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THE ROLE OF ORGANIC MATTER IN THE INHIBITION OF ALUMINUM TOXICITY IN AN ULTISOL

Publio Santiago

Cornell University

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~~The objective of this~~ A study ~~was~~ to determine the effect of variable organic matter increments on the immobilization of active Al in an acid Ultisol and compare organic matter applications with lime rates relative to the growth of sorghum. ~~It was found that~~: (1) organic matter neutralized more Al per unit of Ca in it than ~~was true for~~ $Ca(OH)_2$: (2) maximum yields were obtained on all treatments when the Al saturation was less than seven percent and soil solution Al was less than 0.68 meq/liter; (3) the rate of Ca either from organic matter or $Ca(OH)_2$ at which maximum yields were obtained was ~~at a level~~ equivalent to 100 percent of the exchangeable Al; (4) the yields of sorghum were drastically reduced when the Al saturation was 19 percent or more and the soil solution Al was 1.39 meq/liter or more; (5) the pH at which maximum yields were obtained ranged from 4.55 to 4.80; (6) the maximum yield obtained by adjusting organic matter at zero level of lime was statistically higher, and was obtained with a lower amount of Ca supplied to the soil, than the maximum yield obtained by adjusting $Ca(OH)_2$ at zero level of organic matter; this suggests ~~the possibility of~~ using less liming materials if adequately high levels of organic matter are maintained in acid tropical soils.

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THE ROLE OF ORGANIC MATTER IN THE INHIBITION OF ALUMINUM TOXICITY IN AN ULTISOL

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University for the Degree of

Master of Science

by

Publio Santiago

August, 1972

BIOGRAPHICAL SKETCH

The author was born in Isnotu, Trujillo State, Venezuela, on February 20, 1940. He attended primary school in Lagunillas and high school in Liceo Chavez in Cabimas, Zulia State. His undergraduate training was taken at the University of Zulia in Maracaibo, Venezuela and he received the degree of "Ingeniero Agronomo" in 1966. In 1967 he joined the staff of the faculty of Agronomy, University of Zulia in Maracaibo, where he still holds a position. In 1968, he participated in a three-month conference for Professors of Soil Science at the Inter-American Institute of Agricultural Sciences, Turrialba, Costa Rica.

In July 1970, he took leave from the Faculty of Agronomy, University of Zulia, and enrolled in the Graduate School at Cornell University with a major in Soil Science and a minor in Agricultural Economics.

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INTRODUCTION

Highly weathered soils of the humid tropics (most of them classified as Ultisols and Oxisols in the U. S. Soil Taxonomy, 1970) have developed under conditions in which rainfall exceeds evapotranspiration during most of the year. Under this condition there has been a gradual depletion of soil bases and the development of soil acidity.

It is estimated from the unpublished world soil map of the Soil Conservation Service, U.S.D.A. that there are 350 million hectares of Ultisols and 700 million hectares of Oxisols in the tropics which are potentially arable. Most of these soils have excellent physical characteristics and favorable topography.

Crop production on these acid soils may be limited by: a) deficiency of essential elements and/or b) toxicity of certain elements due in part to soil acidity. Aluminum toxicity is one of the major factors contributing to poor growth of plants particularly in Ultisols and in some Oxisols. This is being intensified by the heavy use of acid-forming nitrogen fertilizers, and by the addition of non-nitrogenous fertilizers which displace exchangeable Al into the soil solution and lower soil pH even more.

Aluminum toxicity causes a combination of effects, of which inhibition of root growth is perhaps the most obvious visually. The limited root system caused by toxic quantities of Al may reduce uptake of water by plants as well as nutrients (particularly Ca and P) thus reducing top growth. Many important crops such as lettuce, beets, sorghum, tomato, alfalfa, cotton, etc. have been reported to be very sensitive to excess Al.

Until now, liming is the most common method of neutralizing toxic concentrations of Al and thus promoting optimum crop growth and efficient use of fertilizer nutrients. There is disagreement among soil scientists about the criteria to use in estimating lime requirement, as illustrated by the papers of Kamprath (1970a, 1970b) and McLean (1970). Kamprath recommends only enough lime to eliminate toxic substances, principally exchangeable Al, while McLean recommends liming to pH 6 to 6.5. Neither gives much consideration to economic factors. In many areas of the humid tropics, lime and capital are very expensive.

Another method of neutralizing Al toxicity is through P fertilization. In this case Al is precipitated as Al $(OH)_2H_2PO_4$ which is relatively insoluble thus Al is no longer a problem for plant growth. This method has been discarded because it is so expensive.

There is some evidence that organic matter has some influence on the availability of Al since plants grow more

satisfactorily on organic soils at considerably lower pH than on mineral soils. This is true even though total Al is quite high in some organic soils (Evans and Kamprath, 1970). It is suggested that the lower critical pH values for plant growth in organic soils compared with mineral soils, is due, at least in part, to the formation of Al-organic matter complexes of lower solubilities (Schnitzer and Skinner, 1963a, 1963b; Greene, 1963; Evans, 1968). However, there is also the possibility that Al is detoxified by chelation in water soluble forms. The formation of Al-complexes or Al-chelates by organic matter reduces the amount of Al in the soil solution and this may be one reason why plants grow well at lower pH in organic soils than in mineral soils. The role that organic matter plays in the immobilization of the active Al in tropical soil has been very little studied. Few investigations have shed light on this important problem.

The implication that organic matter inhibits or reduces Al toxicity leads to the idea that organic matter could be used instead of lime as a means to prevent toxic effects of Al in acid tropical soils. Commercial lime is usually very expensive in tropical countries, and transportation expenses increase even more the cost of liming. This could be a good justification for neutralizing Al toxicity with organic matter, which at the same time adds nutrients to the soil, and improves some physical properties

like structure, aeration, water holding capacity, etc. Several weeds and grasses which are tolerant to high Al concentrations grow naturally in acid tropical soils. It is possible to incorporate these species in the soil in order to increase the organic matter content and thus reduce Al concentrations and make the environment more favorable to other crops that, otherwise, would be unable to grow.

The objectives of this study were: a) to determine the effect of variable organic matter increments on the immobilization of active Al in an acid Ultisol, b) to compare organic matter applications with lime rates in terms of sorghum growth, and c) to determine the effects of organic matter and liming on the foliar composition of sorghum grown under greenhouse conditions.

The research work was carried out in the greenhouse and laboratories of the Experimental Station of the University of Puerto Rico at Rio Piedras, Puerto Rico.

LITERATURE REVIEW

SOILS FACTORS AFFECTING Al TOXICITY

An excellent review of soil acidity has been given by Jenny (1961) in which he reported the various ideas on soil acidity over the last fifty years. He shows how the concept of the predominant cation in acid soils changed from that of Al to H, and then back to Al. Much detailed research has been done recently to elucidate the role of Al in soil acidity.

The solubility of Al and the severity of its toxicity to plants are affected by many soil factors, including soil pH, type of predominant clay mineral, concentrations of other cations, total salt concentration,and organic matter content.

Soil pH

Numerous investigators have established that exchangeable Al decreases as soil pH value increases (Gilly, 1958; Lefebre-Drouet and Lavielle, 1966; Pionke and Corey, 1967). In general, Al toxicity does not occur in soils above pH 5.5 (McCart and Kamprath, 1965), but it is common at lower pH values, and particularly severe below pH 5.0 where the solubility of Al increases sharply (Magistad, 1925). More than half of the cation exchange sites may be occupied by Al at a pH less than 5.0 (Evans and Kamprath, 1970). In the highly

leached soils of Brazil exchangeable Al was the dominant cation at pH 5.0 and below (Pratt and Alvahydo, 1966). Studies with four Ultisols indicated that Al constituted 50% of the exchangeable cations when pH ranged from 4.8 to 5.1 (Kamprath, 1970a), but only 10% of the exchangeable cations when the soil pH values ranged from 5.3 to 5.7.

The solubility of Al in displaced soil solution at various pH values is the same as the solubility of Al in water at the same pH values (Magistad, 1925; Pierre et al., 1932). At a pH of 5.5 the concentration of Al in the soil solution is quite low. However, as the pH drops from 5 to 4.5, the Al concentration increases markedly.

The soil pH at which Al becomes soluble in toxic concentrations and at which exchangeable Al becomes inactive varies with the specific soil. In recent field studies with cotton and corn, Adams (1968, 1969) demonstrated that certain soils of the Coastal Plains of the U.S.A. differ in "critical pH," defined as the maximum pH at which a given crop responds to lime.

Type of Predominant Clay Mineral

Adams and Lund (1966) found that the levels of exchangeable Al toxic to cotton varied greatly in different soils depending on the type of predominant clay mineral. For example, minimum exchangeable Al levels that were toxic were about 0.1, 1.5, and 2.5 meq/100g. for soil containing the major clay mineral components of kaolinite

(Norfolk), vermiculite (Dickson), and montmorillonite (Bladen), respectively. Minimum Al saturation values that were toxic were about 5% for Norfolk at pH 5.4, and 30% for both Dickson and Bladen at pH of less than 5.0. Thus, Al is toxic at higher soil pH level and a lower level of exchangeable Al in Norfolk (predominant kaolinite clay) than in Dickson and Bladen (predominant vermiculite and montmorillonite clay, respectively). In addition, they found that no single critical Al concentration in the displaced soil solution would apply to all the soils studied.

Acid soils in California with primarily illite and montmorillonite clays contained very little exchangeable Al when the soil pH was above 5.0 (Pratt and Bair, 1962).

Concentrations of Other Cations and Total Salt Concentrations

The Al saturation of the effective cation exchange capacity of the soil greatly affects the Al concentrations of the soil solution. Al concentration in the soil solution is quite low until the exchangeable Al saturation exceeds 60%, but then increases rapidly (Nye *et al.*, 1961; Evans and Kamprath, 1970).

As the salt concentration in the soil increases, the concentration of Al in the soil solution increases. This is due to the cation of the salt replacing some of the exchangeable Al, which in solution undergoes hydrolysis, thereby lowering the pH and resulting in a greater

solubility of Al (Black, 1968). The water soluble Al content of a soil at pH 5.1 was doubled with heavy fertilization (MacLeod and Jackson, 1967). The addition of a high rate of KCl to an unlimed soil increased the concentration of Al in the soil solution and markedly reduced the growth of sweet corn roots (Ragland and Coleman, 1959). Therefore, where high rates of fertilization are used, it is desirable that the cation exchange capacity has a relatively low Al saturation in order to avoid the detrimental effect of Al.

On the other hand, increasing the Ca concentration of a nutrient solution at the same initial pH, reduces the toxicity of Al and other excess cations (Foy, et al., 1969; Lund, 1970).

EFFECTS OF Al TOXICITY ON PLANT GROWTH

A relationship exists between soil pH and plant growth. Whether this relationship exists as a result of acidity alone or as a result of some indirect factor has been a topic of considerable research. Most results that have been reported have tended to point toward Al as the toxic factor involved. The most important effects of Al toxicity on plant growth are in the root growth and the uptake of nutrients.

Root Growth

The inhibition of root development was one of the first observable symptoms of Al toxicity noted by Shoop et al. (1961) and other investigators. They reported that the

symptoms characteristic of Al toxicity are the absence of lateral roots and the pronounced browning of the root tissue. The limited root system may reduce uptake of water as well as nutrients. Microscopic examination of plants grown with toxic concentrations of Al has shown an abnormally large number of cells with two nuclei in the meristematic region of the root tip, indicating inhibition of cell division (Rios and Pearson, 1964). Rorison (1958) proposed that the inhibition of branch-root development might be due to reaction of Al with the pectic substances of the young cell walls, causing them to lose their plasticity prematurely and inhibiting elongation.

Roots injured by Al are characteristically stubby and spatulate in appearance. Root tips are inhibited and turn brown. The root system as a whole has many inhibited and thickened lateral roots but is lacking in fine branch roots (Fleming and Foy, 1968; Clarkson, 1969; Reid et al., 1971).

The concentration of Al toxic to plant growth has been studied extensively by means of culture solutions by many investigators (McGeorge, 1925; Sederis, 1925; Villa, 1929). It has been demonstrated that plants are differentially tolerant to given concentrations of Al (Foy and Brown, 1964). Other investigators observed that the level of Al required to be toxic varies with the soil, the concentration of other ions and the plant species or variety (Adams and Lund, 1966; Rios and Pearson, 1964). Clarkson (1965), using $Al_2(SO_4)_3$, found that levels from

5.4 to 54.0 ppm completely inhibited onion root elongation after 6 to 8 hours.

The growth of sorghum roots was severely reduced in acid soils until 80% of the exchangeable Al was neutralized (Ragland and Coleman, 1960). Cotton roots died when the concentration of Al in the soil solution was greater than 1 ppm and at 0.5 ppm the growth of roots was decreased and their appearance was abnormal (Rios and Pearson, 1964).

Uptake of Nutrients

Aluminum toxicity has a number of effects on plant nutrition. Foy and Brown (1963) reported that excess Al in nutrient solution caused decreased uptake of P, Ca, K, Mn, Fe, Na, and B by cotton plants. Moreover, excess Al caused plants to wilt. McLean and Gilbert (1927) observed lower loss of water per unit leaf area from Al treated than from control plants, and they obtained evidence for lesser movement of dyes in and lesser uptake of nitrate by Al treated plants than by control plants. These observations suggest that Al toxicity causes a general decrease in permeability of protoplasm of root cells.

