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LIMING FOR IMPROVED CROP PRODUCTION IN THE HUMID TROPICS - AN OVERVIEW

BY BAL RAM SINGH

A SEMINAR PAPER - DELIVERED TO THE FACULTY OF AGRICULTURE, SOKOINE UNIVERSITY OF AGRICULTURE, MOROGORO TANZANIA AND TO THE RESEARCH STAFF OF THE REGIONAL RESEARCH CENTRE, KASAMA, ZAMBIA, NOV.-DEC. 1984

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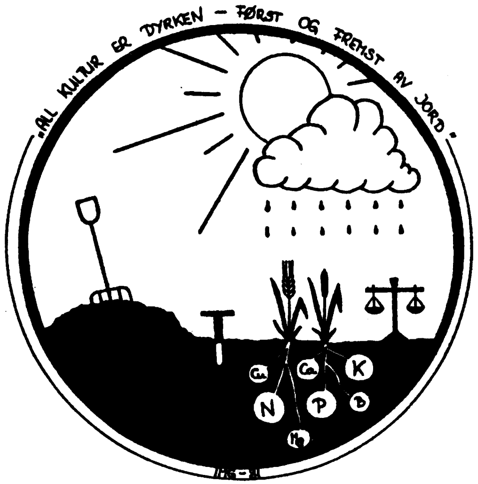
Liming for Improved Crop Production in the Humid Tropics - An overview

by Bal Ram Singh

A Seminar paper - delivered to the Faculty of Agriculture, Sokoine University of Agriculture, Morogoro Tanzania and to the research staff of the Regional Research Centre, Kasama, Zambia, Nov.-Dec. 1984



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CONTENTS

Side

Reeve, N.G., and Sumner, M.E. 1970a. Effects of aluminum toxicity and phosphorus fixation on crop growth on Oxisols in Natal. Soil Sci. Soc. Amer. Proc. 34:263-267.

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1. INTRODUCTION

Many soils in humid tropical regions are very acid (<pH 5) and crop growth is hindered by Al and/or Mn toxicity, Ca and/or Mg deficiency, and Mo deficiency. Results of liming for improved crop production often have been contradictory. Initial studies with liming focused on pH control and supplying of Ca and Mg (Pearson, 1975). Ideas about soil acidity underwent drastic changes in the 1950's when Al rather H was shown to be the dominant cation in acid soils of less than pH 5 (Coleman and Thomas, 1967). The exchangeable acidity affecting plant growth was found to be that which could be extracted with neutral unbuffered salt solution. At pH 5.5 and above, soils contained essentially no KCl exchangeable Al. These findings resulted in reexamination of the traditional concepts of base saturation developed with temperate soils. Soils of the humid tropics were found to be essentially 100% base saturated at pH 5.8 to 6 when cation exchange capacity (CEC) was based on the sum of exchangeable bases and KCl-extractable acidity (Coleman et al., 1959).

In spite of wide differences in results of liming, which have not been satisfactorily explained, there is a general mandate that liming is a keystone of soil management in humid tropics (Ayres, 1961; Laroche, 1966; Kamprath, 1972). In areas with a history of adequate N fertilization, the most common yield-limiting factor of soil fertility is an inadequate liming program (Pearson et al., 1961). In areas just recently brought into cultivation, liming generally shares the "most yield-limiting" soil fertility factor with P fertilization.

The purpose of this paper is not to document all of the studies reported on liming, but rather to focus attention to some of the most important aspects of liming by citing some examples under each aspect.

2. LIMING NEEDS

There are three considerations when adding lime: determination of how much, if any, lime should be added, consideration of the quality of lime used, and promotion of the longest residual effect.

2.1 Quantity needed

In soils of the humid tropics (Ferralsols and Acrisols) lime needs are based on exchangeable Al extracted by 1 M KCl (Kamprath, 1970). Liming needs are commonly based on the following formulas:

Meq Ca/100g soil = 1.5 x meq Exch. Al/100g
tons $CaCo_3$ eq/ha = 1.65 x meq Exch. Al/100g soil

Most of the exchangeable aluminum will be neutralized by the calculated amounts and will raise the soil pH to the range of 5.2-5.5. Various studies have shown that lime rates chemically equivalent to 1.5 to 3 times the exchangeable Al must be added to neutralize the Al (Table 1). Lopes & Cox (1977) suggested that in most cases the percentage aluminum saturation (Exch. Al/Exch. Ca + Mg + K + Al)x100) should be considered first, since soils having the same level of exchangeable aluminum but different degrees of aluminum saturation would have different crop response to liming at the same lime rates. Cochrane et al. (1980) developed a formula for determining the amount of lime needed to decrease the aluminum saturation level of the top soil to the desired range.

Lime required
(tons $CaCo_3$ eg/ha = 1.8 Al-CAS [(Al+Ca+Mg)]/100

where CAS is the critical Al saturation required by a particular crop, variety or farming system to overcome acidity and Al, Ca, and Mg are the exchangeable levels of these cations in meq/100

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g. The advantage of this method is that it requires no soil analysis beyond the 1 N KCl extraction of Al, Ca, and Mg as well as the information about crop tolerance to aluminum in terms of aluminum saturation. When compared with actual field data, the predictability of this equation was excellent (Cochrane et al., 1980).

