Roxa Misturada soils of São Paulo state of Brazil, with an average initial pH of 5.2, showed that cotton production was strongly influenced by the response of lime to applied superphosphate. The fact that as lime rate increased, yield without added P increased gradually to the maximum value obtained in the experiment at the 6-ton rate, and that the response to P decreased to essentially zero at the adequate lime rate, could be interpreted as being due to either of two reactions, or a combination of the two: first, because root development had been improved, and therefore positional availability of native P, the ability of the crop to utilize native P may have been enhanced by liming or, second, Ca was deficient as a nutrient, and the response to superphosphate was due in part to the Ca in the superphosphate. Similarly, Hortenstein and Blue (1968), using a soil from British Honduras in pot tests, found that P uptake by three crop species was increased by liming.

Microbiological factors

Many changes are known to occur in soil microbial populations and activities when soil reactions change. In general, the population shifts from bacteria to actinomycetes to fungi as soil acidity increases, although the acid tolerance of individual microbial species varies widely. Thus, transformations of such nutrient elements as N, P, and S between the organic and inorganic state, and both the symbiotic and nonsymbiotic fixation of N would be affected to an important degree by liming. Ayres (1961) found that organic matter decomposition in Hawaiian soils was speeded up considerably by liming. In an 8-month incubation test, 35 ppm N was released in the unlimed treatment, compared to 125 ppm in the limed soil. Bornemisza (1967) also reported more rapid decomposition of soil organic matter in Costa Rican soils after liming, although Fassbender (1969) did not find any decrease in organic phosphorus for lime applied to a Costa Rican Andosol during one season.

Beans, both *Phaseolus* and *Glycine*, can develop nodules and fix N satisfactorily at surprisingly low pH levels, provided Mn toxicity is not a limiting factor (Döbereiner, 1966). The strain of Rhizobium associated proved to be a significant factor in the effect of acidity on these species, and Döbereiner emphasized the importance of selection of acid-tolerant strains for use in acid tropical soils.

Souto et al. (1969) reported that, when the Mn level in soil is high, it can seriously impair nodulation and N fixation in several tropical legumes. They used (1) *Centrosema pubescens;* (2) *Pueraria javanica;* (3) *Glycine javanica* var. SPI; (4) *Gly ine javanica,* var. Tinaroo; (5) *Stylosanthes gracilis;* and (6) *Phaseolus atropurpureus,* grown in two soils of Rio de Janeiro state, with Mn added in soluble form at three levels in addition to the control. Species (1) was the most tolerant of Mn, while (2), (4), and (5) showed sensitivity by failure to form nodules. Even the lowest level of applied Mn (50 ppm) reduced nodulation and N fixation of the most tolerant species at 2 months. In a second experiment, liming was shown to effectively correct the Mn toxicity symptoms.

In another study of lime effects on nodulation, Mascarenhas et al. (1967) found no clear response by soybeans. In one "acid soil" of São Paulo (pH 4.8), liming appeared to definitely increase the number of nodules per plant, while in another less acid soil (pH 5.5), it did not. However, in the latter case, weight of nodules was clearly increased by liming. Pelleting seed in $CaCO_3$ decreased stands, but greatly increased the number of nodules in the pH 4.8 soil, but not in the other one. Yield was decreased by pelleting, apparently owing to the stand damage.

Martin (1959) observed that peas grown in an acid (pH 4.8) soil of French Equatorial Africa had no nodules. Lime applied on the soil surface at 2 t/ha resulted in a few active nodules near the surface. When lime was applied on the furrow bottom, nodulation occurred in the lower half of the plowed layer, but when it was mixed throughout the 0- to 23-cm zone, nodules were well distributed throughout the limed zone.

Potassium availability

Ideas have varied widely with regard to the effects that liming acid soils has on the forms and availability of K, and there is still no general agreement. Obviously, liming can increase plant efficiency in the use of K simply by removing other growth-limiting factors and improving the positional availability of K through an expanded and more effective root system. In addition, liming usually decreases leaching losses of K, tends to increase reversion of K to less soluble forms, and may or may not affect the rate of release of native mineral K into soluble or exchangeable form (Peech and Bradfield, 1943; York and Rogers, 1947; Rogers, 1948). Thus, the use of lime on highly weathered and leached soils of the humid tropics could conceivably have a wide range of effects on plant growth through its influence on the K economy of the soil, depending upon various soil characteristics. Although Reitemeir (1951), in an extensive review of the question, concluded that the widely held concept that Ca exerts a depressing effect on plant uptake of K (Ca:K antagonism) is not valid, Amarasiri and Olsen (1973) found that yield depression in millet at high rates of liming an Oxisol from Colombia was related to the K/Ca ratio in the plants. They noted that the ratio increased progressively as yield increased, and that 70 percent of the variation in yield from individual pots could be accounted for by this ratio. Ayres (1961) showed that leaching loss of K from two Hawaiian soils was substantially reduced by even modest applications of lime. In one soil, an application of lime of only 2 t/acre halved the K loss. This effect would be especially significant in the generally permeable upland soils of hot humid regions.

Silicate application

During the last decade, substantial interest has developed in the role of Si in tropical soil fertility and plant nutrition (Fox et al., 1967; Ayres, 1966; Monteith and Sherman, 1963). While it is beyond the scope of this paper to attempt a detailed review of the subject, crop response to silicates appears to be closely associated with several factors of acid soil infertility, and silicates are known to react with acid soils much as conventional liming materials do. Normal benefits of liming should thus result from silicate treatments. However, there have been persistent reports of yield increases realized from silicate applications beyond those observed from equivalent treatments with lime, giving rise to the conviction that in some soils and for some crops at least, Si can play a unique role in plant nutrition (Sherman et al. 1964; Silva, 1971). It therefore seems relevant to consider the behavior of Si in relation to ambient pH in connection with liming tropical soils.

Silicate slags are the main economically feasible source of Si for agricultural use and, as mentioned above, their effect on soil acidity is essentially the same as that of the various forms of lime. However, Sherman et al. (1964) noted that an overliming effect had been observed in only one instance where silicate slag was used. Whether this beneficial effect is sup-

plied by the micronutrients in the slag is not known, but it contrasts with the frequent reports of such effects when conventional liming materials are heavily applied. Silva (1971), in a review of possible mechanisms for crop response to silicate application, pointed out that reactions concomitant with increased Si content included decreased Al, Fe, and Mn activity, P fixation, and increased solubility of sorbed P. Silicate applied to P-deficient Latosols in Hawaii, for example, increased extractable P, decreased response to applied P, and increased dry-matter yield of sugarcane (Roy et al., 1971). The authors concluded that the increase in yield was associated with improved plant-P nutrition. Similarly, Suehisa et al. (1963) observed a strong Si × P interaction of sudangrass yield in a Low Humic Latosol, and concluded that the Si enhanced P availability by substitution in the P-fixation reactions.

In addition to the Si × P relationship, there have been persistent references to possible important Si effects through depressed uptake of Mn and other ions in excessive amounts (Williams, 1967). Peaslee and Frink (1969) increased the soluble Si level in an acid soil without affecting its pH, and found that both concentration and total uptake of Al and Mn were decreased in tomato plants. Uptake of Zn and Cu were not affected.

If, in fact, Si, *per se*, does have a role in plant nutrition, its solubility in soils is an important factor of acid soil infertility. According to McKeague and Cline (1964), solubility of amorphous Si is essentially independent of pH between pH 2 and pH 9. This is consistent with results of Elgawhary and Lindsay (1972), which showed no difference in soluble soil Si at pH levels below 8.0. In soil systems, however, more than the simple solubility product of amorphous Si is involved. McKeague and Cline (1963) reported that freshly precipitated hydroxides of polyvalent metals such as Al^{3+} and Fe^{3+} are highly effective in Si sorption. Their observations tend to explain the data of Beckwith and Reeve (1969), which show a strong dependence of Si absorption from solution by soils. They equilibrated the soils of a wide range of categories, adjusted them to different pH values with monosilicic acid, and then measured the Si remaining in solution. Residual levels of solution Si decreased with increasing pH, and they suggested sesquioxides as the probable agent.

It appears, then, that the use of silicate slag or Ca silicate as an amendment on acid tropical soils may well provide some protection against the hazard of overliming, may improve P economy, and exert some control of excess Mn uptake, in addition to the usual benefits derived from liming.

Micronutrient availability

Drosdoff (1972) reviewed micronutrient status in soils of the humid tropics and pointed out that deficiencies are becoming more common with intensification of crop production. The general relationship between availability of the various micronutrient elements and soil pH is widely recognized. Since all but Mo become less soluble as pH is increased, it is probable that liming the highly weathered and leached soils of humid tropical

regions will frequently lead to deficiencies. Presumably this is true where higher lime rates have caused yields to drop, but experiments have seldom given information for identifying specific deficiencies associated with lime application. Moreover, micronutrient deficiency does not occur as commonly as anticipated in such generally infertile soils. Certainly in areas where widespread micronutrient deficiencies have been identified or where incipient deficiencies are known to exist, the use of lime rates beyond minimum levels required for satisfactory crop growth would be hazardous. Hardy (1962) stated that the Red and Reddish-Brown Latosols of the Campo Cerrado are likely to be deficient in one or more micronutrients, particularly Hawaiian researchers have recorded that overliming caused a Zn deficiency in corn and cucumbers (Young and Plucknett, 1963; Fox and Plucknett, 1964), and that when soil pH reached about 7, severe symptoms of deficiency in *Desmodium intortum* became evident. Four soils from Brazil were limed to different pH levels by Meuer et al. (1971) in a study of induced Zn deficiency. When pH was raised to 6.5, Zn deficiency symptoms appeared in plants growing on low-Zn soils, and when it was further increased to 7.4, Zn deficiency occurred in all the soils.

McClung et al. (1961), in a series of experiments with cotton on Latosols, included lime rates up to 6 t/ha, and, in several instances, applied micronutrients as a variable at the high lime rate. Results were inconclusive, although they reported several responses and observed scattered deficiency symptoms.

In Uganda, Foster (1970) reported that an interaction between lime and a complete micronutrient treatment affected groundnut yield at only one of about twenty experiment sites. In this instance, the micronutrient treatment increased yield only in the presence of lime. In the same series of experiments, micronutrient application decreased bean yield in the absence of lime and had no effect when lime was applied, which suggests a toxic effect. Widespread Mo deficiencies in groundnuts have been identified in Uganda by Nye and Greenland (1960), where a 12 percent average yield increase for applied Mo was found in nineteen field trials. This probably explains the frequently observed response of groundnuts to lime on these soils even at pH levels as high as 6. Similarly, in Venezuela, soybeans responded to Mo on an unlimed savannah soil, and peanuts, both limed and unlimed, responded, although response to Mo was greater in the unlimed than in the limed treatments (Chacon, 1968). Kamprath (1971) reviewed examples of lime-induced B, Zn, and Mn deficiencies, although most of those available for reference were reported from temperate rather than tropical areas.

Soil physical condition

Soils whose aggregate units are stabilized by iron oxides generally have good physical condition. They can be worked soon after rain, and the runoff and erosion hazard is low (Barnett et al., 1971). Structural deterioration of such soils has been reported as a result of liming (Peele, 1936; Schuf-

felen and Middleburg, 1954; Venema, 1961). However, many reseachers throughout the humid tropics have been reporting the beneficial overall effects of liming at appropriate levels of application. Without observations of adverse physical effects, one is thus forced to conclude that liming has no unfavorable effect of practical significance on soil structure.

Crop Response to Lime

There is a tremendous range in tolerance of soil acidity among crop species (Hewitt, 1952; Jackson, 1967), and it is now recognized that about as much difference occurs among varieties of the same species (Foy et al., 1967, 1973; Spain et al., 1974). Many tropical crops have evolved in an acid soil environment and consequently some – tea, for example – prefer such conditions (Richardson, 1951). However, no tropical plants of agricultural significance are immune to all factors of acid soil infertility, and lime, at least in modest amounts, is recognized as one of the first requirements for effective use of the soils of most humid tropical areas.

Negative response

Many reports dealing with liming in the tropics emphasize the hazard of overliming that accompanies attempts to adapt temperate-region liming practices to the tropics, yet efforts have seldom been made to identify the specific causes of such effects. In temperate regions, lime rates are usually selected to raise soil pH to some predetermined level, even though the basic objective is elimination of exchangeable Al. Lime rates used in the tropics, however, being usually based on neutralization of exchangeable Al, tend to be relatively low. As a result, not many field experiments in tropical regions report lime rates covering a range that might result in overliming injury. Ignatieff and Lemos (1963) observed that lime depressed yields on Red-Yellow Podsolic soils at moderately high levels (3 tons) but not if Mg, K, and micronutrients are supplied. Similarly, Marin (1968) cautioned against overliming and stated that micronutrient deficiencies, particularly of Mn and Fe, can be induced in such crops as soybeans, some cereals, and horticultural plants.

In Brazil, Mascarenhas et al. (1969) limed a Red Latosol with 1.6-ton increments of $CaCO_3$ up to 4.8 t/ha without any indication of yield depression of soybeans, even though initial pH was 5.5 In other tests, Mascarenhas et al. (1967) had obtained no indication of soybean response to micronutrients in soils of this type in the same region, which is consistent with absence of overliming damage. However, Freitas and Pratt (1969) reported a yield depression of *Phaseolus* and *Stylosanthes* in some soils of the same region above approximately pH 6.4.