One of the most important effects of Al toxicity is the uptake of Ca and P:

a) Ca Uptake. It is difficult to separate the effects on plant growth of low soil Ca levels in acid soils from the toxic effects of Al. In some cases Ca additions have not improved root growth (Clarkson, 1966a; Rios and Pearson,

1964). The soluble Ca salts will replace the Al from the exchange sites and thereby increase the amounts of Al in the soil solution to toxic levels. Fried and Peech (1946) found that the addition of 1000 lbs of $CaSO_4$ per acre increased considerably the Al in the soil solution. On the other hand, Reeve and Sumner (1970) reported that $CaSO_4$ reduced exchangeable Al, increased sorghum growth and did not influence pH on acid Oxisols.

A certain amount of available Ca is necessary for adequate plant growth. Root growth of cotton was inhibited when the exchangeable Ca saturation of the soil was less than 20% (Howard and Adams, 1965). For the growth of lettuce and barley 20% of the exchange complex had to be saturated with Ca (Vlamis, 1949). In addition, reduced Ca uptake is commonly observed in Al-injured plants. For example, Johnson and Jackson (1964) found that Al reduced both the absorption and accumulation of Ca by wheat. Paterson (1965) concluded that Al reduced Ca uptake by corn but did not appear to inhibit Ca transport to plant tops. Lance and Pearson (1969) found that Al at only 0.3 ppm in solution reduced Ca uptake by cotton seedling roots within one hour. This inhibition was prevented by increasing the solution Ca concentration to 600 ppm. Soileau et al. (1969), suggested that Al toxicity and Ca deficiency are closely related and utilized the term "Al-induced Ca deficiency" in the discussion of their results. However, Kamprath (1967) suggested that Ca deficiency

as such does not limit plant growth on acid soils but rather the toxic effect of Al. His conclusion is based on the results obtained by Vlamis (1953) where plants grown in a solution displaced from limed soil were not adversely affected when sufficient H ions were added to lower the pH to 4.2. Differentiation between Al toxicity and Ca deficiency is thus difficult to separate and it may be that both terms refer to a single phenomenon.

b) P Uptake. The effect of Al on P nutrition has received more attention than any other nutritional effect. Al toxicity often appears as a P deficiency in plants grown on acid soils or in nutrient solutions (Foy and Brown, 1963, 1964). Excess Al may reduce the solubility of P in the growth medium and its uptake and transport by plants. Conversely, the addition of P, in sufficient quantities, to acid soils or nutrient solutions can precipitate and thus detoxify Al, increase P uptake and prevent P deficiency symptoms (Kamprath and Foy, 1971). There is also evidence that in the presence of excess soluble Al a higher level of soluble P is required to prevent P deficiency in cotton (Foy and Brown, 1963). Although the exact mechanism of Al toxicity is still debatable, there is considerable evidence that it involves some kind of interference with P uptake and/or metabolism.

The detrimental effects of high Al and low P as growth limiting factors are often extremely difficult to separate

in acid soils. However, Reeve and Sumner (1970) concluded that on eight Oxisols Al toxicity, P deficiency and P fixation were primary but independent growth limiting factors. The beneficial effects of P fertilization were attributed to the elimination of Al toxicity and the resulting increased ability of plants to absorb P rather than to increased P availability in soils. Munns (1965a, 1965b) concluded that P treatments reduced the detrimental effects of Al only when they caused the Al to precipitate in the nutrient solution. He noted that Al decreased P concentrations in both roots and tops of alfalfa. The Al-induced P deficiency symptoms were not corrected by increasing the P level in the growth medium, even when this treatment restored P concentrations of plants to high levels.

In some instances Al toxicity has been associated with reduced P concentrations in both roots and tops (Munns, 1965b). In others Al was believed to precipitate P inside plant roots and thereby cause P deficiency in the tops (Wright, 1937, 1943). The occurrence of Al-Phosphate within the endodermis and within the cell has been described (Wright and Donahue, 1953).

Clarkson (1969) has summarized the evidence for interference of Al in plant metabolism and suggested ways in which Al-P interactions may be involved in the mechanism of Al toxicity. The evidence indicates that Al binds P on root surfaces and cell walls and in the free space of plants

roots (Rorison, 1965; Clarkson, 1966b, 1967), making P less available to metabolic sites within the cells. In addition, some of the Al absorbed by plant roots also appears to penetrate the cells of meristematic tissue and interferes with cell division, respiration, DNA synthesis and sugar phosphorylation (Rorison, 1965; Clarkson, 1966b, 1969; Norton, 1966-1967; Sampson et al., 1965).

EFFECTS OF LIME IN REDUCING Al TOXICITY

Soils are limed for the purpose of (a) neutralizing exchangeable Al, exchangeable H where it is present, and/or exchangeable Mn, and (b) supplying Ca and Mg. However, it is generally agreed today that the main purpose of liming an acid soil is probably to depress toxicity of various elements, mainly Al. Kamprath (1970a) observed that lime applied to acid soils reacted primarily with the exchangeable Al and reduced the Al saturation of the effective cation exchange capacity to less than 30% at the higher rates. Ross et al. (1964), relating lime requirement to physical and chemical properties of nine Michigan soils, showed that grain sorghum and alfalfa responded to lime in proportion to the amount of exchangeable Al in the soil. Shoop et al. (1961), in a study of differential responses of grasses and legumes to liming, observed a linear increase in growth of fescue and clover up to 1000 lbs per acre. Lime rates was coincident with a linear decrease in

exchangeable Al. The yield increase due to lime was apparent up to the point at which the exchangeable Al was immobilized. Such a relationship suggests that Al may be the factor responsible for poor growth of fescue and clover under the conditions of their experiments. The observed increase in yield upon liming may also be the result of increased availability of various nutrients, mainly P. However, reports of research on organic soils show that lime does not always have a beneficial influence on the availability both of native soil P and of that applied as fertilizer and often causes a decrease in crop yields (Lawton and Davis, 1956; Okruszko et al., 1962). Conversely, Evans and Kamprath (1970) obtained significant crop responses to liming for two organic soils when the concentration of soil solution Al was greater than 0.40 meq/liter in the case of corn and 0.20 meq/liter in the case of soybean, respectively.

The proceeding reports suggest that for maximum yield it is only necessary to use enough lime to raise the soil pH sufficiently to eliminate various toxic substances and at the same time provide an adequate amount of nutrient elements.

The work of McIlvaine and Pohlman (1949) indicated that yields of corn, small grain, and tobacco were the same in the pH range of 5.5 to 7.0. Woodruff (1967), studying crop response to lime in midwestern U.S.A., reported that corn yields were not generally increased by raising the pH above 5.5. He concluded that the available data from recent field

experiments do not support the recommended optimum pH values which often are 6.5. In support of this Kamprath (1970a, 1970b), also recommends only enough lime to eliminate toxic substances, principally exchangeable Al. However, McLean (1970) recommends liming to pH 6 to 6.5.

Evidently the response of crops to lime in acid soils is very complex. It involves several contributing factors the relative significance of which probably varies with different crops and soil. Foy and Brown (1964) observed remarkable difference in the yield response of several plant species on acid Bladen soil.

EFFECTS OF ORGANIC MATTER IN REDUCING Al TOXICITY

Organic soils are known to have lower critical pH values for good crop growth than mineral soils (Welch and Nelson, 1950). Hester (1935) found that the detoxification of Al by the addition of organic matter to acid soils was associated with decreased Al solubility. In studying lime potential of soils, Clark and Nichol (1966) reported low measurable Al in some organic soils and believed that this was due to the formation of insoluble Al-organic matter complexes. These results suggested that reducing the solubility of Al may be one way in which organic matter reduces the effects of soil acidity on plants, and that liming to reduce the Al concentration may be unnecessary in some organic soils. The importance of considering both

pH and solubility of Al was indicated as being meaningful in estimating the liming needs of organic soils.

The possibility that organic matter reduces the solubility of Al through complex formation of lower solubilities and results in less Al in soil solution has been reported by many investigators (Pierre et al., 1932; Greene, 1963; Evans, 1968). This possibility may be one reason why plants grow well at a lower pH on organic than on mineral soils.

Retention of Al by soil organic matter is due in large part to formation of inner complexes or chelates. Formation of such complexes depends on the existence of two functional groups, one acidic such as COOH, enolic OH, or oxime, and another coordinating in nature, such as amino, cyclic amino, or carbonyl (Broadbent, 1955). Using infrared techniques, Schnitzer and Skinner (1963a, 1963b, 1964) found that Al would react with organic matter up to 6:1 molar ratio indicating six carbonyl groups per organic molecule. They indicated that it is possible that Al could be electrostatically bound to one or more carbonyl groups depending on the degree of polymerization and effective charge of the Al molecule.

Until now, relatively little research has been done to establish the relationship between organic matter and Al, and to elucidate the role of organic matter in reducing or inhibiting the toxic effects of the Al in acid soils.

EXPERIMENTAL

SOIL

The characteristics of the soil used in this study are presented in Table 1. Bulk samples of Humatas surface soil from 0-20 cm depth were collected, composited, air dried and screened for use in laboratory and greenhouse studies. A representative sample was analysed for cation-exchange capacity, organic matter, P, pH, exchangeable Ca, Mg, Al, K, and Mn. Procedures used were those used by the Agricultural Experiment Station laboratories of the University of Puerto Rico, at Rio Piedras, Puerto Rico.

METHODS OF ANALYSIS

Cation-exchange capacity was determined by the neutral N NH_4OAC method as described by Chapman (1965). Organic matter was determined by the Walkly-Black acid dichromate digestion method as described by Allison (1965). P was determined by Bray II method as described by Bray and Kurtz (1945). The pH was determined with a pH meter using a glass electrode at a soil water ratio of 1:2. The exchangeable Ca, Mg, and Al were extracted with N KCl solution. Chemical determinations for Ca, Mg, and Al were made on this leachate. Ca and Mg were determined by the EDTA method as described by

Table 1. Some physical and chemical properties of Humatas soil

Soil Series	Humatas
Location	Orocovis, P.R.
Classification (S.S.I.R. No. 12, 1967)	Typic Tropohumult, clayey, kaolinitic, isohyperthermic
Origin	Volcanic tuffs
Organic matter (%)	2.3
Cation-exchange capacity (meq/100g)	15.0
pH	3.7
P (ppm)	18.6
Exchangeable Cations	
Al (meq/100g)	8.0
Ca (meq/100g)	1.3
Mg (meq/100g)	0.5
K (meq/100g)	0.5
Mn (ppm)	4.0
Bulk density (g/cm^3)	1.1

Heald (1965) using calcein as Ca indicator and Eriochrome black T as Ca-Mg indicator. Al was determined by the Eriochrome Cyanine R method as described by McLean (1965).

The exchangeable K and Mn were extracted with neutral N NH_4OAC at pH 7. Chemical determinations for K and Mn were also made on the same leachate. K was determined by flame emission photometry as described by Pratt (1965). Mn was determined calorimetrically by the method of oxidation with periodate as described by Adams (1965).

PREPARATION OF SOIL FOR EXPERIMENTS

For each treatment 6.2 kilos of the air dried and screened soil were used. Thirty treatments were used composed of different lime and organic matter levels as will be described in the section on the greenhouse study.

Lime

Based on the exchangeable value of Al as determined above, 6 levels of lime to neutralize 0, 25, 50, 75, 100 and 150% of exchangeable Al were used. $Ca(OH)_2$ was used as a source of lime. The soil was spread thinly, the lime was weighed and sprinkled over the soil, which was then thoroughly mixed and placed in plastic bags.

Organic Matter

The levels of organic matter used were 0, 2, 4, 6 and 8% by weight. The level of 0% was the native organic matter of the soil. As a source of organic matter coffee leaves were used. The leaves were partially decomposed,

oven dried, ground, and passed through a 100 mesh sieve. The chemical composition of this organic matter is given in Table 2. The soil was spread thinly, the organic matter was weighed and sprinkled over the soil and then thoroughly mixed and placed in plastic bags.

Incubation

All the treated soils were moistened to a level approximating field capacity. The soils were incubated in a laboratory room at an average temperature of 28°C for a period of two weeks. The total weight of each treated soil was checked occasionally for moisture loss and water was added when necessary. After removing 5200g of soil for the greenhouse studies, the remaining soil in each bag was returned to the laboratory for further incubation and later analysis. The total amounts of lime and organic matter applied to each treatment are given in Table I in the Appendix.

Extractions and methods of determination used for exchangeable Ca, Mg, Al, K, Mn, and pH of each treatment were carried out as outlined in the previous section.

SOIL SOLUTION

Utilizing plastic tubes of approximately 60 cm in length and 7 cm in diameter, soil solutions were displaced from each treated soil. Glass wool, about 2 cm thick, was placed at the bottom of the soil column and just above the rubber stopper which formed the base of the cylinder to act as a filter. The rubber stopper forming the bottom of the

Table 2. Chemical composition of the coffee leaves used as a source of organic matter in greenhouse and laboratory studies*

Element	Dry weight
N (%)	3.6
P (%)	0.2
K (%)	0.3
Ca (%)	2.0
Mg (%)	0.4
Mn (ppm)	898.0
Fe (ppm)	1000.0
B (ppm)	76.0
Cu (ppm)	19.0
Zn (ppm)	35.0
Mo (ppm)	10.9
Sr (ppm)	22.0
Ba (ppm)	12.0
Na (ppm)	125.0

* All determinations for the elements, except for N, were made by atomic absorption spectroscopy techniques. N was determined by the Kjeldahl method as described by Bremner (1965).

plastic tube had a hole through which was inserted a tight-fitting flexible tube. This tube extended into a 150 ml Erlenmeyer flask in which the displaced solution was collected. The tube was filled with soil at a moisture content of approximately field capacity to within 12 cm of the top. This required about 600g of soil. Solution was displaced with 70 per cent ethanol. When enough soil solution was displaced, the Erlenmeyers were removed and the solution was used for analysis.