Table 1. Liming factor (meq Al/100g x factor) required to give equivalents of calcium carbonate to reduce aluminum saturation to less than 10%.

Area	Soil (Surface 15 cm)	pH	Aluminum (meq/100g)	Aluminum saturation (%)	Factor	Final
Brazil[a]	Red-Yellow Latosol	4.0	0.7	70	3	4.9
	Red-Yellow Latosol	4.4	0.9	75	2	5.5
	Dark Red Latosol	4.0	1.9	86	2	5.0
Colombia[b]	Oxisol	4.3	3.5	78	2	5.3
Panama[c]	Latosol	5.1	1.2	53	1.5	5.9
	Latosol	5.0	3.0	64	1.5	6.0
United States[d]	Ultisol	4.5	0.9	82	2.0	5.9
	Ultisol	4.7	1.0	78	2.0	6.0
	Ultisol	4.5	2.3	73	1.5	5.7
	Ultisol	4.7	4.2	54	1.5	5.6
India[e]		<5.0	-	-	2.0	5.3
Natal[f]	Oxisol	<5.0	-	-	3.3	

a) Soares et al. 1975.
b) Spain et al. 1975.
c) Mendez and Kamprath 1978.
d) Kamprath 1970.
e) Pradhan and Kjera 1976.
f) Reeve and Sumner 1976.

Mendez and Kamprath (1978) reported that the lime rates equivalent to 1.5 times the exchangeable Al resulted in neutralization of 79 to 97% of exchangeable Al and pH values of 5.7 to 6 in Latosols from Panama, La Mesha and Pacora in the

Pacific watershed. However, the lime rates required for these soils were much higher when calculated from titration curves to adjust pH to 7.0 (Table 2). The highly weathered soils of the tropics have colloids whose surface charge is primarily pH dependent (Keng and Uehara, 1974). Once any exchangeable Al is neutralized, added lime will react with the surface hydroxyls of hydrated oxides of Fe and Al.

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Table 2. The $CaCO_3$ requirement, pH and % neutralized in Oxisols based on exchangeable Al and on the $CaCO_3$ equivalent at pH 7

Soil	Exch. Al x 0.75			Exch. Al x 1.5			$CaCO_3$ equiv. based on titration to pH 7
	$CaCO_3$ equiv.	pH	Al neutralized	$CaCO_3$ equiv.	pH	Al neutralized	
	kg/ha		%	kg/ha		%	kg/ha
La Mesa I	450	5.3	17	900	5.5	58	8000
II	187	5.4	0	375	5.4	20	7000
III	4200	5.4	69	8600	5.7	97	16000
Pacora I	3100	5.7	66	6200	6.0	95	10000
II	2250	5.5	80	4500	6.0	89	7000
III	900	5.8	67	1800	5.9	79	5000

2.2 Quality of lime

There is a general mandate that the ideal lime material would be a carbonate, preferably dolomitic limestone with a Ca:Mg ratio of 10:1 and all of it passing a 10 mesh (2.0 mm) sieve and 50% passing the 100 mesh (0.15 mm) sieve (Sanchez and Salina, 1981). The effect of lime as a calcium and magnesium fertilizer relative to these nutrients in fertilizer is a question of cost as well as of efficiency. In low- moderate input systems, relying mainly on acid tolerant crops, it is necessary to correct Ca and Mg and even S deficiencies. In high input systems this is normally taken care of through the application of superphosphate together with lime.

The residual effects of liming are discussed along with the effects of lime on soil properties and crop response to lime.

3. EFFECT OF LIME ON SOIL PROPERTIES

3.1 Soil pH and exchangeable Ca

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.

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 per cent, according to soil and ambient conditions. This was reflected in soil pH, which increased sharply during the first

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The effects of lime are dissipated more rapidly in the tropics and, hence, more frequent and lighter applications are adviseable.

Improvement of rooting depth in strongly acid strongly acid subsoils can only come from surface applied lime and use of residually basic N sources with a tolerant, high N-requiring crop offers one means of achieving this end.

thousand ppm. Manganese concentration is decreased when soils are limed.

The effect of lime on P availability can vary from beneficial to deterimental and similarly lime can increase or decrease the solubility of P in soils. The phosphorus solubility in the oxidic soils depends both on salt concentration and cation valency and the amount solution Al. Both P rate and per cent Al saturation have beneficial effect of liming on P availability.

Micronutrients in general are not a serious problem in acidic soils except in occasional cases of Mn toxicity and Mo deficiency. Availability of these nutrients can be controlled by liming. Liming corrects Mo deficiency by increasing the availability of Mo already present in the soil. Liming also affects favourable availability of sulfate in acid soils by decreasing its adsorption by Fe and Al oxides.

In the humid tropics, cereals generally respond to liming when exchangeable Al exceeds about 15 per cent 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.

Strong response by corn to liming have been obtained from different parts of the tropics when exchangeable Al was made the basis for liming.