In field screening tests on an Oxisol in the Colombian Llanos Orientales, Spain et al. (1974) noted that most of the cassava cultivars included were adversely affected by 6 t/ha of lime, probably as a result of induced micronutrient deficiency, although there was a sharp yield increase from the first 0.5- to 2.0-ton applications. They also observed that most of the acid-

tolerant crop species tested were surprisingly tolerant to high rates of lime, and reported no overliming injury to corn, cowpeas, black beans, or field beans (up to 16 t/ha).

Parra (1971) reported a sharp depression in bean yield on volcanic ash soils of Colombia when more than 2 t/ha of lime was applied. Initial pH of the soil was not listed. Another field test in which overliming injury was reported was carried out by Cabala and Fassbender (1971), where the lowest initial pH of the eight soils used was 5.5. All but one of the soils were already at pH > 5.9. Even so, only a small sorghum vield depression was reported for lime application in two of the eight soils. Another instance of overliming injury was reported by Brams (1971). He found small depressions in yield of both maize and groundnuts at the highest rate of lime used (1689 kg/ha) in his experiments on two Oxisols in West Africa. Brams found no differences in micronutrient composition of the groundnut leaves, which suggests that an induced micronutrient deficiency was not responsible for the yield depression. Nor was there a P×lime interaction on yield. Thus, the cause of the overliming damage was not identified.

Fox and Plucknett (1964) stressed the danger of overliming some Hawaiian soils, from the standpoint both of depressed P uptake and possible induced Zn deficiency in some crops. They reported that chlorosis resulting from Zn deficiency appeared at around pH 7 and reached serious proportions at about 7.4. However, Ayres (1961) reported pot tests with soils from typical sugarcane lands of Hawaii, in which lime rates up to 20 t/acre were used with no adverse effect, even though maximum yield was reached with the first 5-ton increment. Similarly, Rixon and Sherman (1962) stated that on Humic Latosols along the Hamakua and Hilo coasts of Hawaii, lime applications of up to 10,000 lb./acre were not detrimental to sugarcane yield.

Hartley (1968) reported that lime caused a decrease in oil palm yield in one year of a 4-year test on a Nigerian Oxisol. He commented that the yield depression was observed only when superphosphate was applied, even though there was no response to P in this test. Since both phosphating and liming are known to reduce Zn availability, one may speculate regarding possible induced Zn deficiency.

Bornemisza et al. (1967) reported a sharp drop in tomato yield on a Costa Rican Latosol when limed beyond pH 5.5. Similarly, Amarasiri and Olsen (1973) observed a yield depression of millet grown on a Colombian Oxisol when limed to pH above 5.3. In this case, both P and Zn interactions with lime were ruled out as the cause of overliming damage. They observed a close relationship between yield of millet and the K/Ca ratio in the plant, suggesting K-Ca unbalance as a contributing factor to the overliming yield depression.

No instances were reported where plant yield depression from overliming tropical soils was corrected by micronutrient applications, even though incipient deficiencies of certain elements such as Zn, B, and Mn could certainly be intensified by liming. The results, summarized above, of

experiments that included fairly wide ranges in rates of application seem to indicate that the overliming hazard is not reliably predictable. Most records of sharp yield depressions were from pot tests, where the entire root system was confined in the limed zone. It further seems that crop damage from overliming is not likely to be a hazard when application rates are based on the commonly accepted 1.5 to 2 times exchangeable Al equivalent.

Positive response

Cereals. Corn, sorghum, wheat, rice, and millet have been used in liming experiments throughout the humid tropics, and have almost always shown yield response to at least the first increment of applied lime. Corn has been by far the most thoroughly tested crop.

Abruña et al. (1974), using an improved variety of corn developed for the humid tropics, found a strong yield response to lime on five Puerto Rican Ultisols (fig. 8), but considerably less response on three Oxisols with about the same pH range (fig. 9). Some characteristics of the soils are shown in table 3. A fact of particular interest is that rates of lime ranging up to around 30 t/ha were applied to these soils during the course of 6 years, with no evidence of overliming injury. In fact, the Coto, with only 1.1 meq Al/100 g received 17 t/ha in 2 years without yield depression. Among the Ultisols, the relationship between grain yield and soil pH was

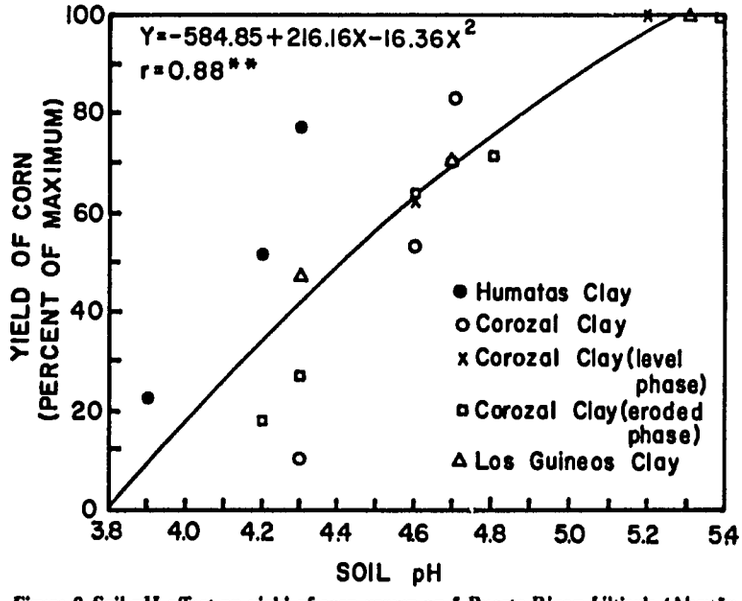

Figure 8. Soil pH effect on yield of corn grown on 5 Puerto Rican Ultisols (Abruña et al., 1974).

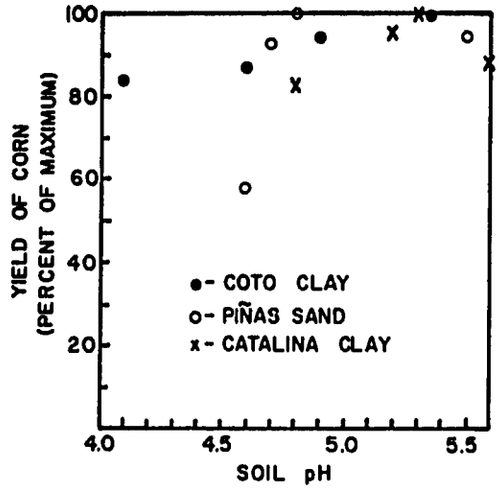

Figure 9. Relationship between pH and corn yield on 3 Puerto Rican Oxisols (Abruña et al., 1974).

not as close as that between yield and percent Al saturation (fig. 10), which the scientists believe to have been the chief cause of yield reduction at the lower pH levels. Yields decreased sharply with increasing levels of Al saturation throughout the range used, and particularly at about 15

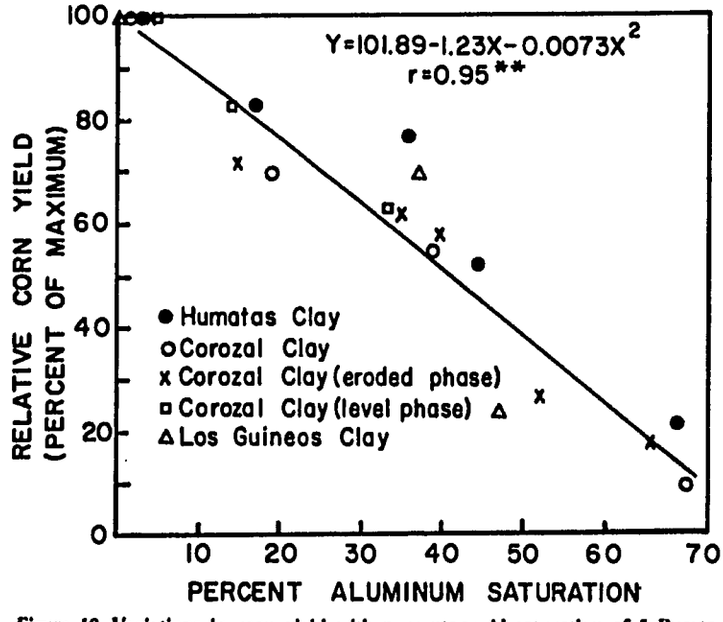

Figure 10. Variations in corn yield with percentage Al saturation of 5 Puerto Rican Ultisols (Abruña et al., 1974).

percent or more. Yield was much less depressed in the Oxisols by a given level of pH, and the effect of percent Al saturation was unconvincing (fig. 11). These observations are consistent with those reported by Ignatieff and Lemos (1963) and McLean (1971) that low pH is not as deleterious to plants grown in highly weathered tropical soils as in those with less severe weathering. They effectively eliminated Mn toxicity and Ca deficiency as important yield factors in either group of soils. The inference, then, is that the soil solution Al level was probably lower at a given pH value in the more highly weathered soils – a conclusion that is supported by earlier results from examining the soil solution of similar soils (fig. 12).

In other tests with corn, Soares et al. (1974) found sharp yield increases (15 to 40%) of corn to 5 t/ha of lime applied to Dark Red Latosols in four out of five locations in central Brazil. Soil pH in the unlimed plots was less than 5.0. The initial 5-ton application raised it to the 5.3–5.6 range, and Al saturation was reduced to less than 10 percent. When the rate of application was increased to 10 t/ha, yield tended to decrease slightly. Also, in Brazil, Freitas et al. (1960) reported a strong response by corn to liming of two Humic Latosols with initial pH values of 4.3 and 4.5, and only traces of exchangeable Ca. They suspected Ca deficiency but could not be sure, since Ca in one form or another was common to all treatments except the control. Mikleson et al. (1963) reported results from what appeared to be an extension of the preceding experiments on two Latosols and a Regosol in São Paulo state. Unlimed soil pH was 4.9, and three rates of lime were used in addition to the unlimed check. The top rate was chosen in each soil to raise pH to 6.0. Corn yield increased to

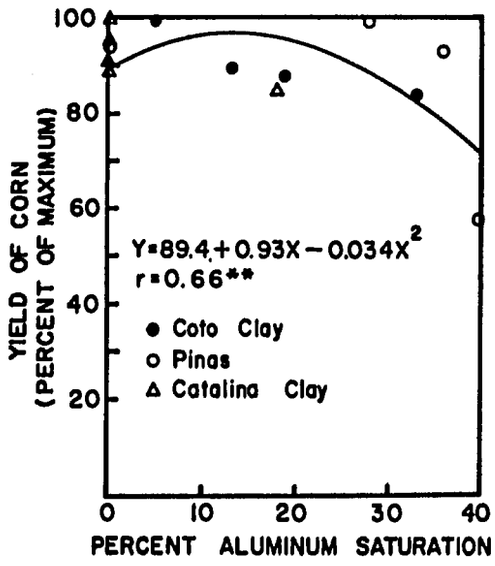

Figure 11. Effect of Al saturation percentage on corn yields on 3 Puerto Rican Oxisols (Abruña et al., 1974).

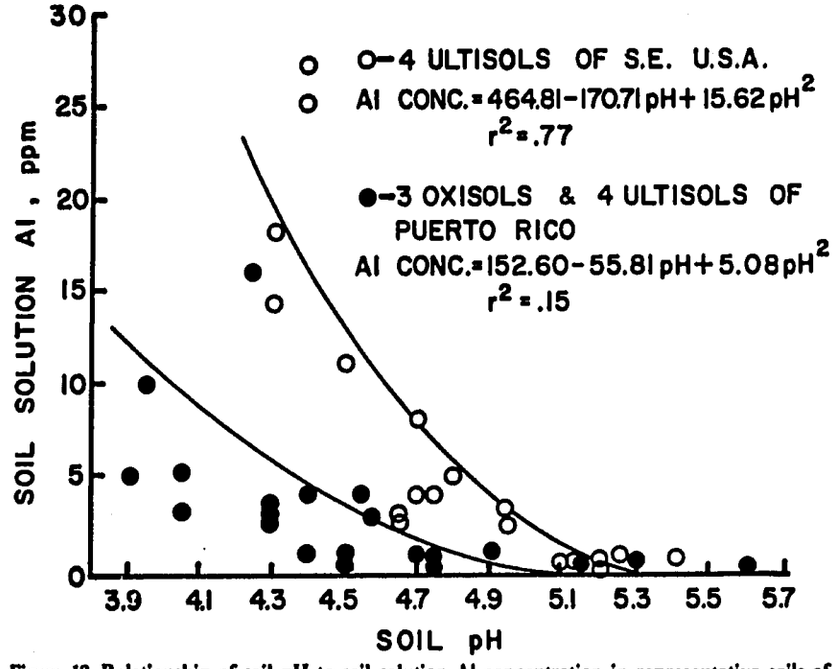

Figure 12. **Relationship of soil pH to soil solution Al concentration in representative soils of southeastern United States and Puerto Rico (Brenes and Pearson, 1972).**

maximum levels in all three soils at the intermediate rates of liming, and remained at that level when higher rates were used. Parra (1971) reported a substantial increase in corn yield on volcanic ash soils of the coffee region in Colombia. Although specific soil data were not given, he stated that pH of these soils ranged from 4.6 to 6.7. He also found that the corn response to lime increased over a period of twelve crops. Similarly, Freitas et al. (1971), in studies designed to determine the specific causes of very poor crop production on various Latosols under savannah growth in the Federal District of Brazil, found that corn yield responded strongly to lime where the untreated soils varied in pH from 4.3 to 5.1.

Trials carried out over a 15-year period in many parts of tropical Africa (Nye and Greenland, 1960) showed that corn yields were good when pH was below 5.0, and that the behavior of Oxisols and Ochrosols was much the same.