The soil solution was analysed for Ca, Mg, Al, K, and Mn following the procedures outlined in the section on methods of analysis.

GREENHOUSE STUDY

A 6x5 factorial experimental design with four replications was used in this study. Variables were 6 levels of lime and 5 levels of organic matter. The treatments are presented in Table 3.

After two weeks of incubation, 5200g of each treated soil were removed from the plastic bags for use in this experiment. The 5200g of each treated soil were distributed in four pots. This gave a total of four pots per treatment, each pot containing 1300g of soil. A blanket application of N, K, Mn, Fe, B, Zn, Cu, and Mo was applied to all treatments at rates of 100, 100, 10, 5, 2.5, 5, 0.5, and 0.1 ppm respectively. N was applied as NH_4NO_3, K as

Table 3. Treatments of lime and organic matter used in the greenhouse and laboratory studies

Treatment number	Treatment	
	% Organic matter	Calculated % of exchangeable Al neutralized with lime
1	0	0
2	0	25
3	0	50
4	0	75
5	0	100
6	0	150
7	2	0
8	2	25
9	2	50
10	2	75
11	2	100
12	2	150
13	4	0
14	4	25
15	4	50
16	4	75
17	4	100
18	4	150
19	6	0
20	6	25
21	6	50
22	6	75
23	6	100
24	6	150
25	8	0
26	8	25
27	8	50
28	8	75
29	8	100
30	8	150

KNO_3, Mn as $MnCl_2$ 4 H_2O, Fe as $FeSO_4$, B as H_3BO_3, Zn as $ZnSO_4$ 7 H_2O, Cu as $CuSO_4$ 5 H_2O, and Mo as $H_2MoO_4H_2O$.

Sorghum (RS-671) was used as the test crop. Ten sorghum seed per pot were planted. After emergence the sorghum was thinned to six plants per pot. All pots were watered to approximately field capacity every day. Plant tops were harvested after 31 days and oven dried at 70°C for weight records. The yield data were analyzed statistically.

Plant top samples were analysed for N, P, K, Ca, Mg, and Mn. For the determination of P, K, Ca, Mg, and Mn the digestion of plant material was made by the method of wet digestion with sulphuric, nitric and perchloric acids, as described by Piper (1942). P was determined by the ascorbic acid method (Watanabe and Olsen, 1965). K, Ca, Mg and Mn determinations were made following the methods outlined in the section on methods of analysis. N was determined by the Kjeldahl method as described by Bremner (1965).

RESULTS AND DISCUSSION

LABORATORY STUDY

The Effect of Lime and Organic Matter Applications on Exchange Properties

Most of the effect of the organic matter addition to the soil was the release of Ca which thereby decreased the exchangeable Al in the soil. The Ca content of the organic matter was approximately 2% (Table 2), which means that for each addition to the soil of 2% organic matter the Ca supplied by this material was 2 meq/100g of soil. Therefore, the addition of 2% organic matter would supply the same amount of Ca as the application of 2 meq of Ca as $Ca(OH)_2$, which is enough to neutralize 25% of the exchangeable Al. In the same way it is possible to consider that, theoretically, the levels of 4, 6, and 8% organic matter at zero lime levels would neutralize 50, 75, and 100% of the exchangeable Al, respectively, as a result of the Ca contained in the organic matter. The organic matter, however, neutralized more Al per unit of Ca in it than was true for $Ca(OH)_2$.

Figure 1 shows the differences between lime and organic matter applications in the neutralization of the total measured exchangeable Al. The dotted line on this

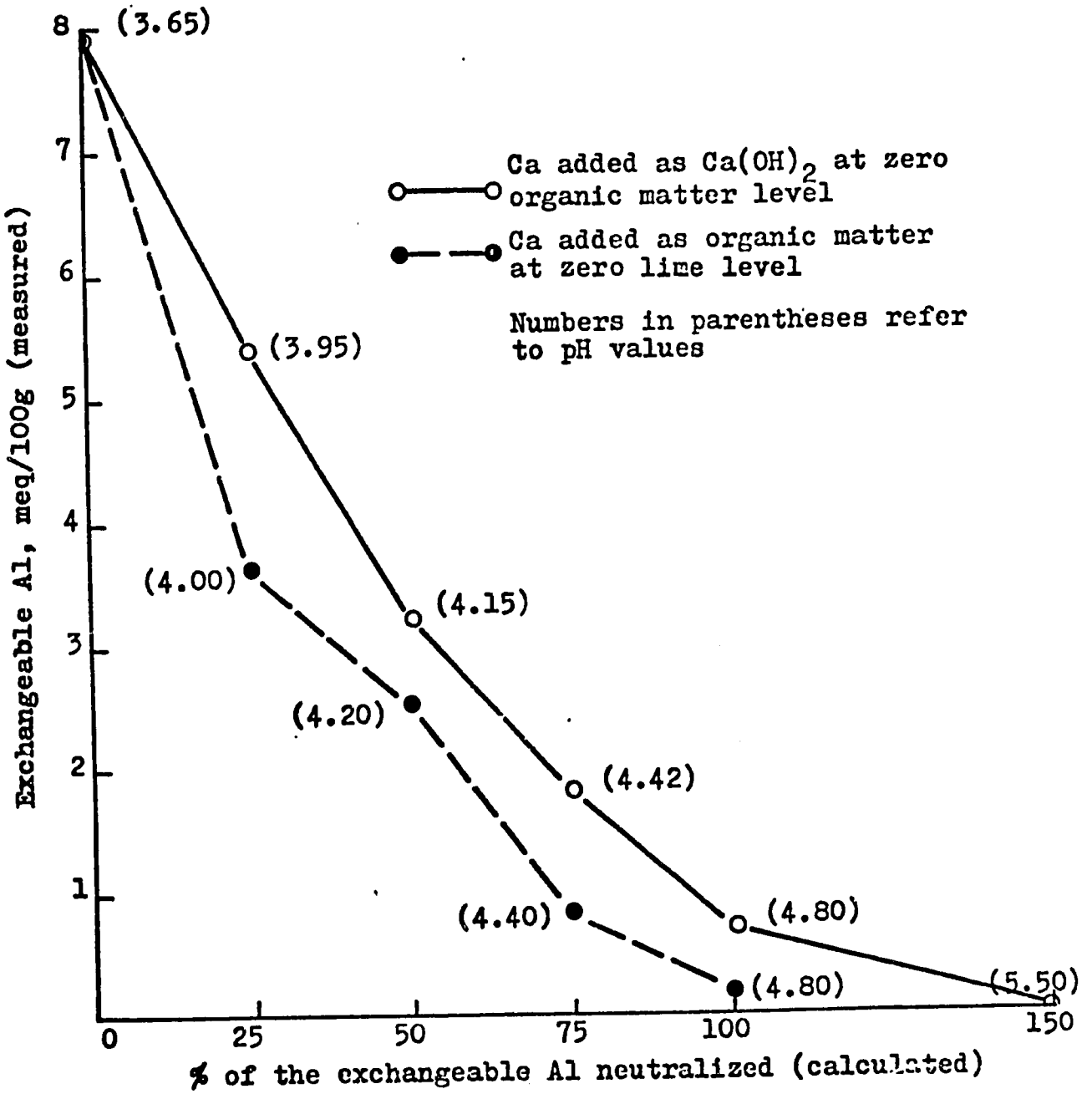

Figure 1. The effect of lime and organic matter applications on exchangeable Al for the Humatas soil.

chart connects points plotted from data for organic matter while the solid line is for $Ca(OH)_2$. The vertical axis represents measured exchangeable Al and the horizontal axis the % of Al that would be neutralized by the Ca that in the one case is added as $Ca(OH)_2$ and the other as organic matter. The fact that the dotted line lies below the solid line reveals that organic matter reduces exchangeable Al more than its Ca content alone would make possible. The greatest difference between organic matter and $Ca(OH)_2$ was at the level of Ca equivalent to 25% of the exchangeable Al with a pH about 4.0, where organic matter neutralized approximately 55% of the exchangeable Al compared with 32% for $Ca(OH)_2$. The reduction of the exchangeable Al with increments of Ca equivalent to 100% of the exchangeable Al at a pH 4.80 was 92% when $Ca(OH)_2$ was the source of Ca and 98% when organic matter was the source. The fact that the organic matter is more effective than lime in neutralizing exchangeable Al, suggests that there are some additional factors in the organic matter, besides the supply of Ca, which cause this effect. One of the reasons may be the supply of Mg. The Mg content of the organic matter was approximately 0.4% (Table 2) which means that for each addition to the soil of 2% organic matter the Mg supplied was 0.7 meq/100g of soil.

The average values for pH, exchangeable Al, Ca, Mg, K, and Mn for all the treatments are presented in Table 4. It is noted from Table 4 that for each increment of Ca added,

Table 4. The influence of lime and organic matter applications on soil pH and exchangeable cations of Humatas soil

Treatment				Measured exchangeable ions				
No.	Organic matter	Calculated Al neutralized with lime	Soil pH	Al	Ca	Mg	K	Mn
	%	%		meq/100g				ppm
1	0	0	3.65	8.00	1.28	0.54	0.53	4
2	0	25	3.95	5.42	3.18	0.47	0.54	0
3	0	50	4.15	3.19	5.00	0.40	0.59	0
4	0	75	4.42	1.75	6.75	0.33	0.59	0
5	0	100	4.80	0.67	8.68	0.32	0.47	0
6	0	150	5.50	0.00	12.10	0.28	0.48	0
7	2	0	4.00	3.61	3.24	1.12	0.56	8
8	2	25	4.10	2.36	5.22	1.02	0.64	4
9	2	50	4.30	1.67	7.23	0.93	0.46	0
10	2	75	4.55	0.53	8.75	0.85	0.37	0
11	2	100	5.00	0.00	10.48	0.80	0.37	0
12	2	150	5.60	0.00	13.78	0.74	0.45	0
13	4	0	4.20	2.57	5.26	1.68	0.67	8
14	4	25	4.40	1.50	7.20	1.44	0.46	8
15	4	50	4.60	0.33	9.20	1.36	0.40	8
16	4	75	4.90	0.17	10.95	0.93	0.38	4
17	4	100	5.20	0.00	12.38	0.82	0.40	0
18	4	150	5.85	0.00	14.83	0.77	0.48	0
19	6	0	4.40	0.83	7.20	2.03	0.51	20
20	6	25	4.60	0.17	9.25	1.67	0.46	14
21	6	50	4.90	0.00	10.55	1.38	0.49	0
22	6	75	5.20	0.00	12.25	1.31	0.51	0
23	6	100	5.55	0.00	13.43	1.21	0.59	0
24	6	150	6.10	0.00	15.28	1.04	0.53	0
25	8	0	4.80	0.17	9.20	2.08	0.54	25
26	8	25	5.10	0.00	10.30	2.18	0.63	14
27	8	50	5.25	0.00	11.88	1.68	0.67	8
28	8	75	5.50	0.00	12.88	1.59	0.67	0
29	8	100	5.90	0.00	14.18	1.42	0.72	0
30	8	150	6.40	0.00	16.00	1.40	0.72	0

either from organic matter or $Ca(OH)_2$ the exchangeable Al decreased. The addi ·.on of Ca from either source theorcti-cally equivalent to 100% of the exchangeable Al reduced the actual Al concentration in the soil by 92% or more. In most cases, when the total Ca supplied to the soil from either source was calculated to be greater than 100% of the exchangeable Al, the Al was reduced to zero.

When increments of lime or organic matter were added to the soil the pH increased and when the exchangeable Al was just reduced to zero by the addition of $Ca(OH)_2$ at the various organic matter levels the pH was in the close neighborhood of 4.90 to 5.00 (Table 4).

Increasing lime or organic matter either alone or combined, the exchangeable Ca increased. The measured exchangeable Ca increased in an amount approximately equal to the calculated amount applied either as lime at the zero level of organic matter, or as organic matter at the zero level of lime. This indicates that reaction of lime and organic matter with the soil was complete. The exchangeable Ca values ranged from 1.28 to 16 meq/100g of soil.

At zero lime and no organic matter application the exchangeable Mg was 0.54 meq/100g of soil. By increments of 2, 4, and 6% organic matter the exchangeable Mg was increased to 1.12, 1.68, and 2.03 meq/100g of soil,respectively. At the level of 8% organic matter the exchangeable

Mg did not increase and it was almost the same as for the level of 6% organic matter.

When increments of lime were combined with the addition of any level of organic matter, the lime caused a decrease in exchangeable Mg. This may be due to change in the Ca-Mg relationship in the soil.

In general, for some unknown reason, the exchangeable K changed very little when increments of lime and organic matter were added either alone or in combination.

The exchangeable Mn in the soil was very low. Additions of 2, 4, 6, and 8% organic matter to the soil gave corresponding levels of 4, 8, 8, 20, and 25 ppm of exchangeable Mn, respectively. Addition of low rates of lime with and without organic matter caused the exchangeable Mn to decrease. At high rates of lime the exchangeable Mn was reduced to zero.