A great variation among varieties of the same species in tolerance to soil acidity are known to exist and this property offers a new approach to the problem of effective land use in humid tropical areas for removed from sources of lime.

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 3). 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 way, Rixon and Sherman (1962) reported that lime applications of up to 46 tons/ha 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 per cent. 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 data show that theoretically some 74 tons of $CaCO_3$/ha would be required to satisfy the difference in CEC between that indicated by Σ cations and that measured by NH_4OAc at pH 7.0. They used an agricultural grade of crushed stone, which probably contained at least 50 per cent 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 30 tons/ha, 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).

Table 3. Effect of lime on pH of several "ferallitic" and related soils included in field trials reported by Foster (1970)

			Soil reaction	
Location	Exchange- able Al	Initial	1 yr after 5 t/ha lime	2-1/2 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 1	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

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. Pearson (1975) found that exchangeable Al practically disappeared from both Ultisols and Oxisols in Puerto Rico at pH values around 5.5 and that it was difficult to maintain levels that high, regardless of the rate of lime used. This is clearly shown in figure 1 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 removed fertilization as a determining factor in the rapid pH shifts observed. Also, inasmuch as in both experiments the lime

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6. SUMMARY AND CONCLUSIONS

In spite of wide differences in results of liming, which have not been satisfactorily explained, there is a general mandate that liming is a keystone of soil management in humid tropics.

Liming needs of soils of the humid tropics 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. Ideal lime material would be carbonate, preferably dolomitic limestone with a Ca:Mg ratio of 10:1 and all passing a 10 mesh sieve and 50% passing the 100 mesh sieve.

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.

Effect of lime on soil pH is not always predictable and soils of tropical regions often respond differently. Sometimes pH rises temporarily and then returns to near the original level with a few months. However, there were instances (red soils of Colombia) where pH increased in a predictable manner.

There was a close relationship among solution Al, per cent Al saturation, and pH. Organic matter seems to play an important role in controlling both solution Al and per cent Al saturation.

As a general rule Mn toxicity is not a problem in any soil unless soil pH is <5.5 but there are great variations in Mn contents of Oxisols and Ultisols which can vary from nil to several

Table 6. Some important food and forest crops considered to be generally tolerant to acid tropical soils (Duke, 1978)

Generally tolerant species:	Generally susceptible spesies with acid-tolerant cultivars:
Cassava (Manihot esculenta)	Common bean (Phaseolus vulgaris)
Cowpea (Vigna unguiculata)	Corn (Zea mays)
Peanut (Arachis hypogaea)	Sorghum (Sorghum bicolor)
Pigeon pea (Cajanus cajan)	Soybean (Glycine max)
Plantain (Musa paradisiaca)	Sweet potato (Ipomoea batatas)
Potato (Solanum tuberosum)	Wheat (Triticum aestivum)
Brazil nut (Bertholletia excelsa)	
Coffee (Coffea arabica)	
Eucalyptus X (Eucalyptus grandiflora)	
Gmelina X (Gmelina arborea)	
Guarana X (Paullinia cupana)	
Jacaranda X (Dalbergia Nigra)	
Oil Palm (Elaeis guineensis)	
Peach palm X (Guilielma gasipaes)	
Pepper, black (Piper nigrum)	
Pine X (Pinus caribea)	
Rubber (Hevea brasiliensis)	
Sugarcan (Saccharum officinarum)	

X Alvim (1981)

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. (1975) 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. 16). 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.

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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).

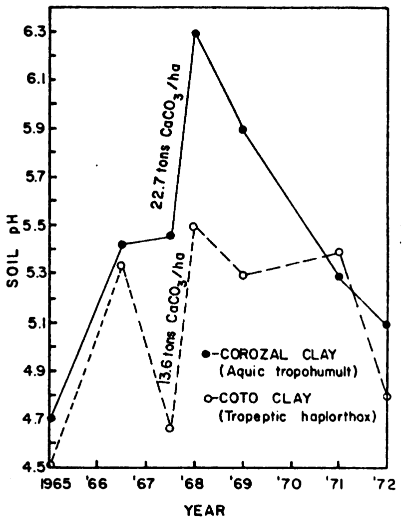

FIG. 1. Changes in pH over time after lime was applied to a Puerto Rican Ultisol and an Oxisol (Pearson, 1975).

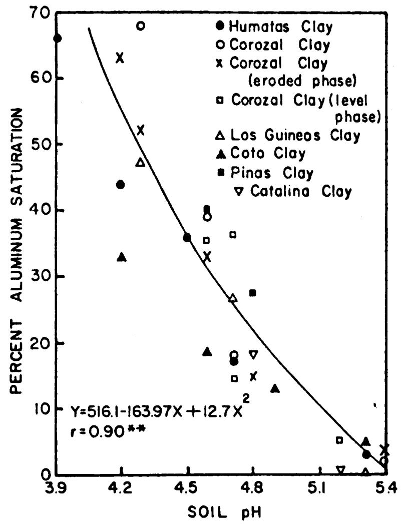

FIG. 2. Changes in Al saturation percentage with pH in several Puerto Rican Ultisols and Oxisols (Abrúna et al., 1975)

In most instances, mechanical incorporation of lime lower than 15 to 20 cm will not be economically advisable because it required too much power. Higher 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 be leaching of the $Al_2(SO_4)_3$ formed, and, if it were leached beyond the root zone, the treatment would be effective.