In southeastern Nigeria, for example, corn grew very poorly on Oxisols below pH 5.0, and showed large responses to small amounts of lime, such as ½ t/acre. Further additions did not prove beneficial. In the central Congo, on soils of pH around 4.5, there were moderate responses to lime. Brams (1971) tested corn response to lime on two Oxisols (pH 4.4) in

West Africa, using four rates ranging up to 1689 kg/ha, in 563-kg increments. He reported only small yield increases, even though Al saturation based on Σ cations was about 80 percent in the unlimed soils. The author concluded that pH values between 4.3 and 5.5 would be satisfactory for corn production on these soils. The inference would be that either yield was limited in all treatments by some unidentified factor, or that in these soils solution Al levels were exceptionally low at high saturation values. Plot size was not given, so yield level of the experiment cannot be calculated.

In Uganda, Foster (1970), in a series of fifteen trials, reported no yield response by corn to lime when soil pH was above 5.5, but there were three instances of response at pH around 5.1. Initial pH at nearly all of his sites was 5.0 or above. Awan (1964), however, reported highly significant corn yield increases from liming two soils in Honduras whose initial pH values were 5.5.

In an extensive screening test at Carimagua, Colombia, Spain et al. (1974) reported a corn response to liming an Oxisol, extending throughout the range of applications used (0 to 6 t/ha). Their results, averaged for twenty varieties, showed corn grain yield increasing from zero on unlimed soil to about 300, 700, and 850 kg/ha for 0.5, 2.0, and 6.0 t/ha of lime, respectively. Untreated soil pH was 4.3, exchangeable Al 3.5 meq/100 g, and exchangeable Ca was 0.5 meq/100 g. In this case, corn yield continued to increase with each increment of lime up to about twice the exchangeable Al equivalent.

In pot tests with a sandy lateritic soil in India (Panda and Das, 1971), increments of basic slag, dolomite, calcitic limestone, and paper mill sludge were applied to raise soil pH from 4.3 to 6.8. Corn growth reached maximum level with the first increment where pH was about 5.3. Thereafter, yield remained constant, except for dolomite, which caused a slight decline at higher rates.

Thus, in the case of corn, the evidence presents a clear picture of important yield increases for liming most soils of humid tropical regions whenever soil pH falls below about 5.0 and exchangeable Al exceeds around 15 percent saturation. Also, it seems probable that as degree of weathering proceeds, Al toxicity becomes relatively less important, and adequate levels of basic cations as nutrients become more important causes of acid-soil infertility. The published data also fail to support the notion of a very narrow margin of safety between enough and too much lime for corn.

Sorghum has also been used in several liming tests with soils of the humid tropics. Awan (1964) found highly significant yield increases in response to lime by sorghum grown on two acid (pH 5.5) soils of Honduras. Similarly, Hortenstein and Blue (1968) reported yield increases on a Puletan fine sandy loam from Honduras by a lime application that raised soil pH from 5.4 to 6.3, but more lime had no effect. In central Brazil, Soares et al. (1974) reported a grain sorghum yield increase of 140 percent from liming a Dark Red Latosol. Most of the effect was realized from the first

increment of 5 t/ha, which reduced Al saturation to 10 percent, but some added improvement in yield was reported from the second 5-ton application. Yet, in Uganda, Foster (1970) reported that sorghum responded in only one out of four liming trials. However, as noted earlier, the initial pH of soils at Foster's sites were rather high. In the case of the sorghum tests, they ranged from 4.8 to 5.3. Response occurred at the site where pH was 5.1. Cabala and Fassbender (1971), in a series of liming experiments on eight soils from the cacao region of south Bahia, Brazil, reported sorghum yield responses on three of the sites. This is a surprising result, since none of the soils included in their tests had pH's below 5.5 before liming. Although average final pH was 6.5, there was only a slight yield depression on two of the soils and none on the others.

Thus, judging from the results of several series of experiments conducted in widely separated geographical areas, sorghum yield response to liming can be expected under about the same conditions as for corn. Responses in some tests at soil pH above levels where Al toxicity would normally be an important factor suggests that sorghum is somewhat more sensitive than corn is to factors other than Al toxicity.

Reports of liming trials with such small grain crops as wheat, oats, and millet are scarce, but generally indicate that response may usually be expected under strongly acid conditions. Nye and Greenland (1960) stated that they had observed only small responses by cereals to lime in Ghana, and only rarely when soil pH is above 5.0. In India, on the other hand, wheat yields were increased sharply (around 30%) in two experiments on lateritic soils, when pH was raised from 5.2 to 6.2 (Tripathi and Pande, 1971). A further small increase was recorded for a second increment of lime that raised pH to 7.2.

Wheat was used as a test crop in a liming experiment on an acid soil in São Paulo state, by Jorge et al. (1965), with modest increases in yield reported. Increases were 4, 12, and 2 percent for 1, 2, and 3 t/ha of lime, respectively.

Soares et al. (1974) quoted an earlier local review of liming results in the Cerrado as indicating that rice and wheat responded inconsistently. In a similar vein, Foster (1970) reported that liming did not once increase finger millet yield in a number of trials on Uganda soils. However, the initial pH levels of most of these soils were above 5.0. Amarasiri and Olsen (1973) reported no growth of millet on an extremely acid (pH 3.8) Oxisol from the Llanos Orientales of Colombia. Dry matter yield was increased sharply by liming to a pH of about 5.2, but above that, yield declined.

Spain et al. (1974) determined response to lime under upland conditions by both semidwarf and conventional rice varieties grown on an extremely acid (pH 4.3) Oxisol of the Colombian Llanos Orientales, and found a strong response to the first increment of 0.4 t/ha in all cases. The semidwarf varieties responded through the 16-ton rate, but the tall varieties did not.

Cate and Sukhai (1964) point out that rice does not generally respond

to liming, even on strongly acid soils, and, at the same time, showed that rice is sensitive to very low concentrations of Al in solution. They also demonstrated that the rice soils of British Guiana were high in Al, and explained the apparent anomaly as being the result of reactions that occur in flooded soils by which soluble Al is precipitated after it is replaced by reduced Fe. Thus, although rice grown under submerged conditions seldom responds to lime, upland rice would be expected to behave much as other cereal crops do whose roots are sensitive to Al.

Soybeans. Many tests of soybean response to liming have been made in the tropics and, with some exceptions, they show a marked improvement in yield when moderately to strongly acid soils are limed. Mikkelson et al. (1963) reported that, although soybean yield was increased by liming two Latosols and a Regosol in São Paulo state where initial pH was below 5.0, soybeans were less responsive than corn or cotton at the same levels of acidity. No deleterious effect was observed when liming rate was increased to bring soil pH to 6.0. In an earlier test in the same area, Freitas et al. (1960) found that soybeans responded on one of two Humic Latosols at pH's around 4.5 and with only traces of exchangeable Ca. Yield levels were high, around 2 t/ha of grain. On the other hand, Foster (1970) reported a yield increase in Uganda, even though initial soil pH was 5.86. Freitas et al. (1971) also reported strong yield responses of soybeans to liming various Latosols in the Federal District of Brazil where pH levels ranged from 4.3 to 5.1. Similarly, Mascarenhas et al. (1969) found that liming increased soybean yields 30 percent in a red Latosol in Brazil, even though initial pH was 5.5 and there were only traces of exchangeable Al. In each of two consecutive years in this experiment, bean yields were increased about 30 percent by initial application of 1.6 t/ha $CaCO_3$. When additional rates of application up to 4.8 t/ha were used, there was no effect on yield. Some of the same researchers had observed soybean yield increases of up to 50 percent for 3 t/ha of dolomite to two acid soils of São Paulo (Mascarenhas et al., 1967). The highest response obtained was on a soil with an exchangeable Ca content of over 2 meq/100 g and only traces of Al. Yet, in another report (Mascarenhas et al., 1968), soybeans did not respond, over a 2-year period, to lime on a red Latosol (pH 4.8) of São Paulo that had recently been cleared from cerrado vegetation. No clue is given for this apparently anomalous behavior, but an unsuspected effect, such as improved Mo availability, may have been a factor – at least in some instances.

Miyasaki et al. (1966) found a large yield response by soybeans to lime applied to a Terra Roxa soil in Campinas, Brazil, that had an initial pH of 4.8. Yields, which averaged 1.26 t/ha in the unlimed plots, were raised to 2 tons by applying either 5 tons of dolomite or 2.78 tons of $Ca(OH)_2$. There was little or no difference in yield between the two materials or between broadcast or sideplaced application. Again in Brazil, Soares et al. (1974) found that yield on two Dark Red Latosols was increased sharply 5 t/ha of lime, which reduced Al saturation to 10 percent. In an earlier

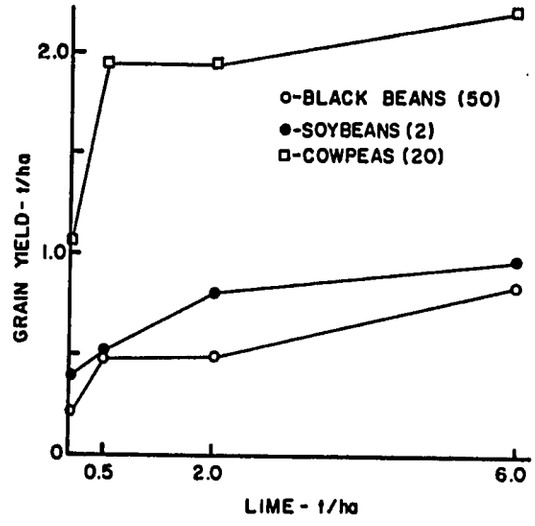

Figure 13. Yield response of soybeans, black beans, and cowpeas to lime applications on a strongly acid Oxisol of Colombian Llanos Orientales. Numbers in parentheses give number of varietal entries averaged for each crop (Spain et al., 1974).

test, liming to pH 5.5 increased soybean forage yield on a strongly acid (pH 4.6) Cerrado soil by about 30 percent over a 6-year cropping period (Neme and Lovadini, 1967). Soybeans also responded to lime applications up to 6 t/ha on a Colombian Oxisol with an unlimed pH of 4.3 (fig. 13), although most of the effect occurred with an application of 2 t/ha.

In attempting to rationalize the liming results with soybeans, three factors must be borne in mind. In the first place, the soybean as a species is known to be relatively tolerant of Al, even though considerable varietal diversity exists in this characteristic (Armiger et al., 1968). Secondly, soybeans are relatively sensitive to Mn toxicity (Hahn, 1973), and the Mn level in tropical soils is extremely variable. And thirdly, Mo availability, an important factor in soybean production, interacts strongly with soil pH. Thus, this crop would be expected to respond weakly to liming in an acid soil, unless Mn toxicity or Mo deficiency were factors of significance in the particular soil, and few experiments have recorded information that permits evaluation of these points.

Sugarcane. Sugarcane seems to be among the crops less sensitive to soil acidity, yet strong yield responses to lime have frequently been observed. Most of the available information comes from Hawaiian researchers working with Humic Latosols (Andept suborder of the Soil Taxonomy System), which are developed on young volcanic ash with excessive rainfall and tropical temperatures. The soils are characterized by high contents of amorphous hydrated oxides, low permanent charge but high pH-dependent charge, giving them an extremely high buffer capacity as pH increases toward 7 (Matsusaka and Sherman, 1950). Also, the combination of high

rainfall and excellent internal drainage (Makilum et al., 1970) provides ideal conditions for rapid leaching. These soils are thus substantially different in several respects from many of those found in other tropical areas. Baver and Ayers (1964) summarized 34 field experiments in Hawaii on the basis of exchangeable Ca level. The results, reproduced in figures 14 and 15, show that a close relationship between Ca level and probability of response of sugarcane to lime, as well as the magnitude of the expected yield increase, did exist in those soils. The exchangeable Ca level varied from 50 to about 3000 lb./acre-foot. They found no yield response when soil Ca was above 400 lb./acre-foot, but there was a response in all 24 cases where Ca was below 400 lb./acre-foot (fig. 14). The relationship between exchangeable Ca and increase in sugar production is reproduced in figure 15. At low Ca levels (e.g., about 200 lb./acre-foot), very large increases of around 3 t/acre were found. Certainly the yield responses reported in this study were related both to functions of Ca as a nutrient and to the reciprocal Ca-Al relationships normally found in soils. Makilum et al. (1970) stated that, in one series of experiments, cane made essentially maximum growth on a Typic Hydrandept at a Ca saturation level of around 12 percent. Also, working with tropical soils developed on volcanic ash, Fassbender and Molina (1969) reported an increase in yield of sugarcane to the third increment of lime (2.8 t/ha of CaO), after which an overliming effect was noted.