The Effect of Lime and Organic Matter Applications on the Chemical Composition of the Soil Solution

Several factors influence the amount of Al in the soil solution, such as the pH of the soil, the Al saturation of the effective exchange capacity, the organic matter content of the soil, and the salt concentration of the system (Evans and Kamprath, 1968; Kamprath, 1971). Figure 2 shows the effect of lime and organic matter applications on Al concentration in solution at different rates of Ca and at different pH values. The data presented in

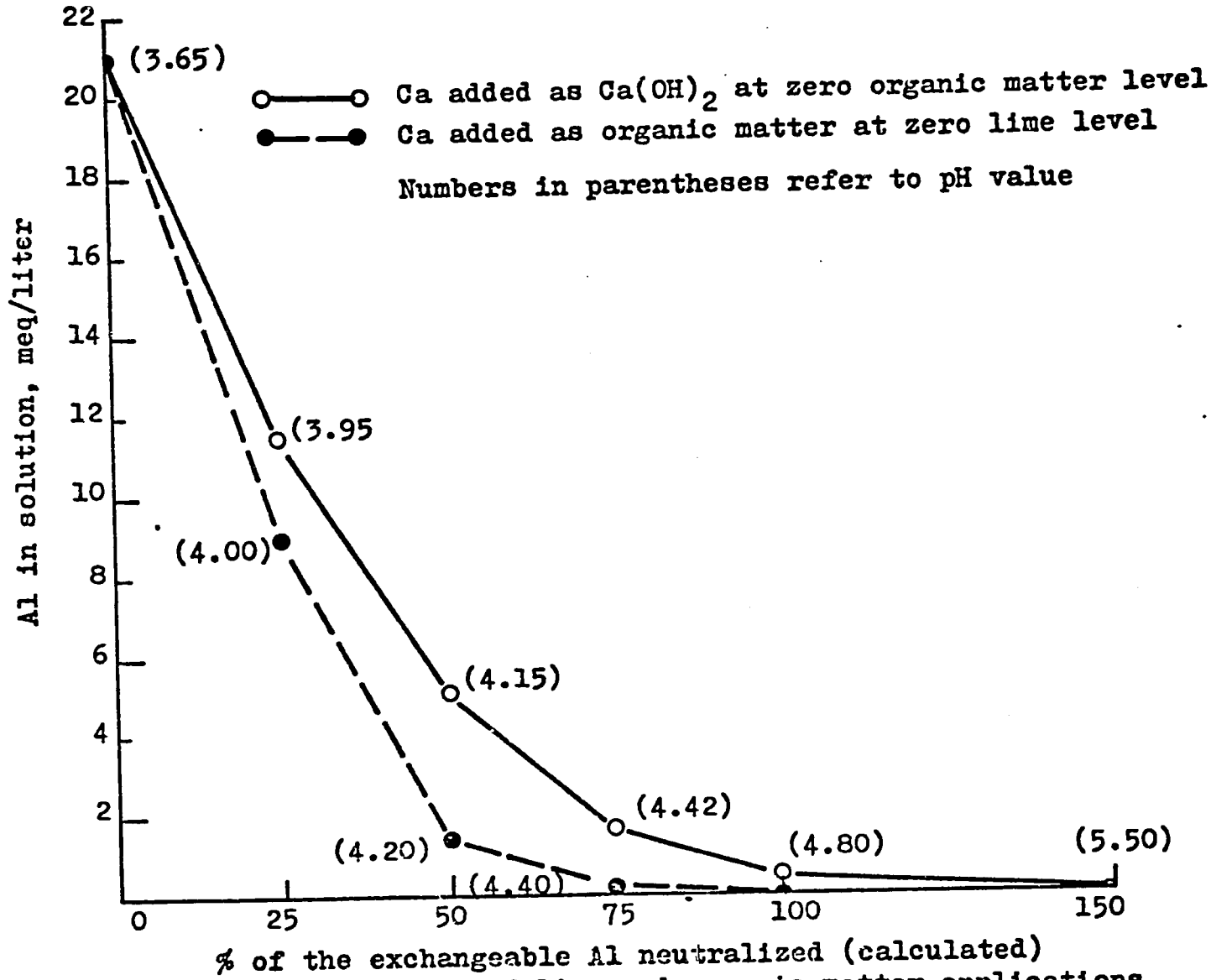

Figure 2. The effect of lime and organic matter applications on Al in solution for the Humatas soil

this figure follows the same general tendency that was observed for Figure 1, namely, increments of lime or organic matter caused a decrease in soil solution Al and an increase in soil pH. Again the organic matter was more effective in reducing Al in solution than $Ca(OH)_2$ alone, although the effect in pH was about the same. The first increase of lime or organic matter caused the greatest reduction of the Al in solution. About 55 and 67% of the Al in solution was neutralized by $Ca(OH)_2$ and organic matter, respectively, with this first increment, at pH values approximately the same. Additional increments of lime or organic matter were less effective in reducing Al in solution. Additions of Ca either from $Ca(OH)_2$ or organic matter equivalent to 100% of the exchangeable Al, reduced the Al in solution by 98 and 100%, respectively, and the resulting pH was 4.80 in both cases.

The differences between organic matter and $Ca(OH)_2$ in neutralizing Al could be very important for plant growth. Cotton roots died when the concentration of Al in the soil solution was 1 ppm and at 0.5 ppm the growth of roots was decreased and their appearance was abnormal (Rios and Pearson, 1964). Ragland and Coleman (1959) found that Al in soil solution as low as 1 ppm is toxic to sorghum roots.

Two significant features of the two curves in Figure 2 are: 1) the rapidity at which Al in soil solution is decreased by small increments of either lime or organic matter, and 2) they differ widely in the middle part of the range, but essentially come together at both ends.

The average values for Al, Ca, Mg, K, and Mn in the soil solution for all treatments are presented in Table 5. It can be observed from this table that increasing lime or organic matter either alone or combined to a level of Ca enough to neutralize 100% of the exchangeable Al, decreased the soil solution Al essentially to zero.

The Ca in the soil solution increased with each increment of lime at any rate of organic matter. The increase of Ca in solution with lime at the rates of 0 and 2% organic matter was greater than at the rates of 4, 6, and 8% organic matter. Additions of 2, 4, and 6% levels of organic matter to the soil at zero lime increased the Ca in solution from 11.25 to 20.75, 24.65, and 27.65 meq/liter, respectively. At the level of 8% organic matter without lime the Ca in solution decreased as compared with the level of 6% organic matter.

The reduction of Ca in solution at the highest rate of organic matter and the fact that lime was less effective in increasing Ca in solution at the rates of 4, 6, and 8% organic matter may suggest that organic matter increased the effective cation exchange capacity of the soil, thus more cations could be adsorbed and less Ca came to the soil solution.

Considering the relationship between Al and Ca in the soil solution, Turner and Clark (1965) and Turner (1965) found that the ratio $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ in solution is a simple function

Table 5. The influence of lime and organic matter applications on the chemical composition of the soil solution of Humatas soil

Treatment				Measured soil solution ions				
No.	Organic matter	Calculated Al neutralized with lime	Soil pH	Al	Ca	Mg	K	Mn
	%	%		meq/liter				ppm
1	0	0	3.65	21.11	11.25	5.40	3.05	0.88
2	0	25	3.95	9.44	21.65	4.60	2.36	0.85
3	0	50	4.15	5.00	28.75	3.89	1.97	0.57
4	0	75	4.42	1.56	33.25	3.65	1.76	0.48
5	0	100	4.80	0.36	41.50	3.38	1.65	0.43
6	0	150	5.50	0.00	55.15	3.20	1.54	0.29
7	2	0	4.00	7.06	20.75	6.37	2.47	2.15
8	2	25	4.10	1.94	27.00	5.94	2.24	1.19
9	2	50	4.30	1.00	31.25	5.72	2.03	1.10
10	2	75	4.55	0.01	37.00	5.47	1.92	0.67
11	2	100	5.00	0.00	45.00	5.24	1.81	0.57
12	2	150	5.60	0.00	59.75	4.33	1.71	0.00
13	4	0	4.20	1.39	24.65	8.23	2.56	1.65
14	4	25	4.40	0.90	29.75	7.79	2.36	1.43
15	4	50	4.60	0.03	34.50	6.58	2.19	1.25
16	4	75	4.90	0.01	41.75	6.49	2.09	1.03
17	4	100	5.20	0.00	47.15	5.89	1.97	0.32
18	4	150	5.85	0.00	56.75	5.41	1.81	0.00
19	6	0	4.40	0.15	27.65	9.07	2.87	1.65
20	6	25	4.60	0.00	30.75	6.70	2.47	1.38
21	6	50	4.90	0.00	33.75	6.53	2.36	1.07
22	6	75	5.20	0.00	38.15	5.93	2.31	0.95
23	6	100	5.55	0.00	41.75	5.77	2.09	0.00
24	6	150	6.10	0.00	52.25	5.70	1.97	0.00
25	8	0	4.80	0.00	25.50	8.10	2.47	1.50
26	8	25	5.10	0.00	28.15	7.51	2.31	0.82
27	8	50	5.25	0.00	33.50	7.06	2.14	0.54
28	8	75	5.50	0.00	37.05	6.39	1.92	0.34
29	8	100	5.90	0.00	40.50	5.72	1.81	0.00
30	8	150	6.40	0.00	45.90	4.36	1.71	0.00

of the quantities of the respective ions in the exchangeable form, and that this relationship is true for a wide range of acid soils. In many soils of the humid tropics Al and Ca are the predominant cations in the soil solution. Therefore the relationship between the solution and exchangeable Al and Ca should be a useful expression for use in order to explain the results of this study in a general way. The relationship between the ratios of Al and Ca in solution and ratios of exchangeable Al and Ca for all treatments is given in Figure 3. The data presented in this figure tend to indicate that the most important effect of the organic matter additions was the release of Ca which neutralized the exchangeable Al in the soil. Charts 1 and 2 indicated, however, that organic matter reduced Al more than could be expected on the basis of its Ca content alone. Thus, organic matter seems to have at least some effect beyond the release of Ca (possibly the release of Mg) in spite of the fact that this is not clearly apparent in Figure 3.

Returning again to Table 5, it is noted that soil solution Mg, K, and Mn were decreased by each increment of lime at any rate of organic matter. These results were similar to those found by Evans (1968).

Organic matter additions at the zero lime level increased Mg in the soil solution except at the rate of 8% organic matter. In contrast, the soil solution K decreased with the first increment of organic matter at 0 lime level from 3.05 to 2.47 meq/liter. With further increments of

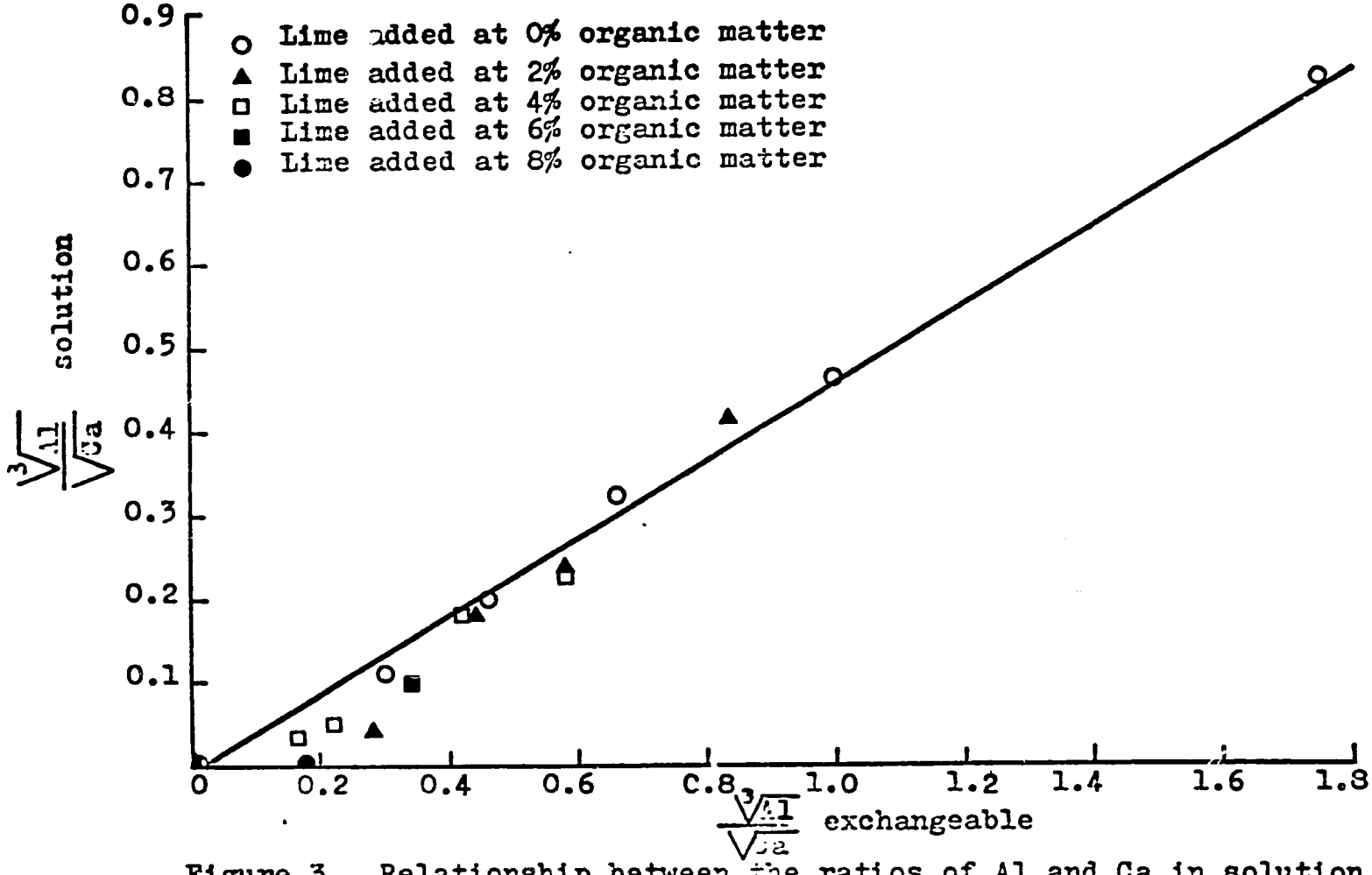

Figure 3. Relationship between the ratios of Al and Ca in solution and ratios of exchangeable Al and Ca in a Humatas soil after lime and organic matter application

organic matter the K in solution remained approximately the same as it was at the first increment.