5. PLANT SPECIES AND VARIETIES TOLERANT TO ACID CONDITIONS

The wide differences among plant species to soil acidity are known to exist but it is only lately that such differences among varieties and lime have been recognized and their potential advantages emphasized. Foy and Coworkers (1965) showed that these differences derived from variations in sensitivity to Al toxicity. Some important food and forest crops considered to be generally tolerant to acid conditions are shown in Table 6.

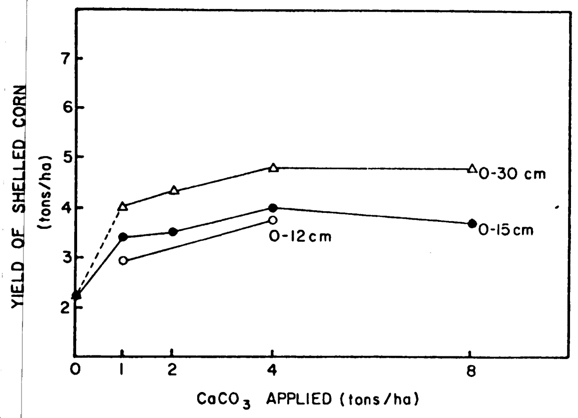

FIG. 15. CORN YIED RESPONSE TO DEPTH AND RATES OF LIME APPLICATION TO A DARK RED LATOSOL (SOARES ET AL., 1975).

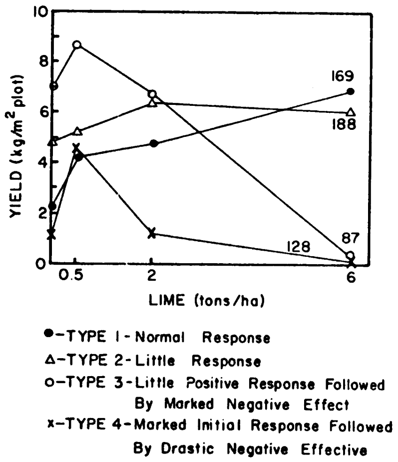

FIG. 16. EFFECT OF LIME APPLICATIONS ON CASSAVA CULTIVAR FRESH ROOT YIELDS (KG PER 7.5 M^2 PLOT) 9 MONTH AFTER BEING PLANTED ON A STRONGLY ACID OXISOL OF COLUMBIAN LLANOS ORIENTALES (SPAIN ET AL., 1975).

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 per cent of applied Ca fixed within 5 months. Amedee and Peech (1976), 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.

Acid tropical soils do not always respond to pH and Ca levels as unpredictably as previously described. Rodriguez 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 changes 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 weathering 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.

3.2 Exchangeable and soil solution Al

3.2.1 Relationship between Al, per cent Al saturation, and pH

As early as 1925, Magistad related pH to the level of Al in soil solution and in culture solutions and showed that the levels of Al in solution decreases rapidly to <1 mg kg^{-1} at around pH 5 and above. Accordingly 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 2, 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 (Brams, 1971; Fox et al., 1962; Brenes and Pearson, 1972).

While soil pH is closely related to Al saturation and solubility of Al, 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 per cent; 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 3 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 4).

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. (1975), the results of which are shown in fig. 15. In this case, lime, when incorporated to a 30-cm depth in the soil, increased corn yield by about 2 t/ha more than when incorporated to 15 cm, which was slightly superior to a 12-cm incorpations.

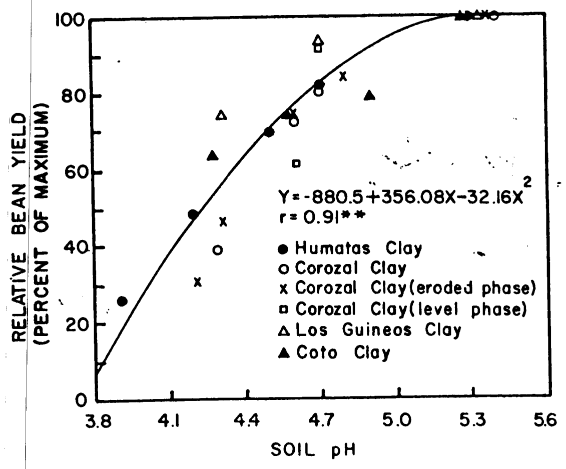

FIG. 13. EFFECT OF SOIL PH IN 5 PUERTO RICAN ULTISOLS AND AN OXISOL ON GREEN BEAN YIELDS (ABRÚÑA ET AL., 1975).