In Puerto Rico, Abruña and Vicente (1967) grew sugarcane on an

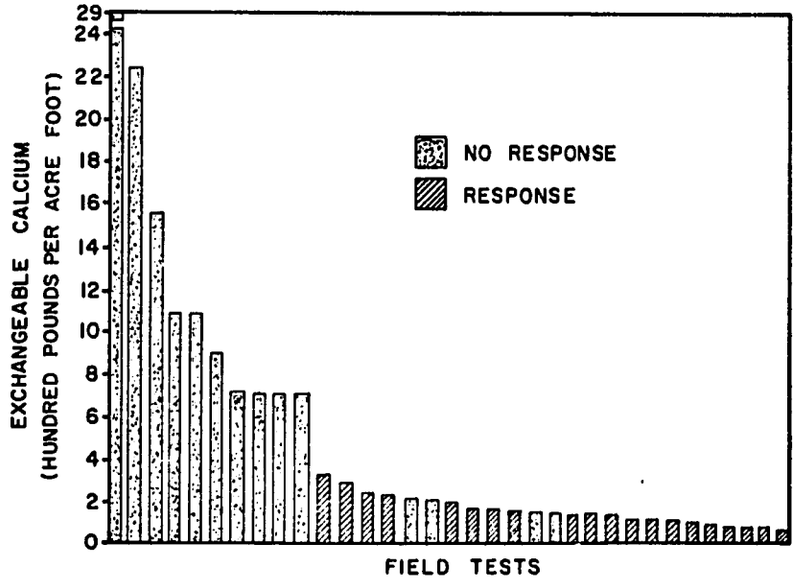

Figure 14. Response frequency of sugarcane as exchangeable Ca varied from about 100 to 2900 lb./acre in a number of Hawaiian soils (Baver and Ayres, 1964).

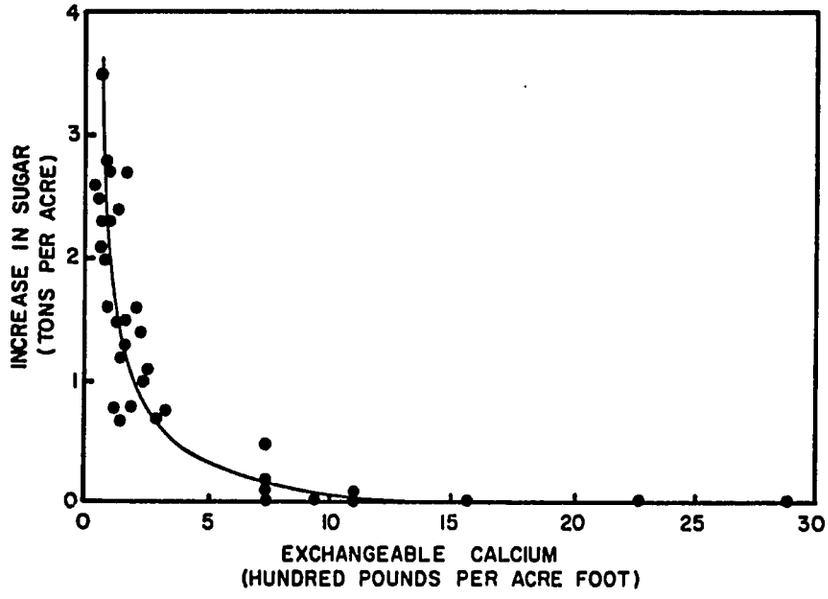

Figure 15. Relationship of increase in sugar yield to exchangeable Ca in a number of Hawaiian soils (Baver and Ayres, 1964).

Orthoxic Tropohumult, which, owing to a past history of differential applications of $(NH_4)_2SO_4$, had developed a wide range in pH values (from 3.8 to 5.0) representing Al saturation percentages ranging from 16 to 80 percent. Cane yields increased with increasing soil pH from 25 t/ha to 100 t/ha (fig. 16). Although the range in soil acidity was too narrow to completely characterize the response curve with respect to definition of the local maximum yield value and a possible decline at higher pH levels, distribution of the upper points on the curve suggest that little response would be expected at pH values above 5.0 on this soil. This agrees with the conclusions of Samuels (1961) and Lugo-López et al. (1959). Abruña and Vicente (1967) pointed out that cane yields increased with decreasing exchangeable Al to the lowest saturation levels reached (around 10 percent based on Σ cations). Yields were generally less than 10 t/acre at the highest Al levels (around 80% saturation) as compared with nearly 125 t/acre at 10 percent saturation.

In any attempt to generalize the results reported for sugarcane, one concludes that response is not markedly different, although it seems to be somewhat less overall, from that found in corn. In highly weathered and leached soils of the humid tropics, soil pH levels below 5.0 would probably respond.

On the basis of the Hawiian researchers' observations of sugarcane behavior in acid soils, Ca as a nutrient may be considered as important

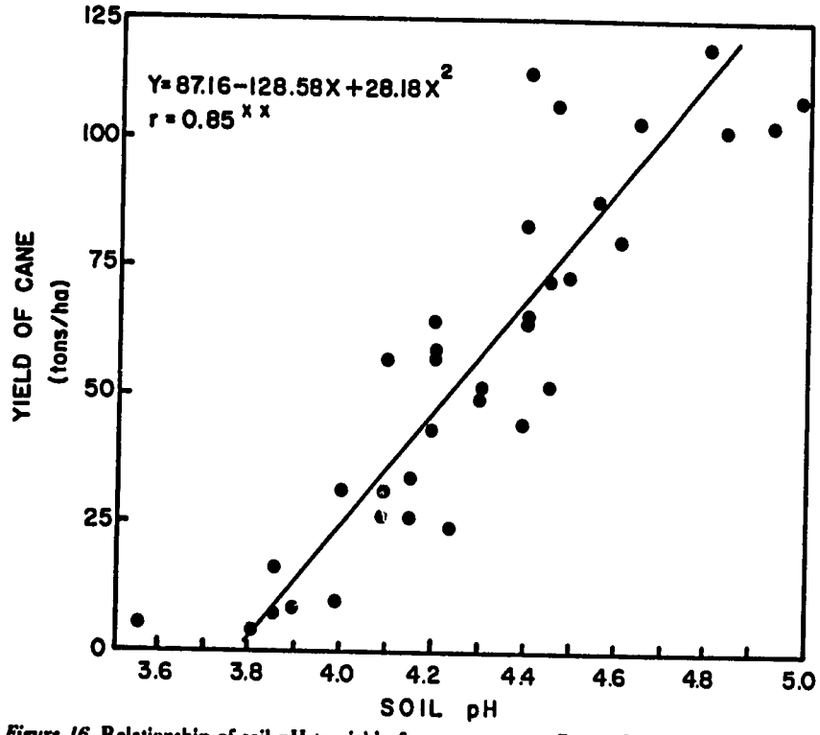

Figure 16. Relationship of soil pH to yield of sugarcane on a Puerto Rican Ultisol (Abruña and Vicente, 1967).

a factor as Al toxicity. This conclusion is supported by the results I achieved hen using an implanted soil mass technique (Lund et al., 1970) to measure sugarcane root response to soil pH. I showed 90 percent as much sugarcane root growth in a Humatas B_2 horizon at pH 4.2 and an Al saturation of 65 percent as at pH 6.5 with only traces of exchangeable Al. Thus sugarcane seems to be much less sensitive to Al toxicity than are most crops. Data on tolerance of elevated Mn levels in acid soil solution are not available.

Beans. Dried beans of a wide variety of cultivars are a staple in the diet of large segments of tropical populations. Oddly, much of this commodity is produced in temperate regions and exported to the tropics. Yet, until recently, little was known of this crop's tolerance to acidity or of its lime requirements. Awan (1964) reported highly significant yield increases of beans grown on two acid (pH 5.5) soils in Honduras when limed to pH 6.3. Yields were increased by both lime and P separately, and a further, almost equal, increase from lime + P over either applied alone. In a series of twenty tests in Uganda, Foster (1970) observed bean yield in-

creases in the four most acid ferrallitic soils used where pH was 5.1, and exchangeable Ca was 5 meq/100 g. A number of the soils that did not show response had pH values near 6. In Campinas, Brazil, dry-bean yield was increased more than 25 percent by liming a moderately acid (pH 5.25), infertile soil (Miyasaka et al., 1965). Limed soil pH was 6.15. They stated that bean yields on this infertile sandy soil were raised by fertilization and liming to equal those commonly expected on the fertile soils of the region. Mascarenhas et al. (1969b) also found a large yield response by beans to 4 t/ha of limestone on a virgin, strongly acid Latosol of São Paulo state. In this case, initial soil pH was around 4.5 and limed pH around 5.0. Exchangeable Al was reduced by liming from nearly 3 to a little over 1 meq/100 g.

More recently, Spain et al. (1974) ran preliminary trials of a number of bean and cowpea varieties on a strongly acid Oxisol in Colombia. Over a 3-year period they tested an extraordinarily large number of black bean, and at least twenty cowpea, varieties for soil acidity tolerance. Their results showed that black beans responded less than cowpeas to lime (fig. 13). Yield of cowpeas was nearly doubled by only 0.5 t/ha of lime, and yield at this point was nearly three times that of black beans. Even without lime, cowpea yield was noticeably higher than bean yield was on the limed plots (fig. 13).

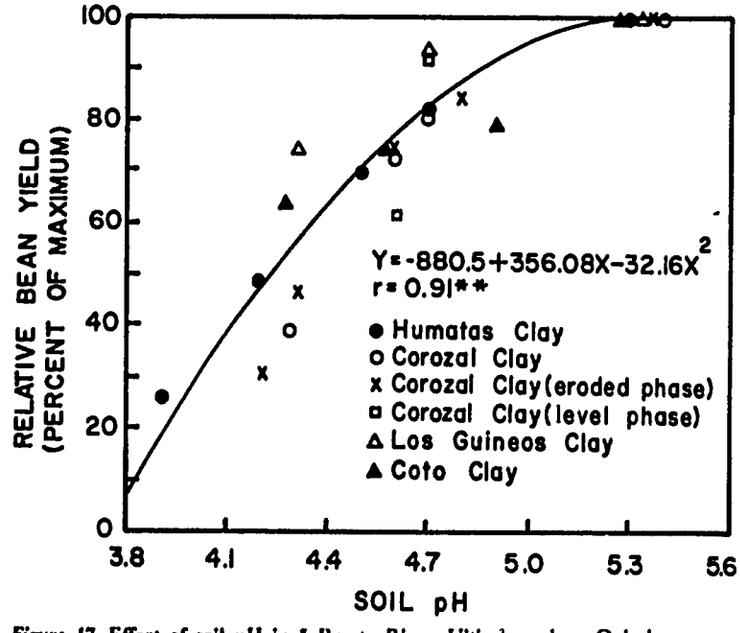

Figure 17. Effect of soil pH in 5 Puerto Rican Ultisols and an Oxisol on green bean yields (Abruña et al., 1974).

Vegetables. Field (green) beans have twice been included in liming tests reported from the tropics. Preliminary results reported by Spain et al. (1974) showed that the average tolerance of field beans to acidity was far less than that of any other food legume tested. In their tests, no yield was made on a very acid Oxisol (pH 4.3) until lime rate reached 6 t/ha, and even then yield was low. Similarly, Abruña et al. (1974) observed a tremendous yield response of field beans to liming in a series of experiments carried out on both Ultisols and Oxisols in Puerto Rico (fig. 17). Even though excellent yields were made in all the tests that used adequate rates of lime (from 7 to 14 t/ha), the shape of the pH response curve indicates that yields may not have reached peak values at the maximum soil pH levels used. Bean yields were closely related to percent Al saturation (fig. 18). An Al saturation level of 20 percent corresponded to a yield reduction of about 20 percent, and the same approximate relationship held throughout the range of these experiments. The Oxisol (Coto clay) gave the lowest response and had a very low Al content, even though the unlimed soil pH was among the lowest of the entire group of soils. Considering all the soils, no clear relationship could be found between leaf-Ca content and yield, nor between leaf-Mn content and yield, but when Ca: Mn ratio in chemical equivalents was considered, a striking relationship emerged, which the researchers did not consider to be fortuitous (fig. 19). This is in agreement with results reviewed by Jackson (1967), which showed a reciprocal relationship between Ca and Mn in plant tissue, even at toxic Mn levels. Thus, the results of Abruña et al. (1974) indicate that bean yields were influenced by both Al and Mn at soil pH levels below 5.0,

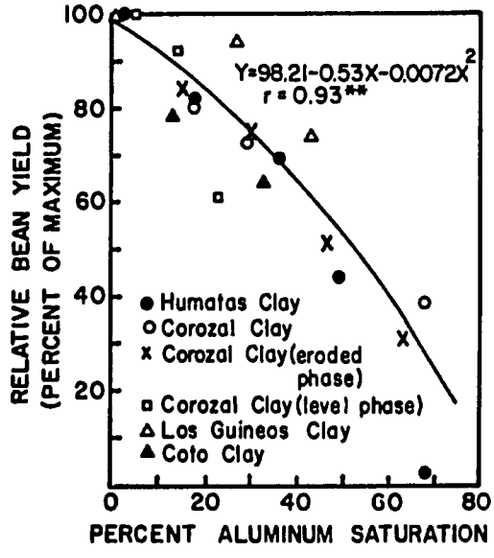

Figure 18. **Relationship of percent Al saturation to green bean yield on 6 Puerto Rican soils (Abruña et al., 1974).**

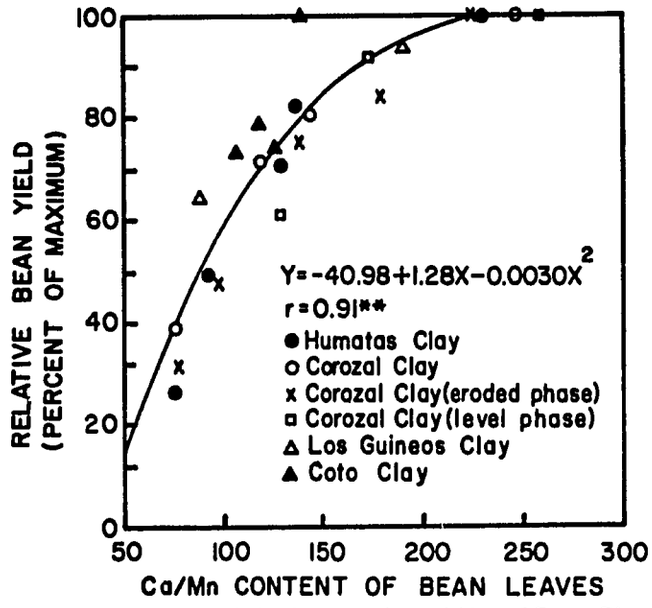

Figure 19. Effect of Ca/Mn level on green bean yields on 6 Puerto Rican soils (Abruña et al., 1974).

and that a Ca:Mn ratio in the leaf of around 225 would be required for maximum yield.