Manganese in solution increased with the first increment of organic matter at the zero lime level. The concentration increased from 0.88 ppm with 0% organic matter to 2.15 ppm at 2% organic matter. The addition of 4% organic matter without lime decreased the concentration of Mn in solution as compared with the level of 2% organic matter. Additions of 6 and 8% organic matter did not change significantly the concentration of Mn in solution as compared with 4% of organic matter level. Above a pH 5.55 Mn in solution was reduced to zero.

It is believed that the decrease in concentration of K, Mg, and Mn in soil solution at the higher rates of organic matter possibly was due to an increase in the effective cation exchange capacity of the soil by lime (Kamprath, 1970a) and because of the probable high retentive capacity for cations of the organic matter. This could then permit more cations to be adsorbed leaving a lower concentration of cations in the soil solution.

GREENHOUSE STUDY

The Effect of Lime and Organic Matter Applications on Dry Matter Production of Sorghum

Sorghum dry matter yields for all treatments are given in Table 6. The statistical analysis for sorghum yields indicated significant differences for lime, for organic

Table 6. Average dry matter yields of sorghum for different rates of lime and organic matter applied to a Humatas soil

Treatment			
Organic matter	Calculated Al neutralized with lime	Dry matter yields	Statistical* significance
%	%	g/pot	
0	0	0.06	
0	25	0.25	
0	50	0.29	
2	0	0.40	
0	75	0.69	
2	25	0.71	
4	0	0.94	
8	150	1.87	
2	50	1.89	
8	100	2.50	
0	150	2.57	
8	75	3.31	
6	150	3.34	
6	100	3.59	
8	25	3.60	
0	100	3.70	
8	50	3.82	
4	25	4.05	
8	0	4.22	
6	75	4.54	
6	0	4.78	
4	150	4.84	
4	100	4.87	
6	50	4.98	
2	150	5.23	
4	75	5.33	
6	25	5.73	
2	75	5.79	
2	100	5.90	
4	50	5.96	

* Each line identifies a group of yields that are not significantly different from each other at the 1% level.

matter, and for the lime and organic matter interaction (Table 3 in the Appendix). The T test was used to detect significant differences among the ranked treatment means. In order to show the comparisons among treatments, yields were ranked from the lowest to the highest yield. The treatment means connected by the same line are not different at the 1% level of significance.

The effect of different rates of lime on yields of sorghum at different rates of organic matter applications is shown in Figure 4. This figure shows clearly that yield responded to a function of the combination of the lime and organic matter applied (but not necessarily a simple sum of the two). When organic matter was low, yield continued to respond to lime up to a high level of use (though not the highest level of use). When organic matter was high no yield increases could be gotten by adding lime. Also, at high organic matter levels lime clearly acted as a depressant. At 8% organic matter, yields were highest with no lime added. At each successively lower organic matter level, yields were increased by successively higher lime applications, though at no level of organic matter did one of the higher lime applications produce maximum yield. The relationships shown in Figure 4 forms such a consistent overall pattern that the results of statistical tests of significance add little that is meaningful.

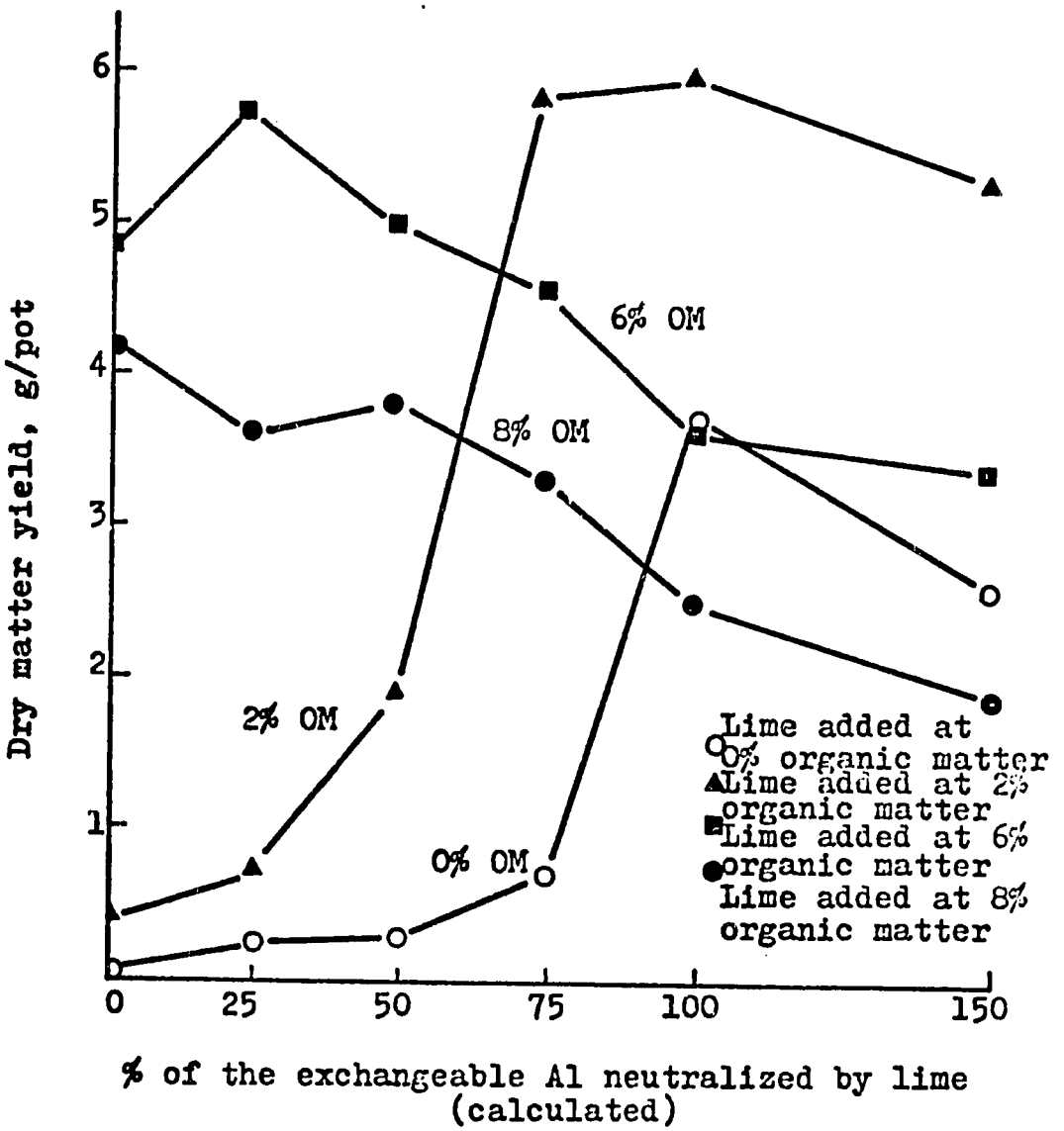

Figure 4. The effect of different rates of lime on dry matter yields of sorghum at different rates of organic matter applications

Figure 4A pictures an almost equally consistent overall pattern and further supports the idea that yield is a function of a combination of the lime and organic matter applied. In this instance yields responded positively to the first addition of organic matter at all levels of lime application, but further response to organic matter is very noticeably a function of the lime level.

Attempts were made to fit the data relating yield to organic matter and lime applications in a joint functional regression plane but these were not successful.

Plant Growth as Related to Soil Acidity Factors

a). Plant growth as related to Al. Sorghum growth responses to liming and organic matter were generally a result of neutralization of toxic levels of Al.

Some of the soil chemical properties at which maximum yields of sorghum were obtained are presented in Table 7. In general, when Ca was applied to the soil either as $Ca(OH)_2$ or organic matter at a level equivalent to the total exchangeable Al, maximum yields were obtained.

Coleman et al. (1959), suggested that a realistic value of the effective cation exchange capacity of a soil is obtained by using the sum of the exchangeable Al, Ca, and Mg replaced by an unbuffered neutral salt such as KCl. The % Al saturation can be obtained by the equation, % Al

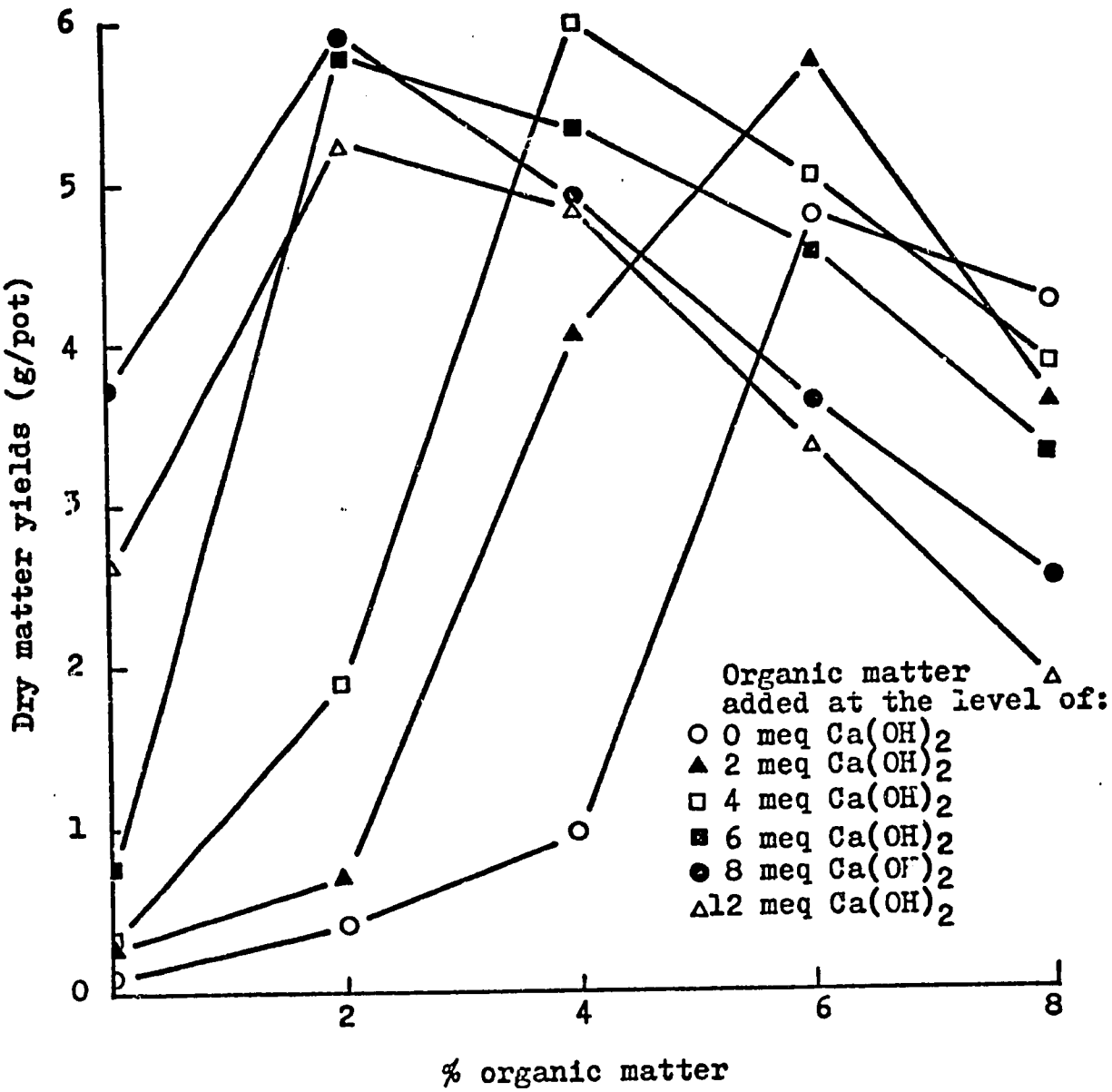

Figure 4A. The effect of different rates of organic matter on dry matter yields of sorghum at different rates of lime

Table 7. Lime levels at which maximum growth of sorghum was obtained at different rates of organic matter, together with some associated soil properties

Treatment							
Organic matter	Calculated Al neutralized with lime	Soil pH	% Al Saturat.	Exch. Al	Solution Al	Exch. Ca	Solution Ca
%	%		%	meq/100g	meq/lit	meq/100g	meq/lit
0	100	4.80	6.6	0.67	0.36	8.68	41.50
2	75	4.55	5.0	0.53	0.01	8.75	37.00
4	50	4.60	2.9	0.33	0.03	9.20	34.50
6	25	4.60	1.4	0.17	0.00	9.25	30.75
8	0	4.80	1.4	0.17	0.00	9.20	25.50

saturation = $\frac{Al}{Al + Ca + Mg + K}$ x 100 with the amounts of the cations expressed as meq/100g. Abruña et al. (1970) and Evans (1968) have demonstrated that the % Al saturation is useful in relating plant response to soil acidity factors. Table 7 shows that maximum yields of sorghum at any given rate of organic matter was obtained only when the Al saturation was less than 7%. These results are quite similar to those obtained by Abruña et al. (1970) for tobacco grown in the same soil series. The soil solution Al was below 0.68 meq/liter at the point where maximum yields were obtained. The results found by Evans (1968) for corn differ from these in that the maximum yields were obtained when the Al saturation was 70% and Al in solution was less than 0.40 meq/liter.