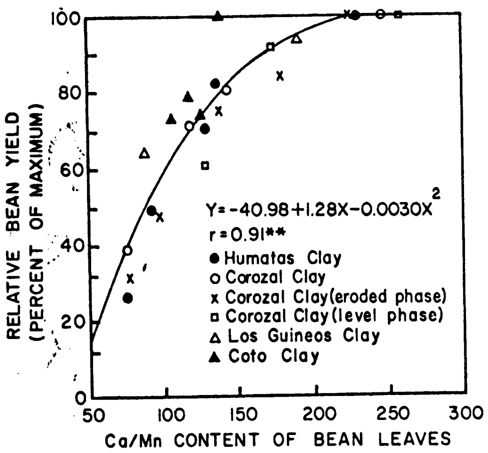

FIG. 14. EFFECT OF CA/MN LEVEL ON GREEN BEAN YIELDS ON 6 PUERTO RICAN SOILS (ABRÚÑA ET AL., 1975).

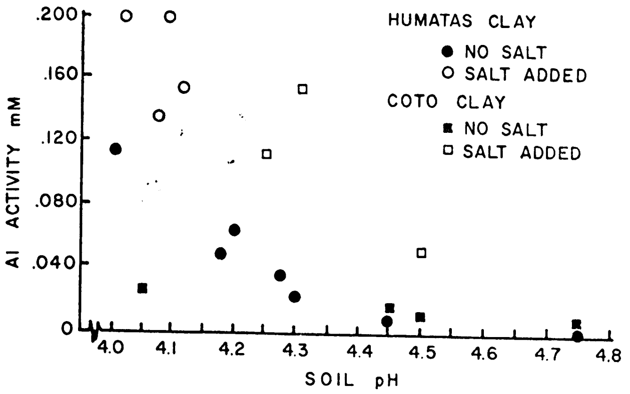

FIG. 3. EFFECT OF PRESENCE OF FREE ELECTROLYTE ON AL LEVEL IN THE DISPLACED SOIL SOLUTION. KCL ADDED AT 0.5 MEQ /100 G AVERAGE TO 2 PUERTO RICAN SOILS AND EQUILIBRATED BEFORE DISPLACEMENT (BRENES AND PEARSON, 1972).

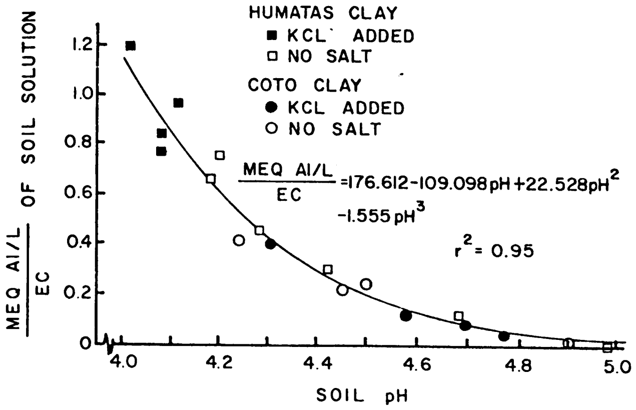

FIG. 4. RELATIONSHIP OF PH TO SOIL SOLUTION AL IN AN OXISOL AND AN ULTISOL WHEN FREE SALT CONTENT AS REFLECTED IN ELECTRICAL CONDUCTIVITY (EC) OF SOIL SOLUTION IS CONSIDERED (BRENES AND PEARSON, 1972).

3.2.2 Relationship between Al and organic matter

Organic matter apparently has some influence on the availability of Al since plants grow more satisfactorily on organic soils at a considerably lower pH than on mineral soils. The strength of bonding or the complexing of Al may result in less Al in the soil solution.

Carboxyl groups of organic matter are the primary functional groups involved in exchange reactions with cations. Using infrared techniques, Schnitzer and Skinner (1963) found that Al would react with organic matter up to a 6:1 molar ratio indicating six carboxyl groups per organic matter molecule. It is possible that Al could be electrostatically bound to one or more carboxyl groups depending on the degree of polymerization and effective charge of the Al molecule. Clark and Nichol (1966) suggested the formation of insoluble Al organic matter complexes. It is possible that organic matter reduces the solubility of Al through complex formation and results in less Al in the soil solution. This may be one reason why plants grow well at a lower pH on organic soils than on mineral soils. Clark and Nichol (1966) suggest that it may be necessary to take into account both the pH and the solubility of Al in estimating the liming needs of organic soils.

Evan and Kamprath (1970) reported that as the organic matter content of soils increased, there was less Al in the soil solution at a given pH. (Fig. 5.) This can be attributed to the complexing of Al by organic matter and reducing the amount of Al in the soil solution. There is only one exception to this relationship, namely, organic 1 which had 25% organic matter. The mineral fraction for this soil was mainly fine sand and the effective influence of organic matter may have been greater than that for other organic soils. Small increments of lime resulted in relatively rapid decreases in soil solution Al for all soils.

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value of 0.91 is clear indication of the close relationship over this range, and the shape of the individual soil response curves indicated that, in general, maximum yield was approached by about pH 5.3, even though yield was increased by the last increment of lime.