Tomatoes have also been used as the test crop in liming experiments with tropical soils. Hortenstein and Blue (1968) reported a good response in a pot test to the first increment of lime applied to a moderately acid (pH 5.4) soil from British Honduras. The first increment of lime raised pH to 6.3, and there was no further yield change when more was applied. Similarly, tomato plant growth increased 35 percent on a Costa Rican Latosol at pH 4.5, when lime was applied to raise pH to 5.5 (Bornemisza et al., 1967). In this case, additional lime application induced a yield drop to about the level of the unlimed soil, for which the authors suggested no cause. Later, Fassbender (1969) found that tomatoes responded strongly to each of several increments of lime applied to a strongly acid Andosol (pH 4.3) in Costa Rica, and that lime had no adverse effect at higher rates. Fassbender and Molina (1969) also pot-tested two Costa Rican volcanic soils in which a lime application that raised pH from 4.2 to 5.1 (in 0.01 M $CaCl_2$) to about 5.8 increased the yield in dry weight of tomato plants by 300 percent. With further lime application, dry-matter production remained about constant in one case but decreased sharply in the other. The researchers offered no explanation for this difference.

One report was found of a liming test with pigeon peas on two soils (Foster, 1970). Liming one ferrallitic soil (pH 4.80) doubled yield of peas,

but did not affect yield on the other (pH was 5.02).

Peanuts. Peanuts should be an important test crop in liming experiments because, while highly Al-tolerant, they are particularly sensitive to low levels of available Ca (Rogers, 1948; Adams and Pearson, 1970).

Chacon (1968) found that peanuts responded maximally at 1 t/ha of lime on an Oxisol (loamy sand) at pH 4.2 in Venezuela, and no further effect on yield was observed when the application rate was doubled. He did not record exchangeable Al values or soil pH of the limed soil, but the first increment of lime probably would have neutralized all the exchangeable Al in this highly weathered sand.

Nye and Greenland (1960) reported that peanuts were among the most consistent responders to lime of all food crops in the savanna zones of Africa, showing some yield increase even at soil pH levels around 6.0. Since Ca would probably not be a limiting factor at pH levels approaching 6 (except in soils with extremely low CECs), some other factor, such as Mo availability, may have been operating in these tests. This suspicion is confirmed by the fact that peanut response to Mo additions was recorded in 19 trials in this general region. Also, Martin (1959) found tremendous increases in peanut yields from liming strongly acid soils (pH 5.0) in French Equatorial Africa. He stated that 4 to 5 t/ha of $CaCO_3$ was needed in two annual installments for best results and that subsequent annual applications of 500 kg/ha of CaO equivalent should be made to offset Ca losses. In further studies on African soils, Brams (1971) reported no response of peanuts to lime applied to a Plinthic Haplustox and a Typic Haplustox in Africa, with pH's at 4.4 and Al saturation around 83 percent based on Σ cations. It can only be assumed that in these soils Mo or Ca as a nutrient was not limiting.

In Uganda, Foster (1970) reported that peanuts responded to lime applied to ferrallitic soils at all but one of a large number of sites where pH ranged from 5.0 to 5.9. Even though only a few kg/ha of lime would have neutralized the small amounts of Al in these soils, rates up to 15 t/ha were applied without detrimental effects. Where response to lime was observed, the mean level of exchangeable Ca of unlimed plots was below 6 meq/100 g in every case, whereas the mean level for the nonresponsive sites was above 12 meq/100 g. It is not possible to isolate the specific factors of response in these tests, since the Ca level would be associated with pH which, in turn, would be related to Mo availability.

Thus, results of tests indicate that peanuts growing on highly leached, poorly buffered soils of the humid tropics will probably respond more sharply to small lime applications than will most crops, because of their critical Ca requirements and possible Mo × lime interaction.

Cotton. Lime requirements of cotton have been tested so extensively in temperate regions that further testing in the tropics was not expected. However, cotton has been used in a number of trials. Freitas et al. (1960) reported a strong response to lime applied to two Humic Latosols in the Brazilian Campo Cerrado, where pH was 4.3 and 4.5. Only traces of

exchangeable Ca were found in either soil. In a followup experiment, Mikkelsen et al. (1963) found increased yields of cotton on two Latosols and a Regosol when lime was applied to raise pH above 4.9. In fact, cotton yield response was greater than that of either corn or soybeans. No harmful effects of liming to pH 6.0 were observed.

McClung et al. (1961) reported on 28 year-location field tests with cotton where fertilizer and lime variables were included. The soils were Terra Roxa Misturada (Dark Red Latosols) located in São Paulo state. Soil pH averaged 5.2 and exchangeable Al 2.2 meq/100 g. On the basis of Σ cations, percent Al saturation averaged 46. Three levels of lime were used: L_0, L_x, and L_{4x}, where L_{1x} was the rate required to raise soil pH to 6.0, and averaged about 3.5 t/ha. Micronutrients (Mo, Zn, and B) were applied to complete treatments that included adequate fertilizer and lime. Cotton's outstanding response to treatment was to lime application, as shown in figure 20, which presents results from seven typical sites where adequate N, P, and K and micronutrients were used. Cotton yield increased regularly from L_0 to the highest lime rate used, giving a response at that point of around 700 kg/ha, with no indication of any injurious effect of liming as high as 6.0, even though this rate was three to four times the theoretical amount needed to neutralize exchangeable Al. It should be emphasized that both B and Zn – micronutrients whose solubility decreases with increasing pH – were applied in these experiments, which may have avoided yield depression at elevated pH levels in these tests. The researchers speculated that Ca and Mg deficiencies may have been involved in the consistent response pattern of this group of soils. In another area, Foster (1970) reported that cotton responded to liming in two out of fourteen trials on ferrallitic soils ranging in pH from just below 5 to nearly 6. In both cases, soil pH was below 5.2.

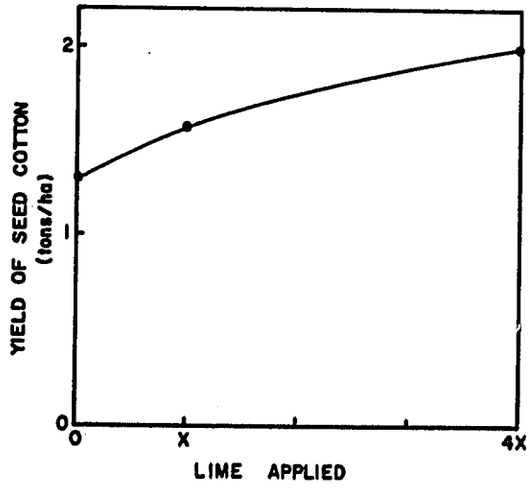

Figure 20. Cotton response to liming at 7 experiment sites on Terra Roxa Misturada soils in São Paulo State, Brazil (McClung et al., 1961).

Thus it seems that response of cotton to liming in the tropics may not be greatly different from that in temperate and subtropical regions, where wide differences exist even among similar soils (Adams, 1968). Also, cotton seems not especially sensitive to overliming injury in tropical regions.

Forage grasses. A substantial amount of research with forages has been reported from tropical areas. Grasses are generally tolerant of acidity and will often persist on soils too acid for many other plant species. The chief exceptions to this are sorghum-related grasses. However, the grass forages are in a vulnerable position in one respect – they are highly responsive to N and must be fertilized heavily in any intensive management system that takes advantage of tropical climate. This means that acid-forming N fertilizers can drive soil pH down to levels intolerable to other crops that may follow, and the grass will show no warning symptoms.

Abruña et al. (1964) reported that three heavily fertilized tropical grasses – napier-, guinea-, and pangolagrass – responded strongly to liming on a Typic Tropohumult and a Vertic Paleudalf, where pH had been reduced to exceptionally low levels by residually acid N fertilizer. The response shown in figure 21 is typical of their results, with maximum yield being reached at pH levels around 4.5. The progressive effect, over a period of 4 years, of N fertilization on lime requirements of napiergrass is shown in figure 22. Reduction in relative yield was more than 10 percent on the

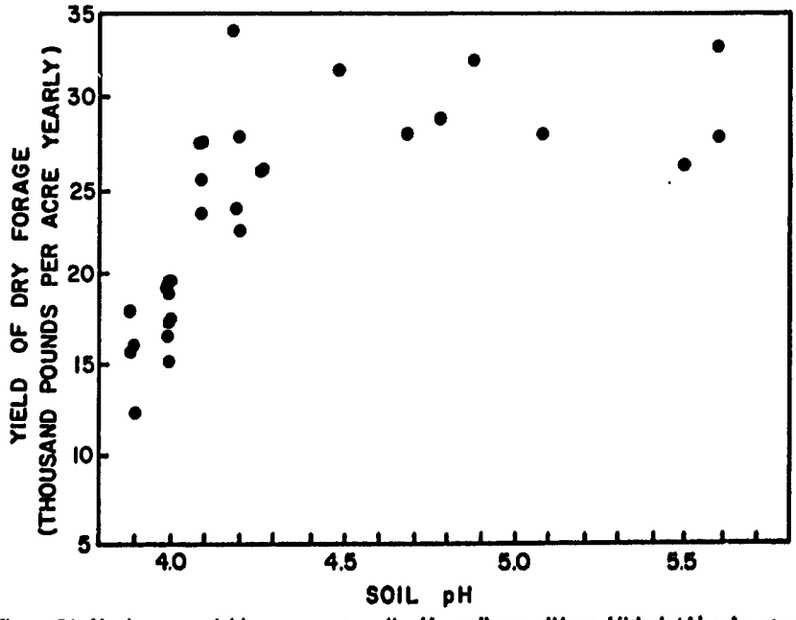

Figure 21. Napiergrass yield response to soil pH on Puerto Rican Ultisol (Abruña et al., 1964).

unlimed plots each year over a 4-year period of fertilization with 800 lb./acre of N as $(NH_4)_2SO_4$.

Rhodesgrass yield in Uganda was increased 55 percent by adding lime to acid sandy soil (pH 4.5), although the same grass did not respond to lime at pH 5.6 (Ledger, 1950). McClung et al. (1957), in a survey of fertility requirements of Campo Cerrado soils in Brazil, grew several crops, including pangolagrass, on seven acid soils with and without lime applied to raise pH to about 6.0. Pangolagrass responded in one experiment. Also in Brazil, Jones et al. (1970) reported a sharp response to lime by seven cool-season grass species on a soil of the state of Rio Grande do Sul (fig. 23). The soil was extremely acid (pH 3.9). Increments of lime were added to give a range in pH up to 6.2. The exceptionally low yields of most of the grasses at L_0 suggest that both nutritional and toxicity effects were involved. Even though maximum yield was reached at the 1 t/ha rate of lime, yield of only one grass declined at the 2 t/ha rate (pH 6.2), indicating that cool-season grasses may not be especially susceptible to overliming.

Lotero et al. (1971) reported that, in general, grasses gave very little response to lime in Colombia. They further pointed out differences among the grasses in this respect, and stated that gordura, puntero, pangola, and imperial grasses were more tolerant of high soil acidity than ryegrass, kikuyo, oats, and elephantgrass.

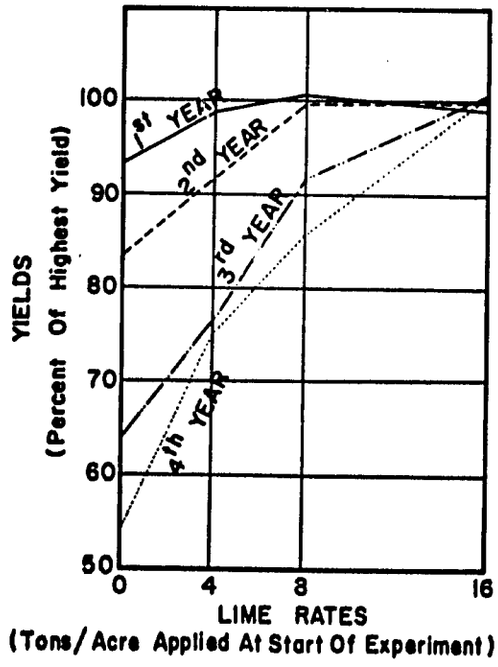

Figure 22. Napiergrass yield at various rates and times after applying limestone to a Puerto Rican Typic Tropohumult. Experiment fertilized with $(NH_4)_2SO_4$ at rate of 800 lb./acre of N annually (Abruña et al., 1964).