The growth of sorghum was drastically reduced when the Al saturation of the effective cation exchange capacity was 19% (1.75 meq/100g) or more and the soil solution Al was 1.39 meq/liter or more. This result differs from that found by Ragland and Coleman (1959) in which Al in solution as low as 0.11 meq/liter was toxic to sorghum roots. The yield in the check was almost zero when the Al saturation reached a value of 77% (8 meq/100g) and the soil solution Al was 21 meq/liter. There was no yield increase in sorghum in this experiment until the Al saturation was 16% (1.67 meq/100g) or less and Al in the solution was 1.0 meq/liter or less.

The range of pH at which maximum yields occurred at any given rate of organic matter was quite narrow being

from 4.55 to 4.80. This range of pH corresponds to the treatments in which the exchangeable Al was reduced by 92% or more from the original amount contained in the check. Yields of sorghum increased from 0.06g/pot in the check at a pH value of 3.65 to a maximum of 5.96g/pot at a pH value of 4.60. At any given rate of organic matter the yields decreased when the pH was increased above 5.0. It is believed that this decrease in yield when the pH was above 5.0 might be due to an excess of Ca or any other factor such as micronutrient deficiency that was not measured in this study. The effect of the exchangeable Ca on yields will be discussed later.

Calcium in solution was 41.5 meq/liter or less at the point where maximum yields were obtained for all rates of organic matter, and the Ca in solution decreased as the organic matter applications increased. Probably, the decrease of Ca in solution observed with the increase of organic matter was due to an increase in the effective cation exchange capacity of the soil by the organic matter addition as was discussed previously. The Ca concentration in the soil solution for the check was 11.25 meq/liter which is far above the level of 1.5 meq/liter required to be adequate for corn growth (Barber et al., 1963). The poor growth of the plants on the check was therefore not due to lack of Ca but rather to the detrimental effect of Al. Figure 5 shows the difference between lime and organic matter applications in neutralizing Al toxicity as related to dry

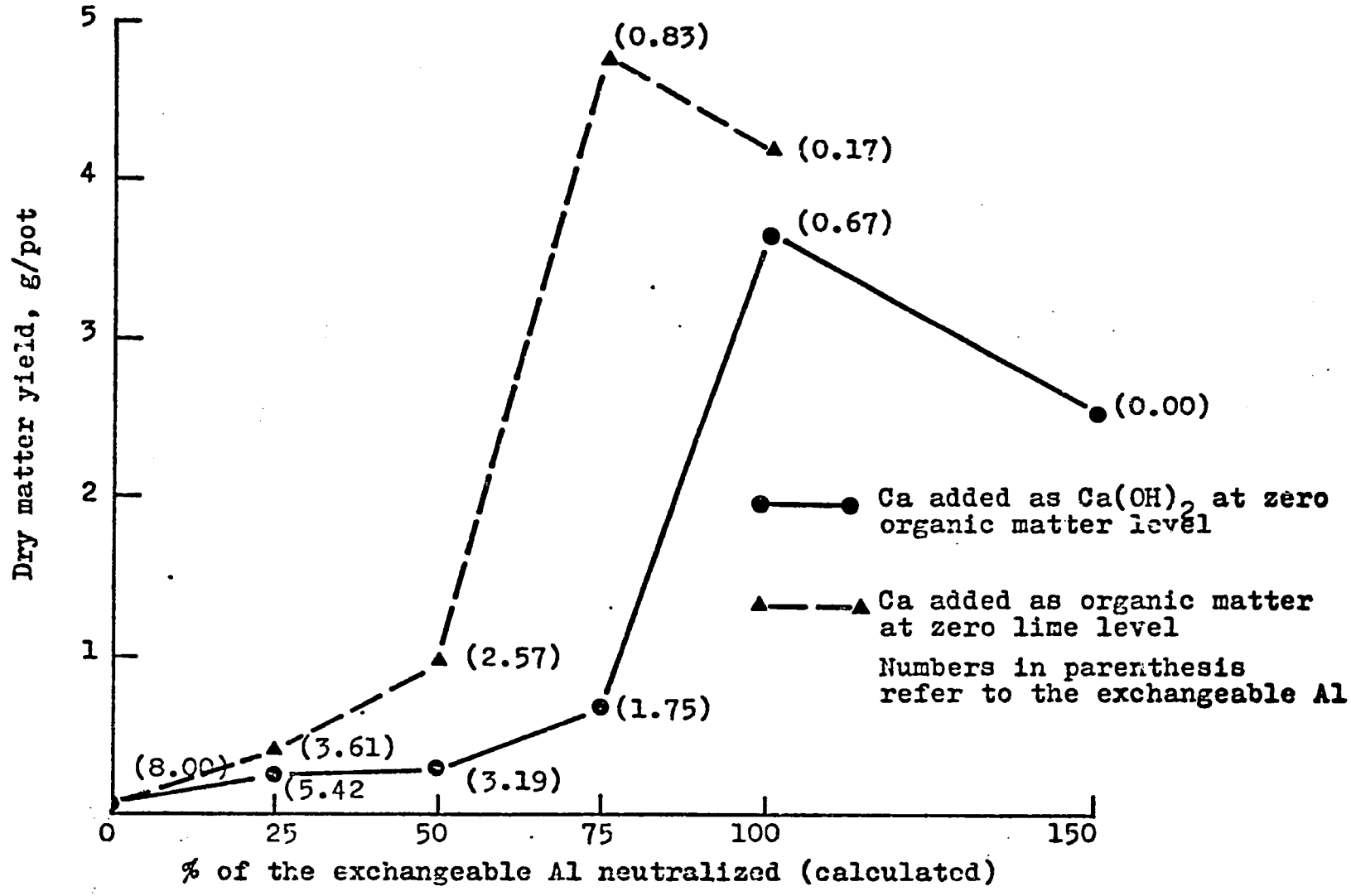

Figure 5. The effect of lime and organic matter applications in neutralizing Al toxicity as related to dry matter production of sorghum

matter production of sorghum. It was coincidental that based on the analysis of the organic matter for each addition of 2% organic matter to the soil the amount of Ca supplied was about equivalent to 25% of the exchangeable Al. In this way additions of 2, 4, 6, and 8% organic matter is approximately equivalent to 25, 50, 75, and 100% of the exchangeable Al. Increments of $Ca(OH)_2$ added to the soil were equivalent to 0, 25, 50, 75, 100 and 150% of the exchangeable Al.

It can be noted from Figure 5 that with the same amounts of Ca applied to the soil, either as organic matter or $Ca(OH)_2$, the yields were higher and the exchangeable Al was lower when organic matter was the source of Ca. As previously emphasized, this suggests that there was some factor besides the supply of Ca that caused the better efficiency of the organic matter.

There was no significant yield response to lime or organic matter until the quantity of Ca supplied reached the third increment (equivalent to 50% of the exchangeable Al). At the addition of the fourth increment of Ca (equivalent to 75% of the exchangeable Al) the yield was much greater when organic matter was the source of Ca than when the source was $Ca(OH)_2$. There was no significant yield response with the addition of the fourth increment of Ca by $Ca(OH)_2$. Yields of sorghum with organic matter as a source of Ca ranged from 0.94g/pot at the third increment of Ca to 4.78g/pot at the fourth increment of Ca. The yields of sorghum with $Ca(OH)_2$ as a source of Ca were 0.29 to 0.69g/pot at the third and fourth increment of Ca, respectively. The difference in yield between

organic matter and $Ca(OH)_2$ at the fourth increment of Ca was statistically significant at the 1% level. Probably, the difference in yield observed at the fourth increment of Ca was due to the fact that exchangeable Al in the soil was 1.75 meq/100g with the $Ca(OH)_2$ application and only 0.83 meq/100g with organic matter application. It must be noted that in this experiment the yield of sorghum was severely reduced when the concentration of the exchangeable Al in the soil was 1.75 meq/100g or more (19% Al saturation).

At the fifth increment of Ca (equivalent to 100% of the exchangeable Al) the yield with $Ca(OH)_2$ as a source of Ca was 3.70g/pot. This yield was significantly higher at the 1% level as compared with the yield with $Ca(OH)_2$ at the fourth increment of Ca. At that level of Ca exchangeable Al was reduced to 0.67 meq/100g which was not detrimental to plant growth. The yield was decreased when the Ca supplied by organic matter was equivalent to 100% of the exchangeable Al. This addition of organic matter reduced the exchangeable Al to 0.17 meq/100g. Probably, the decrease in yield with organic matter at the fifth increment of Ca was due to a deficiency in N observed in all treatments with 8% organic matter which will be discussed later. Yields obtained when Ca was supplied by either $Ca(OH)_2$ or organic matter at the fifth increment of Ca were statistically similar. Maximum yield obtained when organic matter was the source of Ca was statistically

higher than the maximum yield obtained when $Ca(OH)_2$ was the source.

Comparison between organic matter and $Ca(OH)_2$ at the level of Ca equivalent to 150% of the exchangeable Al was not possible because there was no addition of organic matter which supplied that much Ca.

b) Plant growth as related to the ratio of Al and Ca in solution. The ratio $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ based on the concentration in solution might be a useful expression in relating plant response to soil chemical properties for purposes of this study. Other evidence, Zandstra (1971), indicates that this is useful. Figure 6 shows the relationship between dry matter yields of sorghum and the above ratio of the solution concentration. It can be observed that with the same amount of Ca applied to the soil, either as organic matter or $Ca(OH)_2$, the yields were higher and the Al-Ca ratio lower when organic matter was the source of Ca.

There was no significant yield response to lime or organic matter applications until the ratio $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ in solution was less than 0.20. The ratio with the addition of the fourth increment of Ca as organic matter (6 meq of Ca/100g of soil) and with the fifth increment of Ca as $Ca(OH)_2$ (8 meq of Ca/100g of soil) were almost the same (0.10 and 0.11) and corresponded to the maximum yields obtained with organic matter and $Ca(OH)_2$. Although the ratio with the fifth increment of $Ca(OH)_2$ and fourth increment of organic matter

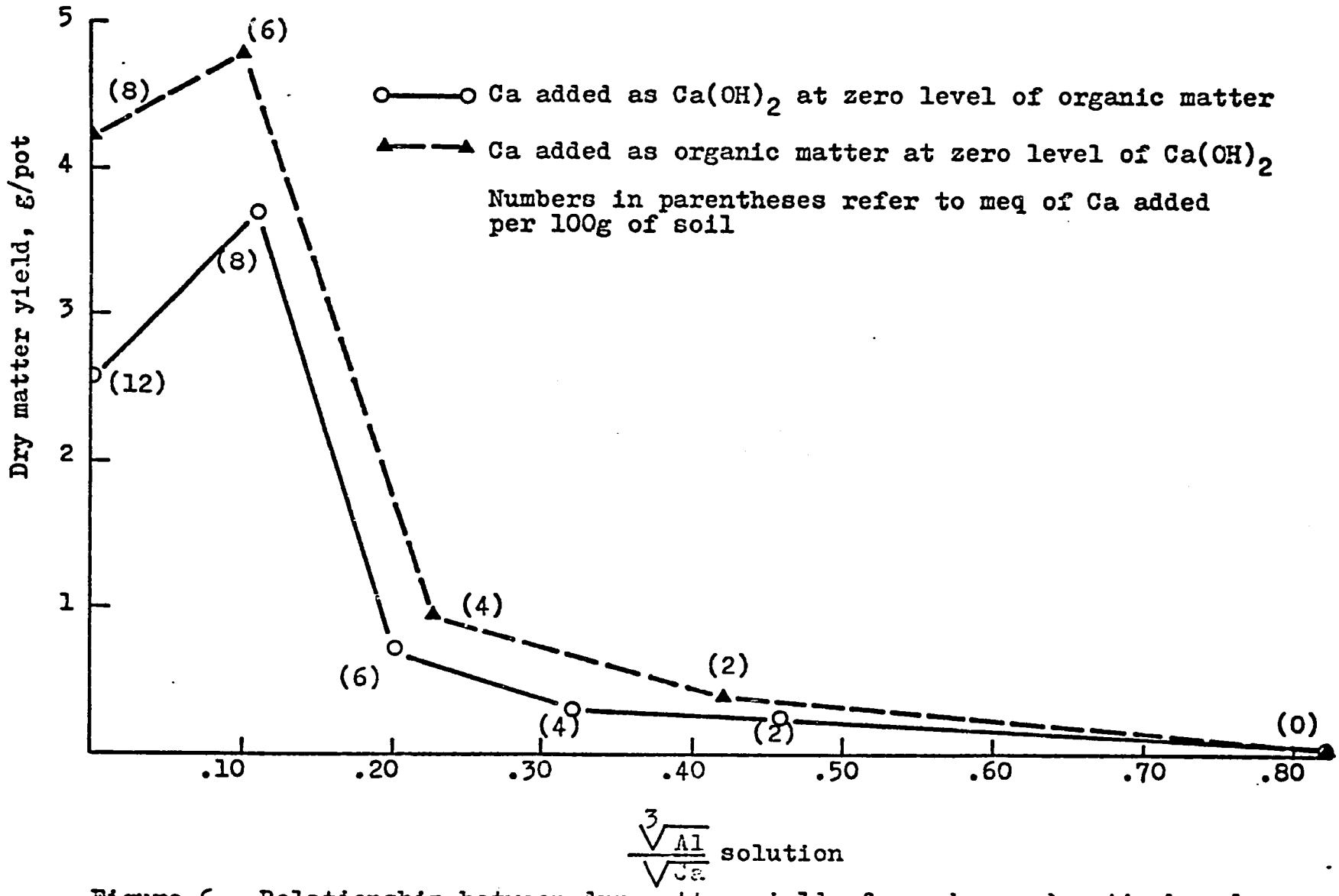

Figure 6. Relationship between dry matter yield of sorghum and ratio based on concentrations of Al and Ca in the soil solution

were almost the same, the maximum yield obtained with organic matter at that ratio was significantly higher than the maximum yield obtained with $Ca(OH)_2$. These findings suggest that high organic matter contents, fairly common in tropical soils, may be responsible for the relatively high yields in acid soils. It also points to the possibility of using less liming materials if adequately high levels of organic matter are maintained in these soils.