A highly significant inverse relationship between bean yield and per cent Al saturation was found. As in the case of corn yield, only more clearly defined, any increase in exchangeable Al from the zero level was accompanied by a reduction in yield. When Al saturation reached about 50%, bean yields were reduced by about one half.

They further found that no clear relationship could be found between leaf-Ca content and yield, but when the ratio of Ca:Mn, expressed in terms of chemical equivalents, is considered together with yield a strikingly close relationship emerges (Fig. 14). In view of the extremely wide range in easily reducible Mn content among these soils and the differences in exchangeable Ca, the relationship shown in Fig. 14 is not believed to be fortuitous. It is also comparable with results of other research reviewed by Jackson (1967) which showed clearly the existence of a reciprocal relationship between Ca and Mn in plant shoots even at toxic levels of Mn. Thus, the data presented in this paper suggest that in the case of beans both Al and Mn were yield-limiting factors at soil pH levels below 5.0 and that a Ca:Mn ratio in the leaf of around 225 would be required for maximum bean yield.

Yields decreased sharply with increasing levels of Al throughout the range found in these soils and the presence of even small amounts of exchangeable Al coincided with a decrease in yield and when Al accounted for as much as 15% of the exchangeable cations yields were distinctly reduced for the Ultisols as a group.

Corn yield was depressed much less by a given level of soil acidity in the Oxisols than in the Ultisols. In two of the three soils good yields were made at pH levels below 5.0, and there was no significant relationship between per cent Al saturation and yield on the Oxisols as a group. These, results indicate 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 also supported by the studies of Brenes and Pearson (1972), where they found consistently low soil solution Al in Oxisols of U.S.A. and Puerto Rico as compared to Ultisols of south-east U.S.A.

In Uganda, Foster (1970) 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. In an extensive screening test in Colombia, Spain et al. (1975) reported a corn response to liming on Oxisol, extending throughout the range of applications used (0-6 ton/ha). Their results, averaged for 20 varieties showed corn grain yield increasing from zero on unlimed soils to about 300, 700, and 850 kg/ha for 0.5, 2.0 and 6.0 ton/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 upto about twice the exchangeable Al equivalent.

Abruña et al. (1975) found progressive increase in bean yield as soil pH was raised throughout the range covered (Fig. 13). The r

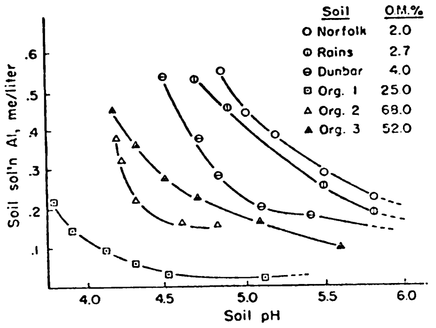

Fig. 5. Effect of organic matter on the soil solution Al-pH relationship (Evan & Kamprath, 1970)

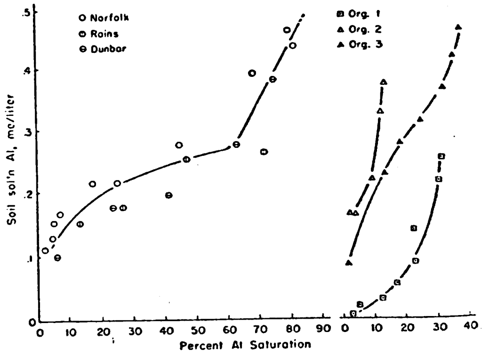

Fig. 6. Relationship between per cent Al saturation and soil solution Al (Evans & Kamprath, 1970)

The relationship between soil solution Al and per cent Al saturation for the mineral and organic soils is shown in Fig. 6. The concentration of Al in the soil solution of mineral soils is determined by the per cent saturation of the effective CEC with exchangeable Al. All mineral soils behaved similarly and one line appeared to satisfactorily characterize that relationship. At about 60 to 70% Al saturation there was a relatively sharp change in slope of the curve with large increases in soil solution Al as per cent Al saturation increased above 70%. These results agree quite well with those of Nye et al. (1961) in which they report low concentrations of soil solution Al in soils of small electrolyte concentration when Al saturation is below about 60%.

With the organic soils there was no general relationship between per cent Al saturation and the amount of Al in the solution such as was found with the mineral soils. For organic soils, small changes in per cent Al saturation resulted in large changes in soil solution Al. The lines are almost linear and do not show a sharp break at a given point as was the case for mineral soils. The data suggest that for organic soils, the amount of exchangeable Al rather than the per cent saturation is more important in determining the amount of Al in the soil solution.