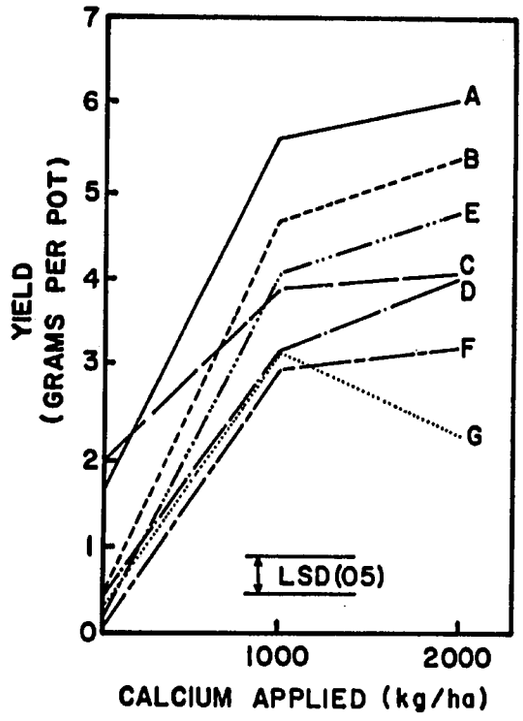

Figure 23. Effect of lime rates applied as $Ca(OH)_2$ on yield of 7 grass species growing on a strongly acid (pH 3.9) soil of state of Rio Grande do Sul, Brazil: (A) tall fescue; (B) ryegrass; (C) *S. Urugayensis;* (D) tall oatgrass; (E) Hardinggrass; (F) orchardgrass; (G) *B. Auleticus* (Jones et al., 1970).

Spain et al. (1974) determined growth response of several tropical forage grasses to lime in a greenhouse test using a very acid (pH 4.3) Oxisol in Colombia. Only small yield increases were obtained for liming, and in no case was there a response to more than 150 kg/ha. Researchers concluded that the response was to Ca and/or Mg as nutrients. They reported that the most promising forage grasses for use on acid soils were molasses-grass *(Melinis minutiflora),* puntero *(Hyperrhenia rufa),* brachiara *(B. decumbens),* and pasto negro *(Paspalum plicatulum).*

In pot tests, pangolagrass responded to lime applied to raise pH of a soil of Honduras from 5.4 to 6.3 (Hortenstein and Blue, 1968). Further liming to pH 7.3 did not change forage yield. In another test, a highly weathered and leached soil of British Honduras was limed with 100 and 600 ppm Ca as $Ca(OH)_2$ (Blue, 1969). Relative yields of pangolagrass were 65, 73, and 100 percent for L_0, L_{100}, and L_{600}, respectively.

Reeve and Sumner (1970a) used $CaSiO_3$ and $CaCO_3$ as amendments applied to eight Natal Oxisols for growth of sudangrass. Soil pH ranged from 5.0 to 5.6, and exchangeable Al from 0 to 2.7 meq/100g, representing up to 57 percent saturation based on Σ cations. Yield response of about 100 percent was reported for all three amendments at optimum rate, and yield was closely related to exchangeable Al. The results are

shown in figure 24. Lime was the only amendment that raised soil pH above about 4.8, and as pH increased up to a maximum of 6.0, yield decreased, even though Al was at near zero level. Reduction of exchangeable Al by $CaSO_4$ treatment is difficult to rationalize in view of the common experience of intensified Al toxicity resulting from presence of any soluble salt. The researchers suggest a possible SO_4-induced Al polymerization. Manganese was not related to yield. The $CaSO_4$ treatment increased exchangeable Mn, whereas $CaSiO_3$ and $CaCO_3$ decreased it.

Forage legumes. Response by legumes to liming is a net result of the effect of soil acidity on the symbiotic N-fixing bacteria and on the host plant itself. The former aspect has already been briefly reviewed in an earlier section. The present discussion will present overall liming effects.

In a list of 23 legumes used in tropical pastures, Hutton (1970) pointed to only three that might respond to lime, presumably at somewhat higher than moderate levels of soil acidity. These are the white clovers, lucerne,

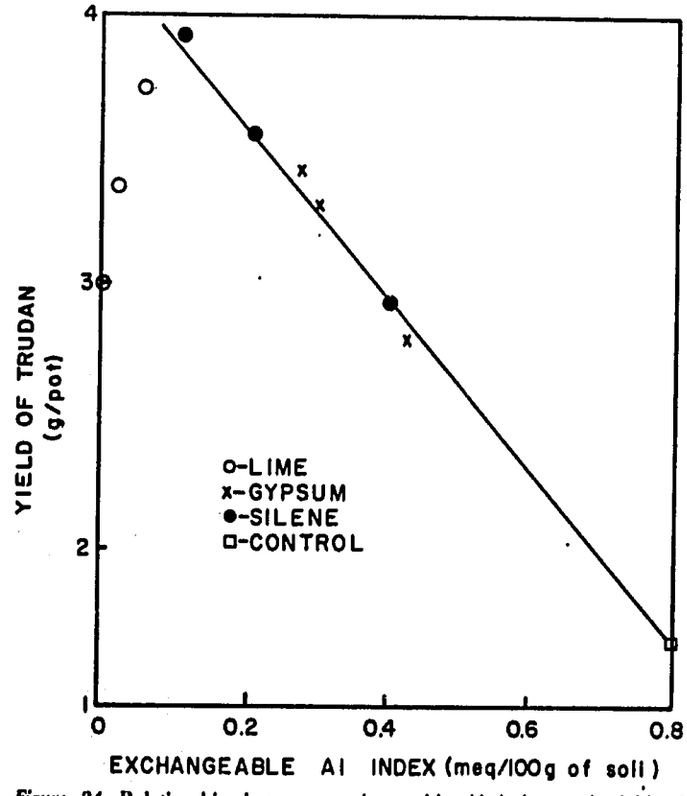

Figure 24. Relationship between exchangeable Al index and yield of Trudan on Natal Oxisols as exchangeable Al was varied by applications of several amendments (Reeve and Sumner, 1970a).

and Peru leucaena. He suggested that the tropical legumes are generally tolerant of acidic soils because their associated Rhizobium strains adapt to an acid environment. Even so, their tolerance is relative, and yields are usually reduced in strongly acid soils, especially if Mn is fairly abundant. In Puerto Rico, when the original soil pH was 4.4, liming increased nodulation and yield of tropical kudzu *(Pueraria phaseoloides)*, but increases were negligible when pH was 5.1 (Landrau et al., 1953). In a later Puerto Rican study, yield of tropical kudzu and its proportion in a molassesgrass *(Melinis minutiflora)* mixture were increased by liming a Typic Tropohumult at pH 4.8 (Caro-Costas and Vicente-Chandler, 1963). Protein content of the kudzu was also increased. Although manganese toxicity can reduce yield of tropical legumes at low soil pH, Souto and Dobereiner (1969) found that Mn did not affect germination of six forage legumes common to the tropics, but that three did not nodulate at elevated Mn levels. These were *Glycine javanica* (var. Tineroo), *Stylosanthes gracilis*, and *G. javanica*, (var. sp-1). The other three, *Centrosema pubescens*, *Pueraria*, and *Phaseolus atropurpureus*, were more Mn-tolerant, but showed a strong response to Mn level reduction both in numbers of nodules and in amount of N fixed. In another experiment on two high-Mn soils, two varieties of *G. javanica* gave a strong response to lime.

In Brazil, Freitas and Pratt (1969) reported responses by lucerne, *Stylosanthes*, and *Phaseolus* to liming on eight acid soils of São Paulo, including Latosols, Terra Roxa, and Red-Yellow Podsols. Lucerne responded to lime throughout a pH range of 4.5 to 6.0. *Phaseolus* and *Stylosanthes* were highly sensitive to Mn toxicity and responded to lime up to about pH 5.5, but in some soils a yield depression was observed at higher pH levels. Local maximum of *Stylosanthes* yield was at about pH 6.4 in a Red-Yellow Podsol, with a very sharp drop in yield above that pH. There was also a yield depression for this legume growing on one of the Latosols as pH was raised toward 7. There was little or no indication of overliming in the Terra Roxa soils even though pH ranged up to 7.5. Again in Brazil, Soares et al. (1974) found the yield of *Stylosanthes guyanensis* on a very acid Dark Red Latosol was increased about 25 percent by application of 5 t/ha of lime.

Spain and associates (1974) carried out a series of pot tests in Colombia, with four tropical forage legumes growing on an extremely acid (pH 4.3) Oxisol limed at four rates. They included a very low rate of lime (150 kg/ha) in this study, which gave maximum yield in each instance (fig. 25). They point out that the attainment of maximum yield with such a low rate of lime probably means that Ca and Mg were deficient as nutrients. Since 150 kg/ha of lime could not affect soil pH or solubilities of Al and Mn significantly, phytotoxicities could hardly have been a factor in the reduced plant growth in the unlimed soil. *Stylosanthes*, *Kudzu*, and *Centrosema* stood out as promising legumes for tropical pastures where soil acidity is a problem.

Miscellaneous crops. Very little information seems to be available on lime requirements of tropical root crops. Nye and Greenland (1960) ob-

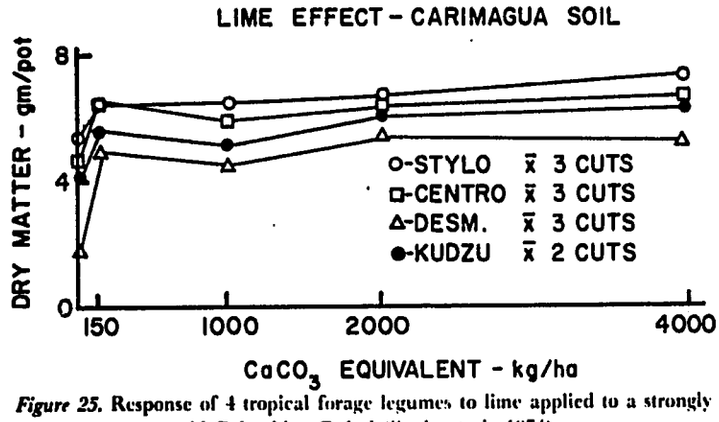

Figure 25. Response of 4 tropical forage legumes to lime applied to a strongly acid Colombian Oxisol (Spain et al., 1974).

served that yams generally responded minimally to liming on soils of tropical Africa. They also reported that sweet potato yields were increased by liming in only two of a number of trials in Uganda, and these were on soils with pH below 5.0. In tests in Brazil, sweet potatoes were similarly unresponsive to liming (Camargo et al., 1962). On the other hand, sweet potato yields were increased 36 percent by liming an acid Aquic Tropohumult (pH unknown) in Puerto Rico (Lugo-López et al., 1957). In a test with taniers (*Xanthosomo* sp.) in Puerto Rico on three acid Ultisols (around pH 5.0), Abruña-Rodriguez et al. (1967) found no yield increase for lime on two and a yield depression on one (pH 4.7). While they did not attempt an explanation, it has since been found that the soil with the yield depression has a very low Mn content, and that liming may have induced the deficiency (personal communication, F. Abruña-Rodriguez, 1974). At any rate, excellent yields (up to 14,000 lb./acre) of corms were made in these acid soils without lime, showing a high tolerance of adapted tanier varieties to soil acidity. In Brazil, Boock and Freire (1961) sharply increased potato yields when they experimented with liming soils of pH below 5.5.

In a commercial plant in Honduras, bananas responded to surface-applied lime scratched into only the top 2 to 3 inches, lest roots of the growing plants be damaged (Bhangoo and Karon, 1962). Soil pH ranged from 4.8 to near 6 on this plantation. Increases in number of fruit bunches, average weight per bunch, and weight of marketable fruit per acre were all highly significant. However, plantains did not respond to lime on a highly acid soil in Puerto Rico (Vicente and Figarella, 1962).

Abruña et al. (1964) found that heavy fertilization of forage grasses over a 4-year period without liming sharply depressed yields of subsequently planted tobacco, so that tobacco responded to lime applications of 16 t/acre – the highest rate used. In a later experiment (Abruña et al., 1970), liming up to a pH of about 5.0 sharply increased tobacco on three strongly acid soils (two Ultisols and an Oxisol). The relationship between pH and

yield over the range included (pH 3.5 to 5.5) and the relationship between percent Al saturation and yield were both highly significant ($r = 0.72$ and 0.81, respectively). On the Oxisol, yield response to the first two increments of lime seemed to result from reduced Mn toxicity, since little exchangeable Al was found in this soil. Mn content of the tobacco leaves ranged from 1200 to 2300 ppm in the unlimed or inadequately limed plots.

On the basis of several field experiments, Pennock (1949) concluded that acid soils of about pH 5.0 are best adapted to pineapple growing. Subsequently, Hernández-Medina et al. (1970) showed that liming to pH 6.5 adversely affected a recently planted crop, although there was no effect on the second crop.

Coffee is highly tolerant of soil acidity, provided soluble Mn remains below toxic levels. Rodriguez et al. (1964) reported that liming did not affect yield of two adapted coffee cultivars growing on two lateritic soils in Puerto Rico. The first really definitive information came from experiments of Vincente-Chandler et al. (1969), who carried out liming tests on three extremely acid Ultisols in Puerto Rico, using intensively managed, sungrown Arabica coffee. Yields were around a ton of market coffee per acre on these soils at pH 3.9 and 4.0 and 70 percent Al saturation, without lime. Yet there was no yield response to lime on either soil. Vincente-Chandler and coworkers caution, however, that coffee is sensitive to Mn toxicity. Their experience showed that a toxicity hazard appeared when foliar content of Mn reached 500 ppm and severe toxicity occurred at 1000 ppm. Further, they found that when $(NH_4)_2SO_4$ caused unexpectedly rapid soil acidification, severe Mn toxicity suddenly set in and an entire plantation was almost completely defoliated. However, surface application of lime effected complete recovery within two years. Even though most of the plant roots were still in zones unaffected by lime application, either Mn uptake was reduced or its deleterious effects alleviated by the increased Ca supply. On the basis of his experiments in Colombia, Suarez de Castro (1956) reported that liming was of questionable value in coffee production and further emphasized that high rates of lime may even affect coffee adversely. Thus it seems clear that the decision to lime coffee should be based primarily upon the Mn status of the soil. In low-Mn soils no response would be expected, regardless of pH, unless low-Ca fertilizer was used. In this case, Ca as a nutrient could become a factor and light dressings of lime would be indicated, particularly in soils having very low exchange capacities.