Until more information is known about the complexity of organic matter and its relationships with Al, the implications made on these observations can only be speculative in nature.

c) Plant growth as related to exchangeable Ca. Figure 7 shows the relationship between dry matter production of sorghum and exchangeable Ca at different rates of organic matter applications. The yields were better related with the total exchangeable Ca of the soil than with the % Ca saturation. Until the exchangeable Ca was increased to 7.20 meq/100g the differences in yields observed in each curve were due primarily to Al toxicity which was present in different concentrations in each treatment. For example, at the level of 7.20 meq/100g of exchangeable Ca there were differences in yield among treatments with 2, 4, and 6% organic matter. Yield with 2% organic matter was significantly lower than the yield with 4% organic matter, and that at 6% organic matter significantly higher than the yield at 4% organic matter. The exchangeable Al was 1.67, 1.50, and 0.83 meq/100g

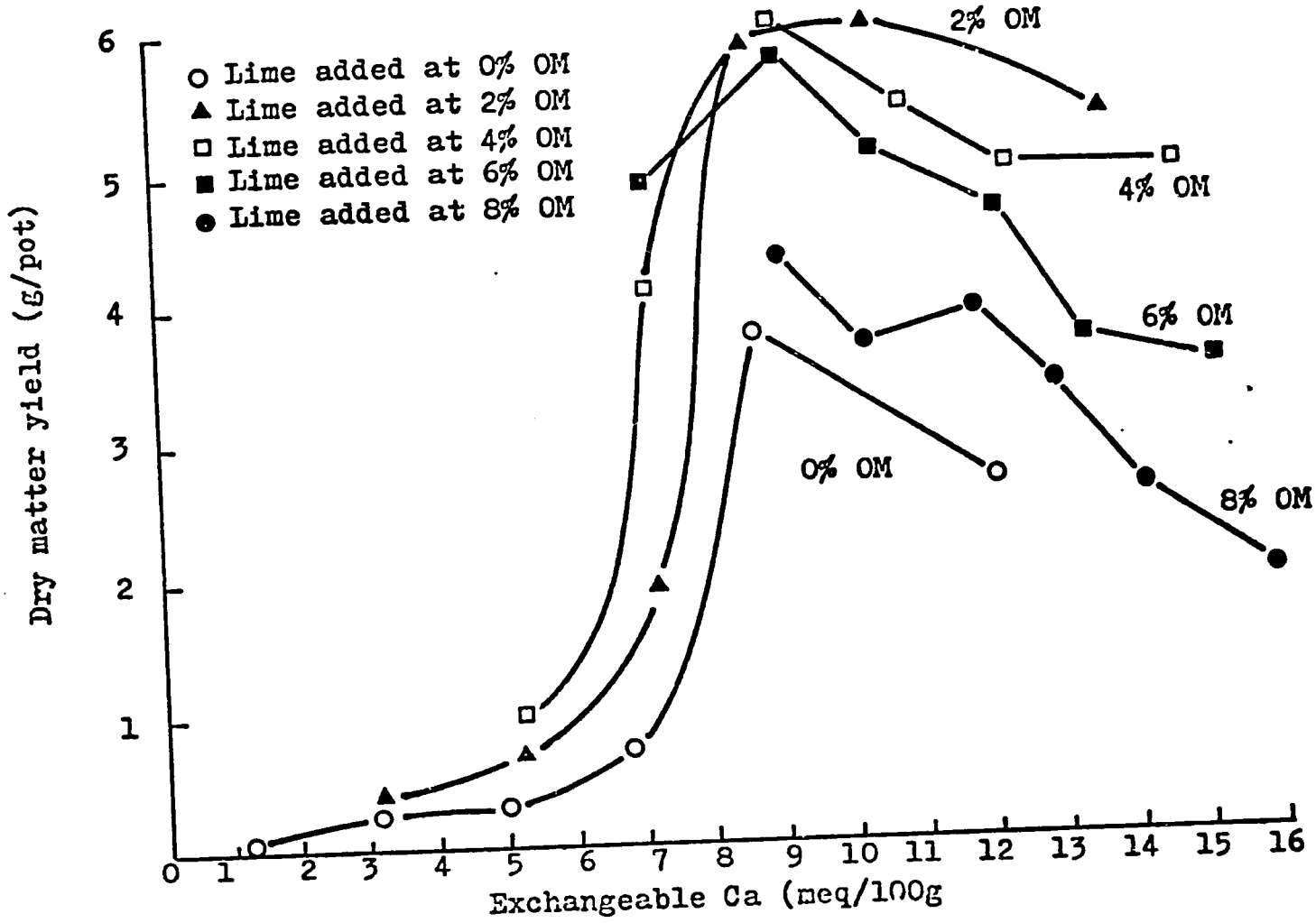

Figure 7. Relationship between exchangeable Ca and dry matter yield of sorghum at different rates of lime and organic matter applications

for the rate of 2, 4, and 6% organic matter, respectively, while the soil solution Al for the same rates of organic matter was 1.00, 0.90, and 0.15 meq/liter.

Maximum yields were obtained for each rate of organic matter when exchangeable Ca was between 8.70 and 9.25 meq/100g which corresponded to additions of Ca to the soil equivalent to 100% of the exchangeable Al. The implications of these findings are that exchangeable Al as measured in this study can be used quite successfully as a basis for applying lime to the Humatas soil.

It is important to note that maximum yields for each level of organic matter were obtained at approximately the same total Ca application. However, the maximum yields were about equal and statistically significantly higher than the maximum yield with zero organic matter application. These differences can not be explained on the basis of Al toxicity because at that level of Ca, toxic levels of Al had already been eliminated. So there was something else in the organic matter which produced better yields than any level of $Ca(OH)_2$ alone. The difference in maximum yields observed between the rates of 8% organic matter and 2, 4, and 6% organic matter additions was due to a deficiency in N observed in all treatments with 8% organic matter which will be discussed in more detail in the next section.

Plant analysis data shows that the N content for maximum yield with 8% organic matter was 0.85%. The N concentration

for maximum yields at 2, 4, and 6% organic matter were 1.79, 1.64, and 1.22%, respectively. The N deficiency was also present in the treatments with 4 and 6% organic matter but was less severe than at the 8% level. Probably, the differences among the curves for levels of exchangeable Ca above 9.25 meq/100g with 2, 4, 6, and 8% organic matter were due to N deficiency which was more severe as the organic matter applications increased.

The decrease in yield observed in each curve at any level of organic matter when the level of exchangeable Ca was greater than 10 meq/100g, probably was due to an excess of Ca which caused some micronutrient deficiency such as Cu or an ionic desequilibrium. Because Cu is strongly complexed by organic matter, the higher the soil organic matter level, the greater the possibility of Cu deficiency (Kamprath and Foy, 1971). According to Berger and Pratt (1963) when Cu is applied to soils, that portion which is not chelated by organic matter is probably precipitated as $Cu(OH)_2$ at soil solution pH values above 4.7.

The Effect of Lime and Organic Matter Applications on N, P, K, Ca, Mg, and Mn Content of Sorghum Plants

Plant analysis for all treatments are presented in Table 8. The N content of sorghum plants decreased with increased organic matter and lime applications. The N content decreased with organic matter additions from 3.21 % N at the level of 2% organic matter to 0.85% N at the rate of 8%

Table 8. The effect of lime and organic matter applications on N, P, K, Ca, Mg, and Mu of sorghum plants

Treatment			Dry weight composition of plants					
No.	Organic matter	Calculated Al neutralized with lime	N*	P	K	Ca	Mg	Mn
	%	%	%					ppm
1	0	0		0.19	2.30	0.62	0.22	80
2	0	25		0.15	2.32	0.69	0.27	32
3	0	50		0.11	2.08	0.90	0.20	48
4	0	75		0.18	2.37	0.87	0.22	39
5	0	100	3.19	0.20	4.10	0.71	0.20	113
6	0	150	3.51	0.20	4.23	0.78	0.24	74
7	2	0		0.12	2.04	0.46	0.21	36
8	2	25		0.19	2.20	0.57	0.18	73
9	2	50	3.21	0.25	3.84	0.83	0.21	158
10	2	75	2.03	0.19	4.26	0.54	0.21	144
11	2	100	1.79	0.16	4.34	0.51	0.21	116
12	2	150	2.25	0.19	4.01	0.63	0.26	44
13	4	0		0.19	2.82	0.68	0.24	258
14	4	25	2.09	0.23	4.50	0.59	0.23	212
15	4	50	1.64	0.14	3.90	0.42	0.17	144
16	4	75	1.49	0.15	4.15	0.47	0.21	118
17	4	100	1.47	0.16	3.81	0.50	0.21	56
18	4	150	1.35	0.14	3.66	0.56	0.20	28
19	6	0	1.31	0.17	4.09	0.45	0.21	205
20	6	25	1.22	0.14	3.29	0.35	0.19	149
21	6	50	1.06	0.15	3.84	0.41	0.18	122
22	6	75	0.90	0.16	3.73	0.42	0.17	108
23	6	100	0.90	0.12	3.58	0.43	0.19	62
24	6	150	0.91	0.12	3.40	0.51	0.19	28
25	8	0	0.85	0.17	3.64	0.39	0.17	180
26	8	25	0.81	0.16	3.61	0.34	0.16	135
27	8	50	0.78	0.15	3.47	0.37	0.17	108
28	8	75	0.79	0.13	3.23	0.40	0.17	99
29	8	100	0.73	0.14	3.62	0.41	0.18	82
30	8	150	0.70	0.14	3.30	0.58	0.17	95

* Data for treatments No. 1, 2, 3, 4, 7, 8, and 13 were not included in this table because of insufficient plant material.

organic matter. According to Miller (1958) the N content in sorghum plants before maturity is considered low if it is below the level of 1.04%. Probably the decrease in N content with additions of organic matter was due to a depletion of the soil N by soil microorganisms which in the presence of organic matter became active and multiplied rapidly. Under these circumstances N was taken up by microorganisms due to the microbial demand for this element to build their tissues.

The N content of sorghum plants also decreased with increased lime applications at each of the organic matter levels. This might be expected because each pot received equal amounts of N. Luxury consumption of N occurred on the lower lime treatments, whereas a dilution effect was observed at the higher lime treatments. This might also indicate that N may have been somewhat more limited on the higher lime treatments than on low lime treatments. These results agree with those found by Vitosh (1968).

The % P in sorghum plants varied considerably among the treatments at different rates of lime and organic matter applications. High levels of lime at higher rates of organic matter decreased slightly the P content in plants as compared with additions of lime at low rates of organic matter. In general, with only two exceptions, the treatments that gave the lowest yields (numbers 1, 2, 4, 8, 13) have higher P contents. This is contrary to the most common results found

in the literature in that Al generally reduces the uptake of P by plants (Munns, 1956b; Wright and Donahue, 1953). However, Randall and Vose (1963) found that higher levels of Al in the soil solution (50 ppm) increased P contents in both roots and tops of 8 week-old ryegrass plants (perennial), but depressed total P uptake by reducing growth. It was concluded that Al binds P within the plant in some way that it can no longer promote plant growth which then depresses total P uptake. These findings could be an explanation of the results found in this study.