3.3 Manganese solubility

Pearson (1975) noted that Ultisols in Puerto Rico seldom present a Mn problem, whereas Oxisols frequently do. In other areas, however, Ultisols frequently present Mn problems (Adams and Pearson, 1967), while Oxisols may contain only traces of MnO_2 (Ayers, 1961). The solubility of MnO_2 increases as pH decreases or as the redox potential decreases because of the reaction

$$MnO_2 + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$$

An increase in solution Mn^{2+} is favored by lower pH, soil drying, soil heating, and lower redox potentials. The latter condition is enhanced by waterlogging conditions, especially

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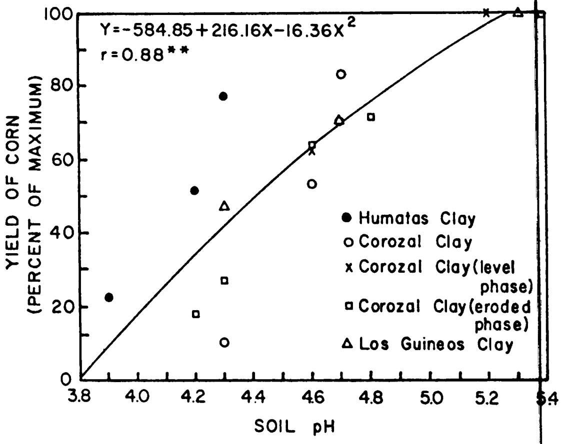

FIG. 11. SOIL PH EFFECT ON YIELD OF CORN GROWN ON 5 PUERTO RICAN ULTISOLS (ALBRÚNA ET AL., 1975).

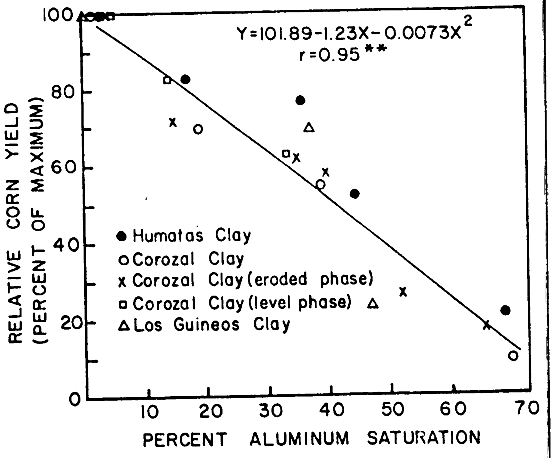

FIG. 12. VARIATIONS IN CORN YIELD WITH PERCENTAGE AL SATURATION OF 5 PUERTO RICAN ULTISOLS (ABRÚNA ET AL., 1975).

4. CROP RESPONSE TO LIME

There is a tremendous range in tolerance of soil acidity among crop species and many tropical crops have evolved in an acid soil environment and consequently some - tea, for example - prefer such conditions (Richarson, 1951). However, no tropical plants of agriculture significance are immune to all factors of acid soil infertility, and lime, at least in modest amounts, is recognized as one of the first requirement for effective use of the soils of most humid tropical areas.

In the past, negative responses of crops to liming, based on temperate-region liming practices (neutralization to pH 6 or 7), have been reported. These have been attributed to micronutrient deficiences of some crops as a result of overliming. Liming rates used in the tropics lately, being usually based on neutralization of exchangeable Al, tend to be low and crop damage from overliming is not likely to be hazard. Therefore, positive response of crops rather than negative response are emphasized here.

There are many reports dealing with positive yield response to liming in the tropics. In this paper, however, only a few will be cited to emphasize the importance of liming for crop production.

Abruna et al. (1975) reported a strong yield response to liming on five Puerto Rican Ultisols (Fig. 11) and when yield data were plotted against per cent Al saturation of the soil a much closer relationship emerged (Fig. 12).

when accompanied by rapid decomposition of organic matter (Redman and Patrick, 1965). As a general rule, Mn toxicity is not a problem in any soil unless soil pH is <5.5 (Adams and Pearson, 1967; Pearson, 1975).

Threshold toxic concentrations of Mn in solution were reported by Morris and Pierre (1949) to vary from about 1 to >10 ppm. They also reported the following relative tolerance to excess solution Mn: peanuts > cowpeas (Vigua sinensis Endl.) = soybean > sweetclover > lespedeza (Lespedeza striata Thurb.). 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 (Abruna et al., 1975), indicating that soil solution levels of Mn decreased as soil pH increased.

3.4 Phosphorus availability

A common benefit ascribed to liming is that it renders P more available. But there has been controversy over this benefit and as pointed out by Kamprath (1972), published results show that the effect of lime on P availability can vary from beneficial to deterimental.

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 has 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_o, 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. Per cent P in the plants increased with liming at the lower le-

Data by Soltanpour et al. (1974) showed that all rates of lime decrease the availability of all levels of previously added P. The observation that liming sometimes increases the availability of soil P may result from an increased P release from organic matter because of an accelerated decomposition rate (Awan, 1964). It may also be the result of an improved root system because a Ca deficiency was corrected (Hortenstine and Blue, 1968).

Since the neutralization reaction of lime results in the precipitation of exchangeable Al, adding successive increments of lime prior to fertilizing can be expected to render the fertilizer P progressively more available until enough lime has been added to reduce the exchangeable Al to nil; above this pH, additional lime increments can be expected to progressively decrease P availability (Amarasiri and Olsen, 1973; Reeve and Sumner, 1970a; Soltanpour et al. 1974).