In Nigeria, oil palm yield was not increased by liming an Oxisol at two locations (Hartley, 1968). The experiment was run for 4 years and showed a small decrease for lime at one location in the fourth year. No soil characteristics or lime rates were given.

Varietal differences in response to lime

Although differences in tolerance of soil acidity have been known to exist among plant species since the beginning of liming as an agricultural practice, it is only recently that such differences among varieties and lines

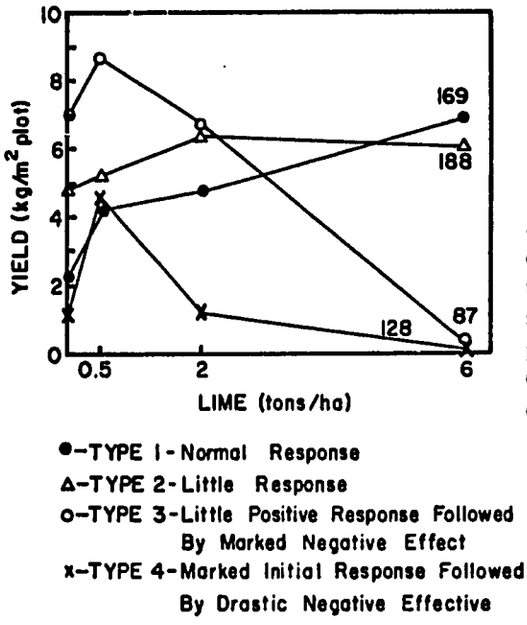

Figure 26. Effect of lime applications on cassava cultivar fresh root yields (kg per 7.5 m² plot) 9 months after being planted on a strongly acid Oxisol of Colombian Llanos Orientales (Spain et al., 1974).

have been recognized and their potential advantages emphasized. Following earlier observations (Neenan, 1960) of varietal differences in tolerance of wheat and barley to soil acidity, Foy and coworkers (1965) showed clearly that these differences derived from variations in sensitivity to Al toxicity. Thus, the entire problem of selection of lines adapted to acid soil conditions, as well as breeding for acid tolerance, was put on a rational basis. They showed that wheat and barley varieties bred in the eastern United States and those from Brazil were exceptionally tolerant of soil acidity. Of the 27 wheat varieties screened on a strongly acid soil, the three from Brazil gave the highest yields of dry matter. Subsequently, Foy et al. (1967) showed similar varietal differences in dry beans, snap beans, lima beans, cotton (1967), and tomatoes (1973). Armiger et al. (1968) found similar variations in soybean tolerance. Thus the phenomenon seems to be universal, at least among those species that have developed under varying degrees of soil acidity. As emphasized by Spain et al. (1974), this characteristic could be valuable in making most effective use of acid tropical soils, particularly where the unavailability of lime or its cost discourages its use.

No doubt many of the apparent inconsistencies in results from liming experiments have simply reflected genetic differences in acid-soil tolerance among the test-crop lines. For example, the 138 cassava cultivars used by Spain et al. (1974) in a screening study ranged from no response to a good response to lime on an extremely acid Oxisol. In a follow-up experiment with the cultivars selected from the preceding test, four different response

patterns were identified (fig. 26). These ranged from normal, in which yield increased rapidly at first with increasing lime rates and then more slowly, to a slightly positive response to 0.5 t/ha, followed by a sharp yield decrease with added lime. In the follow-up test, yield on this extremely acid soil without lime was as high as that of any other cultivars with lime, indicating the magnitude of possible improvement in crop production in the tropics by judicious variety selection.

Spain et al. (1974) also reported extensive screening of rice varieties for acid tolerance, and the results, already reviewed in a preceding section, indicate remarkable possibilities for improvement in upland rice production on acid soils of the tropics.

The same workers found marked differences in response to lime among the cowpea lines tested (fig. 27). Whereas the average yields leveled off at about 200 g/pot with 0.5 t/ha application of lime, one variety yielded 50 percent more than the average when limed.

Root response. There is very little specific information regarding root response to soil acidity in the humid tropics. That most adapted tropical crops have developed under acid conditions suggests their having at least a fair degree of root-tolerance to Al toxicity. I recently made a survey of several crops for their relative root sensitivity to acidity in a soil with a very high percent Al saturation at pH 4.2, as compared with the same soil limed to pH 6.5. The results, listed in table 4, show that root growth was little affected in any of the crops except tobacco. Coffee is widely

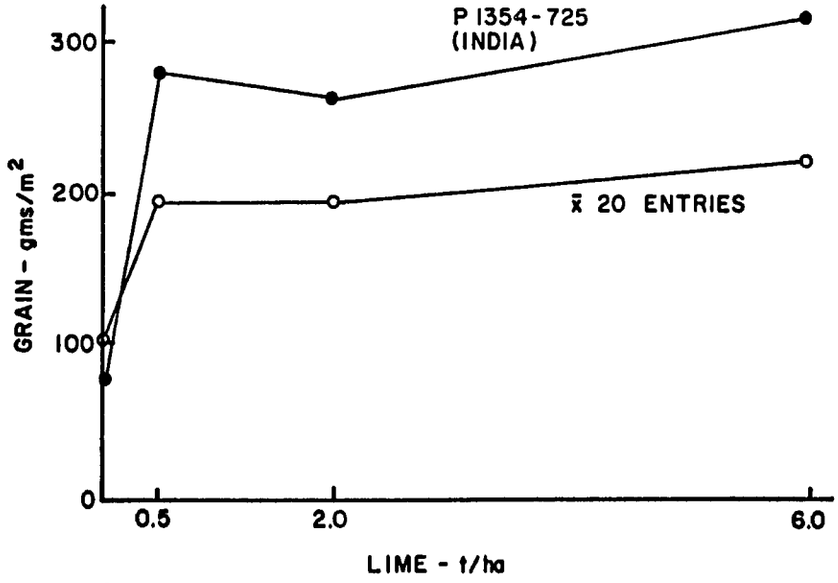

Figure 27. Average yield response of 20 cowpea lines and response of highest yielding entry in tests on a strongly acid Colombian Oxisol (Spain et al., 1974).

Table 4. **Effect of pH on root extension of several tropical crops under field conditions on a Typic Tropohumult in Puerto Rico***

Crop	Root yield, percent maximum†		
	pH 4.2	pH 4.8	pH 6.5
Tobacco	34	64	100
Coffee	100	--	96
Sugarcane	90	--	100
Napiergrass	89	--	100

* Data of author

† Using implanted soil mass technique (Lund et al., 1970).

recognized as an acid-tolerant crop. Its roots are almost immune to Al toxicity, as shown by the root weight results in table 5, and the tracing of root distribution in figure 28 from a Typic Tropohumult whose pH ranged from 4.4 to 4.8 throughout the depth excavated. This was a typical tree in a plantation that yielded over a ton of market coffee per acre annually.

Brenes and Pearson (1972) reported that sorghum roots were highly sensitive, corn roots were moderately sensitive, and stargrass *(Cynodon plectostachyus)* roots were very tolerant to soil solution Al in representative acid Ultisols and Oxisols of Puerto Rico. Both corn and sorghum root growth dropped sharply when levels of Al in soil solution became measurable, whereas no difference in yield of stargrass roots was observed as Al in the soil solution increased to 115 μM at pH 3.95.

In most cases, plant tolerance of soil acidity and relative root tolerance of Al go hand in hand, as Foy and co-workers, among others, have shown. However, there is another aspect of the root growth question that must not be ignored. As soils become acid through leaching of bases, the con-

Table 5. **Coffee root distribution and soil pH profile of a Typic Haplorthox in Puerto Rico***

Depth	pH	Root weight†
		% of total
0.0- 2.5	4.7	31
2.5- 5.0	4.6	17
5.0-10.0	4.5	16
10.0-15.0	4.8	10
15.0-20.0	4.8	13
20.0-30.0	4.8	6
30.0-40.0	5.0	3
40.0-50.0	5.0	2
50.0-60.0	5.0	2

* Author's data.

† Measured 60 cm from the trunk.

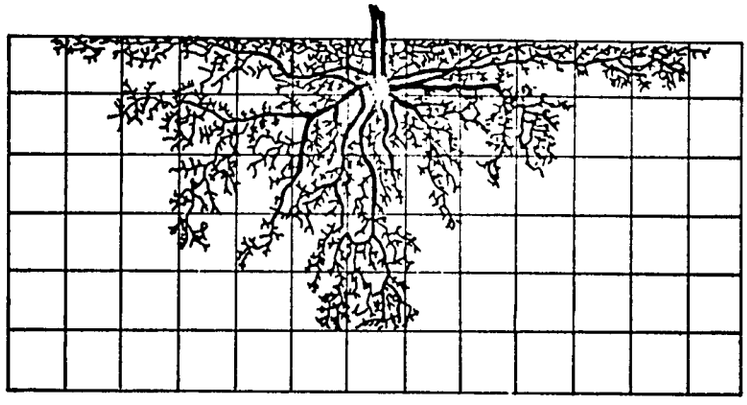

Figure 28. Root distribution of high-yielding, 10-year-old coffee tree growing on strongly acid Puerto Rican Ultisol. Space between grid lines represents 20 cm; limit of depth of excavation was 100 cm.

centration of several toxic ions increases but, by the same token, the level of basic cations decreases, and Ca must be present at the site of root growth for development to occur. It cannot be absorbed elsewhere and translocated to a particular point to permit root elongation in that zone. Howard and Adams (1965) have shown that root growth is dependent upon an adequate level of Ca in relation to other cations in solution. Subsequent work by Bennett and Adams (1970) has further shown that Ca deficiencies can be induced by applying amendments or fertilizers high in soluble cations other than Ca. Thus the use of ammonium phosphate together with normal rates of KCl for an infertile soil can induce Ca deficiency. Actually, this relationship was probably part of the cause of what has been called in earlier times "K-Ca antagonism".

At any rate, root extension restriction seems likely to occur when the Ca:total cation ratio in tropical soils is inordinately low, particularly under these conditions: (1) when developed from materials high in Mg and relatively low in Ca, such as serpentine; (2) if occurring in coastal or tidewater areas where there is acutely brackish water; (3) if weathered to the point of having essentially no base retention capacity; or (4) if Al has replaced Ca to an extreme degree following intensive acidification from heavy rates of residually acid N fertilizer. However, Ca deficiency is not as difficult to correct as Al toxicity, since relatively small amounts of a soluble amendment such as gypsum will take care of Ca deficiency, even at some depth in the profile, within a few weeks after application.

Improvement in rooting depth has had little attention in the humid tropics, in spite of the fact that subsoils are universally acid and dry seasons common in many regions. One exception is the work reported by Soares et al. (1974), the results of which are shown in fig. 29. In this case, lime, when incorporated to a 30-cm depth in the soil, increased corn yield

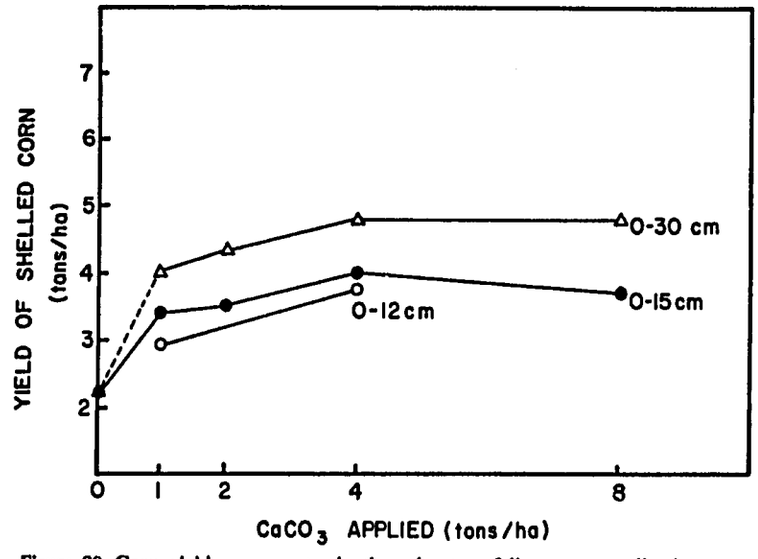

Figure 29. Corn yield response to depth and rates of limestone application to a Dark Red Latosol at Brasilia Experiment Station (Soares et al., 1974).

by about 2 t/ha more than when incorporated to 15 cm, which was slightly superior to a 12-cm incorporation. Hernandez-Medina et al. (1970) found that root development of acerola trees increased in almost direct proportion to pH in an Aquic Chromudert in Puerto Rico (fig. 30). These observations are consistent with experience in the temperate regions and indicate the crop's effective exploitation of H_2O stored deeper in the subsoil. In most

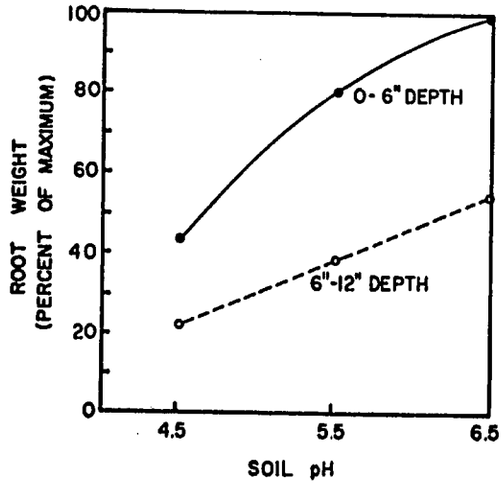

Figure 30. Effect of rate and depth of lime incorporation on acerola root development in acid Puerto Rican soil (Hernández-Medina et al., 1970).

instances, mechanical incorporation of lime lower than 15 to 20 cm will not be economically advisable because it requires too much power. High subsoil acidity that causes severe yield restriction can be relieved by use of residually basic sources of N for a crop with relatively Al-tolerant roots (Adams and Pearson, 1969). Since many crops, such as the warm-season forage grasses, have both Al-tolerant roots and a high N-uptake capacity, this approach to subsoil acidity correction should be entirely practical.

Reeve and Sumner (1972) stated that surface-applied gypsum reduced exchangeable Al in the subsoil of Natal Oxisols more than surface-applied lime. Although they did not include exchangeable Al values in the subsoils, Al level in the 0- to 15-cm layer was reduced by gypsum application. This could be achieved only by leaching of the $Al_2(SO_4)_3$ formed, and, if it were leached beyond the root zone, the treatment would be effective.

Residual Effects of Lime

It seems clear that the effects of lime application are often dissipated much more rapidly in the humid tropics than in temperate regions. This is to be expected in view of the generally higher rainfall, soil permeability, and rates of reaction. In some special cases applied lime has disappeared with incredible speed (Mikami and Kimura, 1964). In general, however, its residual effect is about what can be predicted on the basis of soil texture and structure, rainfall, and particularly, rate of residually acid N fertilization used. The latter factor is one of prime importance, since every pound of N applied as $(NH_4)_2SO_4$ (probably the most common source of N in tropical areas) requires nearly 6 pounds of $CaCO_3$ to maintain an unchanged pH in the soil. This is clearly illustrated in figure 22. Thus, an application of 1 t/acre of limestone would have no residual value after 1 year if 360 lb./acre of N had been applied as $(NH_4)_2SO_4$ per year, even discounting leaching and plant uptake losses of Ca.

In Brazil, Neme and Lovadini (1967) reported that soybean forage yield responded strongly on an acid cerrado soil limed to pH 5.5, and that the effect of liming to this pH did not diminish during a period of 6 years. Another study in Brazil showed that lime applied to a Terra Roxa soil in Campinas, either as $Ca(OH)_2$ or dolomitic limestone in amounts to raise soil pH from 4.8 to 5.9, was as effective in increasing soybean yield after 3 years as in the first year (Miyasaki et al., 1966). In São Paulo state, Freitas and Van Raij (1974) limed a Red-Yellow Latosol once with 10 t/ha of dolomitic limestone to raise pH to around 6, then cropped the soil for 6 years to cotton, corn, soybeans, and peanuts, all of which gave increased yield. No further additions of lime were made, but at the end of the period, pH of limed plots was still between 5.5 and 6.0, and the effect of lime on yield was about the same as initially. They attributed some of the effect in the later part of the experiment period to decreasing pH in the unlimed plots, which lowered the base of comparison. Also, in Colombia, Parra (1971) found that the improved yield of corn from applying 2 t/ha

of lime to volcanic ash soils was but little diminished after 12 crops. On the other hand, Martin (1959) reported that strongly acid soils of French Equatorial Africa required annual applications of around 500 kg CaO equivalent to offset Ca losses. Vicente-Chandler et al. (1964) found that for forages growing on acid soils of the humid region of Puerto Rico, surface application was as effective as incorporation of limestone, and one application every 2 years was as effective as split, annual applications, even with the use of high rates of residually acid N fertilizer.

The data presented in figure 3 and that for two Puerto Rico soils discussed with reference to exchangeable Ca and pH change with time, have already illustrated the rather erratic behavior of soils of tropical regions after lime is applied. Inasmuch as the available information indicates the tolerance of many tropical plant species for low soil pH, and a greater likelihood of deficiencies of Ca and Mg as yield-limiting factors than in temperate region soils, one point of practical significance seems clear. The safest practice with lime is to use relatively low rates of application (very low, if lime availability or cost is a problem) and to repeat the applications more frequently than is generally necessary in temperate regions. Spain et al. (1974) have clearly shown that sometimes extremely low rates (so low that residual effects are not an important consideration) can be highly effective.

Prediction of Lime Requirements of Tropical Soils

It is now generally accepted that the most effective basis for predicting lime requirements of soils of tropical regions is the level of exchangeable Al (Brauner and Catani, 1967; Freitas et al., 1968; Reeve and Sumner, 1970a, 1970b; Kamprath, 1972). This contrasts with the theory in temperate regions, where attainment of a specific pH is usually the criterion.

There are, of course, exceptions for specific soil conditions and crop requirements (Ayres, 1961), and some authors, such as Venema (1961), even suggest that liming in the tropics should be restricted to those situations where Ca is limiting as a nutrient.

In an early attempt to develop a satisfactory method for predicting lime requirements of tropical soils, Abruña and Vicente (1955) proposed direct titration of a soil suspension with $Ca(OH)_2$, using heat to reach equilibrium conditions within 5 minutes. Their results agreed with those obtained in field experiments. The method should be useful for determining the amount of lime needed to neutralize exchangeable Al, in view of the consistent relationship of soil pH to the exchangeable Al saturation level (fig. 4). Marin (1968) recommended applying lime at 1 t/ha, with a neutralizing value of at least 80 percent for each meq exchangeable Al when soil pH is below 5.5 and organic matter content is less than 10 percent. When organic matter content exceeds 10 percent, he recommended liming only if pH is below 5.0 and cautions that both soil texture and crop requirements should be considered.

Freitas et al. (1968) used soils of São Paulo State in incubation experiments after $CaCO_3$ additions, as a standard for evaluation of several rapid laboratory procedures for estimating lime requirement. They found that the satisfactory way to predict the lime required for pH control was by the Woodruff (1948) or the SMP methods as used in Ohio (Shoemaker et al., 1961), but with the amount of soil in the suspension reduced to about half. A method based on acidity extracted with KCl or on (Ca + Mg) supply was satisfactory for neutralizing exchangeable Al and for supplying Ca +Mg, but it gave low correlation with the lime requirement for pH control. Without making a specific statement, they suggest that a rapid buffer method would be as satisfactory for Oxisols as it has been for Ultisols in temperate regions (Adams and Evans, 1962). They assume this on the consensus that liming to neutralize exchangeable Al is about the safe limit of liming for many soils of the tropics, unless precautions are taken against induced micronutrient deficiencies and/or cation imbalance, and because the relationship between exchangeable Al and soil pH in these soils is generally consistent.

Tobón and León (1971) stated that the Woodruff method was not satisfactory for rapidly estimating lime requirements of several Colombian soils, but that the titration procedure of Dunn (1943) and the SMP method described by McLean et al. (1966) gave good results.

Reeve and Sumner (1970b) reported that maximum yield of Trudan occurred in eight Natal Oxisols at only about 1/6 the level of $CaCO_3$ predicted by the buffer method of Shoemaker et al. (1961) for raising soil pH to 6.5, and suggest use of the readily determined "Al index" as a satisfactory approach to routine lime requirement predictions.

Pratt and Alvahydo (1966) found that the relationship of percent base saturation to soil pH in a Ca $(OAc)_2$ system was consistent among a wide range of Latosols and Red-Yellow Podsols of São Paulo State, and suggested that it provides a satisfactory basis for predicting the lime requirements of these soils. However, the relationship did not hold for B-horizon material, and for this reason eroded soils would present a special problem in the prediction of their lime requirements.

Grant (1970), working with a wide range of acid soils in Rhodesia, found that 500 to 1000 ppm calcitic lime applied to sandy soils, and 2000 ppm to clay soils raised soil pH to within the range of 5.2 to 5.8, regardless of initial pH. He emphasized that these rates should not be exceeded, and stated that the application should be split into two annual doses, since smaller applications have higher efficiencies and less hazard of induced minor element deficiencies.

Soares et al. (1974) reported that lime application based on exchangeable Al content is a satisfactory approach to practical correction of acidity in the Red-Yellow and Dark Red Latosols of central Brazil. They found that lime rates equivalent to 1.5 to 3.0 times the exchangeable Al gave best results.

In predicting lime requirements in the tropics, as in other climatic zones, there are several points to be considered besides the crop to be grown and the amount needed to counteract exchangeable Al. When a residually acid N fertilizer such as $(NH_4)_2SO_4$ is used, even at modest rates, it can neutralize an entire lime application in 2 or 3 years. Each pound of N applied in this form requires around 6 pounds of lime to offset its residual acidity. Soil Ca^{++} and Mn^{++} contents can be important factors. The lime required to neutralize exchangeable Al in some Oxisols could be inadequate to meet Ca requirements as a nutrient. And, finally, the availability and cost of lime in relation to crop values are essential aspects in prediction.

It seems likely that liming rates for soils of the tropics often have been overestimated, as Spain et al. suggest (1974), even when based on Al suppression. In nearly every reported lime study on Oxisols, maximum crop response has occurred with the first increment of lime, even when the rate was very low. Perhaps in such soils the most economical use of lime would be at conventional fertilizer rates applied annually, especially when availability and/or cost of lime are unfavorable.

Summary and Conclusions

Differences in response to lime among soils of the humid tropics are as great as between soils of tropical and temperate regions. In general, however, liming is basic to their effective use. Although many tropical crops evolved under acid soil conditions and are probably tolerant of soil acidity, few, if any, are immune to all the factors of acid soil infertility.

Relatively low rates of application are usually adequate for maximum crop production. In many cases lime seems to be effective chiefly as a source of Ca and Mg as nutrients. Maximum yield has usually been reached with the first increment of lime, even when it was very low. Apparently, the level of Al in solution at a given soil pH is considerably lower in highly weathered soils of the humid tropics than in less weathered soils of temperate regions. Soils of humid tropical regions are usually highly resistant to pH change above 5.5, and any attempt to lime them to conventional pH levels, such as 6.5 to 7.0, is inadvisable.

Soil pH *per se* is a less dependable criterion of lime need in soils of the tropics than in those of temperate regions. In the tropics, maximum crop yields often are made at pH levels that would be intolerable in less weathered soils.

After lime is applied, soil pH often behaves erratically, rising temporarily and then returning to near the original level within a few months. Full explanation for this behavior cannot be offered yet, although accelerated leaching loss of Ca is probably a factor.

The commonly expected beneficial effects of liming acid soils on P availability are not important factors in the use of lime on soils of tropical regions. The effect of lime varies with the soil from beneficial to detrimental.

Many tropical legumes can make maximum growth in extremely acid soils, and some strains of Rhizobium are highly acid-tolerant, provided soil Mn level is low. Manganese toxicity is one of the chief causes of poor nodulation of legumes in acid soils of the tropics.

The use of silicate slag or Ca silicate as an amendment on acid soils of the tropics provides protection against overliming injury, improves P economy, and appears to offer an additional benefit in suppressing Mn uptake and reducing soil acidity.

Overliming injury of crops on soils of the humid tropics seems to have been overemphasized in the past for two reasons: the cost and availability of lime in most areas of the tropics automatically prevent use of more than minimal rates, as a rule; and yield depression seems to be less frequent than was believed, and tends to be restricted to certain crops. Use of exchangeable Al as a basis for liming, and recognition of the futility of attempting to maintain pH levels above 5.6 to 6.0 are adequate safeguards.

In the humid tropics, cereals generally respond to liming when exchangeable Al exceeds about 15 percent saturation and pH falls below 5.0.

Soybeans are more tolerant of Al toxicity than the cereals, but less tolerant of Mn toxicity. Further, Mo availability is improved by lime and can affect soybean yield. This crop should respond to lime in high-Mn, low-Mo soils whenever pH drops to around 5.0.

Sugarcane response appears to be about the same as that of the cereals except that cane is more tolerant of Al and apparently more sensitive to Ca and Mg level as nutrients.

Food legumes, such as beans and cowpeas, appear to be responsive to liming, although cowpeas are capable of producing far higher yields at low pH than are black beans. Green beans are extremely sensitive to acidity.

Peanuts, while highly tolerant of Al, are especially sensitive to soil acidity because of the Ca requirement. This was one of the food crops studied in the humid tropics that responded to lime most consistently.

Cotton has responded to liming in tropical areas in much the same way as in temperate regions. Further, it does not seem to be sensitive to overliming injury.

Forage grasses adapted to the tropics are highly tolerant of soil acidity unless they have sorghum in their heredity. However, when used under intensive N fertilization, they can lead to profile acidity intolerable for other crops.

Forage legumes' response to liming is a net result of the effect of acidity on the Rhizobium and on the host plant itself. Few legumes adapted to the tropics respond to lime unless Mn toxicity is a factor.

Definitive information on the lime requirements of tropical root crops is scarce, although generally they seem to be tolerant, as are coffee and plantains.

Tremendous differences are known to exist among varieties of the same

species in tolerance of soil acidity, and this property seems to offer a new approach to the problem of effective land use in humid tropical areas far removed from sources of lime.

Improvement of rooting depth in strongly acid subsoils can only come from surface-applied amendments, since mechanical incorporation at depths below about 15 cm is not practicable. Use of residually basic N sources with a tolerant, high N-requiring crop offers one means of achieving this end.

The effects of lime are dissipated more rapidly in tropical, than in temperate, regions. Thus, it is logical to make more frequent and lighter applications in tropical regions.

Lime requirements should be based on exchangeable Al rather than pH, *per se*. In many cases remarkably low rates will be adequate and should be the most economical approach to efficient crop production on soils of humid tropical areas.

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