Stoop (1983) reported that P solubility in the oxidic soils depended mainly on salt concentration and cation valency. It was decreased by the accompanying cation according to $K < Mg \leq Ca$. This cation effect on P solubility decreased with increasing contents of layer silicate clay minerals and/or increasing base saturation of the soil. The P solubility increased greatly when the pH was raised with NaOH as compared to $Ca(OH)_2$. (Table 4)

3.5 Micronutrient availability

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.

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 per cent 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.

Liming an acid soil has a pronounced effect on Mo availability (Fig. 9). Generally, it corrects Mo deficiency, either partially or completely, by increasing the availability of Mo already present in the soil (Anderson and Moye, 1952).

Legumes are somewhat more responsive than non-legumes to the increased availability of Mo. The response difference is not necessarily because of a greater Mo requirement per se of legumes; it appears to be because the increased Mo increases the N fixation capacity of the Rhizobium organisms.

Table 5. Effect of liming and P rate on dry matter production and P concentration of millet grown on Latosols

Fertilizer P, ppm	No lime Tops	No lime P	Lime Tops	Lime P
	mg/pot	%	mg/pot	%
		La Mesa I		
0	24	-	36	-
115	439	0.27	595	0.25
230	591	0.30	752	0.35
460	680	0.60	752	0.60
LSD$_{0.05}$L x P	73			
		Pacora II		
0	36	-	65	-
35	261	0.17	651	0.14
70	674	0.18	958	0.20
140	818	0.30	1026	0.37
LSD$_{0.05}$L x P	167			
		Pacora III		
0	23	-	46	-
35	223	0.17	354	0.17
70	762	0.20	791	0.20
140	772	0.32	928	0.32
LSD$_{0.05}$L x P	146			

Table 4. Effect of pH on the concentration of P in solution when using NaOH and $Ca(OH)_2$ to raise the pH*[1]

Soil	Treatments added P (µg P/g soil)	Treatments pH	P in solution (ppm)
Honokaa	3000	4.8	0.6
	3000	5.8 NaOH	7.7
	3000	5.8 $Ca(OH)_2$	0.9
Halii	1500	4.8	1.7
	1500	5.8 NaOH	3.3
	1500	5.8 $Ca(OH)_2$	1.5
Wahiawa	750	4.8	2.3
	750	5.8 NaOH	5.1
	750	5.8 $Ca(OH)_2$	2.7
Waialua	375	5.8	4.1
	375	6.8 NaOH	3.8
	375	6.8 $Ca(OH)_2$	2.5

*[1] Equilibration was in 0.01 N KCl and phosphate was added as $NH_4H_2PO_4$

This result explains why in many oxidic soils even moderate liming rates were not found to increase the P availability. He further showed the negative effect of the Ca ion on P uptake by Sudan grass in two Oxisols (Fig. 8).

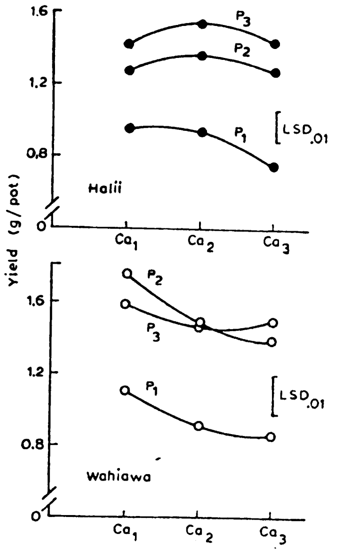

Fig. 8. **Yields of Sudan grass as a function of Ca and P treatments for the Halii and Wahiawa soils (Stoop, 1983)**

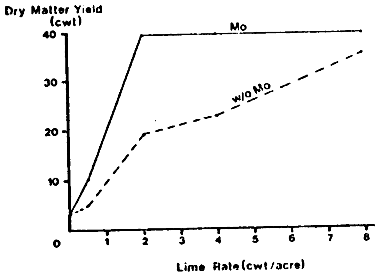

Fig. 9. **Effect of lime and molybdenum on yield of subterranean clover (Trifolium subterraneum L.) on an acid soil in southeastern Australia (Anderson and Moye, 1952)**

Mendez and Kamprath (1978) reported that liming had relatively little effect on P concentration of the tops as compared with P rate (Table 5). The increased plant growth with liming at the lower P rates without any effect on P concentration supports the view that liming improved P absorption by plants rather than affecting solubility of soil P (Reeve and Sumner, 1970a).

Both P rate and % Al saturation had significant influences on the beneficial effect of liming on P response. Neutralization of Al by liming increased relative growth at low rates of applied P. However, with larger amounts of applied P there was no benefit from liming when the Al saturation was <60%. Previous studies have shown that if the Al saturation is <60%, the amount of Al in the soil solution is relatively low as compared with Al saturations >60% (Evans and Kamprath, 1970). At these lower concentrations of Al the larger P additions either precipitated Al internally and still provided sufficient P for metabolic purposes (Wright, 1937), or removed the detrimental effects of Al by precipitating it in the soil (Munns, 1965). When Al saturations were >60%, large P additions apparently could not completely overcome the detrimental effects of Al on plant growth.