The K content in sorghum plants was higher than 2% in all of the treatments and this level is considered high for sorghum plants before maturity (Miller, 1958) indicating that there was no K deficiency. However, the K content in sorghum plants increased as the Al toxicity in the soil decreased. It can be noted from Table 8 that with additions of Ca to the soil, either from organic matter or $Ca(OH)_2$, equivalent to 50% of the exchangeable Al the K content of the plants did not exceed 2.82%. When Ca was added from organic matter or $Ca(OH)_2$ equivalent to at least 75% of the exchangeable Al the K content in the plants increased to at least 3.23%, with the exception of the treatment 4 (0% organic matter--6 meq of lime).

These results agree with those found by Chamura and Hoshi (1960) in which greater Al sensitivity in sorghum (compared with corn) was associated with a greater reduction

in K uptake. The effects of Al on K uptake were greater in young than in old plants. Jacobson et al. (1960) also has found that the absorption of K is enhanced at low pH by Ca. The stimulating effect is present at pH values below 6.5. In contrast, some investigators (DeWard and Sutton, 1960) had associated Al toxicity with reduced uptake of Ca and Mg and increased uptake of K and Al. They suggested that the ratio of K/Ca + Mg in plant tops can be used as index of Al injury.

There was no apparent relationship between Ca content and yield with different rates of lime and organic matter applications. The concentration of Ca in sorghum plants was higher than 0.30% in all of the treatments and this level is considered sufficient for sorghum plants before maturity (Miller, 1958) indicating that there was no apparent Ca deficiency in the plants. Soil solution Ca in the treatments that gave the lowest yield was also higher than that which is required to be adequate for plant growth (Barber et al., 1963). So Ca deficiency, per se, apparently was not a primary growth limiting factor. It can be noted from Table 8 that the Ca content in the check was similar to treatment number 12 which produced some of higher yields and lower than treatment number 15 which produced the highest yield.

There is the possibility that Mo deficiency may have been partly responsible for the poor growth of sorghum in the treatments where the pH was about 4.2 (Davis, 1956;

Kamprath and Foy, 1971). The low yields observed at high levels of lime with higher rates of organic matter probably might be due to some micronutrient deficiency, like Cu as was mentioned previously.

The Mg content in sorghum plants changed very little with lime and organic matter applications. With a few exceptions, Mg contents were not lower than that concentration which is considered to be deficient for sorghum plants before maturity (Miller, 1958). In general there was approximately the same Mg content in plants with the rates of 0, 2, and 4% organic matter at any level of lime. Additions of 6 and 8% organic matter, at any level of lime, decreased slightly the Mg concentrations in plants as compared with the rates of 0, 2, and 4% organic matter at any level of lime. The average Mg content in sorghum plants ranged from 0.22% at the rates of 0, 2, and 4% organic matter to 0.17% at the rate of 8% organic matter. Therefore Mg content was not responsible for the differences in yields observed at different rates of lime and organic matter applications. Apparently Al did not interfere with Mg uptake by sorghum plants in this study.

The Mn content in sorghum plants had great variation at different rates of lime and organic matter applications. For example, the Mn content of plants from the check was greater than that for plants of treatment 12 which gave one of the higher yields and it was lower than the content of

the treatment 15 which gave the highest yield. In general, applications of organic matter at the rates of 4, 6, and 8% increased the Mn content of the plants at the zero level of lime. High levels of lime at any rate of organic matter decreased the Mn content of the plants. This decrease in Mn content probably was due to a decrease of Mn in the soil solution when the pH increased because of Ca applications. The pH at which Mn began to decrease was about 5.2. Mn toxicity or deficiency in plants was not observed in this study. It seemed that Mn had very little influence on the variation of yields observed with applications of different lime and organic matter levels.

In conclusion, it appears that the applications of lime and organic matter to the soil had very little effect on the P, Mg, Ca, and Mn concentrations in the plants, nor on the dry matter yields.

SUMMARY AND CONCLUSIONS

Aluminum toxicity is one of the major factors contributing to poor growth of plants particularly in Ultisols and in some Oxisols. The role that organic matter plays in the immobilization of the active Al in tropical soils has been very little studied. The objectives of this study were the following: a) to determine the effect of variable organic matter increments on the immobilization of active Al in an Ultisol, b) to compare organic matter applications with lime treatments as related to sorghum growth in the greenhouse, and c) to determine the effects of organic matter and liming on the foliar composition of sorghum grown under greenhouse conditions.

A representative Ultisol of Puerto Rico, Humatas clay, similar to soils from large areas of other tropical countries, was used for this study. A factorial pot experiment with 6 levels of $Ca(OH)_2$ and 5 levels of organic matter was used. The levels of $Ca(OH)_2$ were calculated to neutralize 0, 25, 50, 75, 100, and 150% of the exchangeable Al as measured by KCl extraction. Organic matter was applied at the levels of 0, 2, 4, 6, and 8% by weight. Partially decomposed coffee leaves were used as a source of organic matter.

Organic matter was much more effective in neutralizing exchangeable and soil solution Al than $Ca(OH)_2$ at a given rate of Ca applied to the soil and at approximately the same pH. Additions of Ca from lime or organic matter equivalent to 100% of the exchangeable Al reduced the exchangeable and soil solution Al by at least 92 and 98%, respectively. When the total Ca supply to the soil was greater than 100% of the exchangeable Al the concentration of the exchangeable and soil solution Al was reduced to zero. The pH at which the exchangeable Al was reduced to zero ranged from 4.90 to 5.00. Exchangeable Ca increased in an amount approximately equal to the amount applied either as lime or organic matter.

Soil solution cations were determined for all treatments. Increments of Ca from lime or organic matter equivalent to 25% of the exchangeable Al caused a decrease in Al in solution by 55% or more. Lime and organic matter additions increased the Ca in the soil solution, but at the rate of 8% organic matter the Ca in solution was lower than at the 6% organic matter level.

The relationship between the ratio of $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ in solution and the ratio $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ exchangeable, both based upon the measured concentrations of the ions tends to indicate that the most important effect of the organic matter additions was the release of Ca which neutralized the exchangeable Al in the soil. However, the Mg in the organic matter may also have some effect.

In the greenhouse experiment, maximum yield was obtained when additions of Ca from organic matter or $Ca(OH)_2$ were equivalent to 100% of the exchangeable Al. The Al saturation was less than 7% and the soil solution Al less than 0.68 meq/liter when maximum yields were obtained. It was concluded that exchangeable Al as measured in this study was suitable for determining the lime requirements of Humatas soil. The yield was drastically reduced when the Al saturation was 19% (1.75 meq/100g) or more and the soil solution Al was 1.39 meq/liter or more. The range of pH at which maximum yields were obtained at any given rate of organic matter was between 4.55 to 4.80 which corresponded to the treatments in which the exchangeable Al was reduced by at least 92% from the original amounts in the check. The exchangeable Ca at which maximum yields occurred was between 8.70 and 9.25 meq/100g of soil and corresponded to additions of Ca, from organic matter or $Ca(OH)_2$, equivalent to 100% of the exchangeable Al. Sorghum yields were reduced whenever the exchangeable Ca exceeded 10 meq/100g which corresponded to additions of Ca as $Ca(OH)_2$ or organic matter equivalent to at least 125% of the exchangeable Al. Ca in solution was 42 meq/liter or less at the point where maximum yields were obtained. There was no concentration of Ca in soil solution low enough to limit growth because of Ca deficiency. Plant responses to lime and organic matter were generally a result of neutralization of toxic levels of Al.

Maximum yield for organic matter application at the zero lime level was reached with a rate of 6% organic matter which supplied a level of Ca equivalent to 75% of the exchangeable Al, while the maximum yield for $Ca(OH)_2$ at zero organic matter level was reached with a level of Ca equivalent to 100% of the exchangeable Al. The maximum yield when Ca was supplied by 6% organic matter was statistically higher than the maximum yield with Ca supplied as $Ca(OH)_2$. The ratio $\frac{\sqrt[3]{Al}}{\sqrt{Ca}}$ in solution plotted against the yield demonstrated that with the same amount of Ca supplied to the soil the yields were higher and the Al-Ca ratio lower when organic matter was the source of Ca than when the source was $Ca(OH)_2$. Even when the Al-Ca ratio was about the same the organic matter gave better yields than $Ca(OH)_2$ alone.

It was suggested that probably the high organic matter contents may be responsible for the relatively high yields in acid soils. This also points to the possibility of using less liming materials if adequately high levels of organic matter are maintained in acid tropical soils.

With the exception of N and K no apparent differences in plant composition due to lime and organic matter applications were observed for most elements. N deficiency was observed in all the plants with higher levels of organic matter. Liming the soil increased the deficiency. The K content in sorghum plants was increased with additions of Ca, either from $Ca(OH)_2$ or organic matter, equivalent to at

least 75% of the exchangeable Al. However, the K content in sorghum plants in all of the treatments was considered high. The following conclusions were drawn:

1. Organic matter neutralized more Al per unit of Ca in it than was true for $Ca(OH)_2$. No definite reason for the greater effectiveness of organic matter in this respect was identified in this study. Probably one of the reasons might be the additional supply of Mg by the organic matter.

2. Maximum yields were obtained on all the treatments when the Al saturation was less than 7% and soil solution Al was less than 0.68 meq/liter.

3. The rate of Ca, either from organic matter or $Ca(OH)_2$, at which maximum yields were obtained was at a level equivalent to 100% of the exchangeable Al. Thus exchangeable Al as measured in this study was suitable for determining the lime requirement of Humatas soil.

4. The yields of sorghum were drastically reduced when the Al saturation was 19% or more and the soil solution Al was 1.39 meq/liter or more.

5. The pH at which maximum yields were obtained ranged from 4.55 to 4.80.

6. Exchangeable Ca increased in an amount approximately equal to the amount of Ca applied either from organic matter or $Ca(OH)_2$. However, the increase in concentration of Ca in solution was less than exchangeable Ca as the organic matter applications increased.

7. The levels of exchangeable Ca at which maximum yields were obtained ranged from 8.70 to 9.25 meq/100g and these levels were obtained with additions of Ca, either from organic matter or $Ca(OH)_2$, equivalent to 100% of the exchangeable Al. Increasing Ca additions above 125% of the exchangeable Al decreased the yields at any rate of organic matter. The Ca in soil solution where maximum yields were obtained was less than 42 meq/liter.

8. The maximum yield obtained by adjusting organic matter application at zero level of lime was statistically higher, and was obtained with a lower amount of Ca supplied to the soil, than the maximum yield obtained by adjusting $Ca(OH)_2$ at zero level of organic matter. This suggests the possibility of using less liming materials if adequately high levels of organic matter are maintained in acid tropical soils.

9. The K content of the sorghum plants was increased with additions of Ca, either from organic matter or $Ca(OH)_2$, equivalent to at least 75% of the exchangeable Al.

10. N deficiency was observed at higher rates of organic matter probably due to immobilization of soil N by soil microorganisms. Liming the soil increased the deficiency.

LITERATURE CITED

Abruña-Rodriguez, F., Vicente-Chandler, J., Pearson, R. W., and Silva, S. 1970. Crop response to soil acidity factors in Ultisols and Oxisols: 1. Tobacco. Soil Sci. Soc. Amer. Proc. 34:629-635.

Adams, F. 1965. Manganese. In C. A. Black et al (ed.). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 1011-1018.

Adams, F. 1968. Response of cotton to lime in field experiments. Auburn Univ. Agric. Expt. Stat. Bull. 376.

Adams, F. 1969. Response of corn to lime in field experiments on Alabama soils. Auburn Univ. Agric. Expt. Stat. Bull. 391.

Adams, F., and Lund, Z. F. 1966. Effect of chemical activity of soil solution aluminum on cotton root penetration of acid subsoils. Soil Sci. 101:193-198.

Allison, L. E. 1965. Total Carbon. In C. A. Black et al. (ed). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 1346-1366.

Barber, S. A., Walker, J. M., and Vasey, E. H. 1963. Mechanisms for the movement of plant nutrients from the soil and fertilizer to the plant root. Jour. Agr. and Food Chem. 11:204-207.

Berger, K. C., and Pratt, P. F. 1963. Advances in secondary and micronutrient fertilization. In McVickar, Bridges, and Nelson (ed.). Fertilizer technology and usage. Soil Sci. Soc. of America, Madison, Wisconsin, pp. 287-329.

Black, C. A. 1968. Soil plant relationships. 2nd edition. John Wiley and Sons, Inc., New York.

Bray, R. H., and Kurtz, L. T. 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Sci. 59:39-45.

Bremner, J. M. 1965. Total nitrogen. In C. A. Black et al. (ed). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 1149-1178.

Broadbent, F. E. 1955. Basic problems in organic matter transformation. Soil Sci. 79:107-114.

Burgess, P. S., and Pember, F. R. 1923. Active aluminum as a factor detrimental to crop production in many acid soils. Rhode Island Agric. Expt. Stat. Bull. 194. June.

Chamura, S., and Hoshi, A. 1960. Studies on the relation between the tolerance of crops to soil acidity and that to low pH: 10. On the uptake of K ion in passive and active processes. [Jour. Ecolog.]. Proc. Crop Sci. Soc., Japan 31:108-111.

Chapman, H. D. 1965. Cation exchange capacity. In C. A. Black et al. (ed.). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 891-901.

Clark, J. S., and Nichol, W. E. 1966. The lime potential-percent base saturation relations of acid surface horizons of mineral and organic soils. Can. J. Soil Sci. 46:281-285.

Clarkson, D. T. 1965. The effect of aluminum and some other trivalent metal cations on cell division in the root apices of Allium cepa. Ann. Bot. 29:309-315.

Clarkson, D. T. 1966a. Aluminum tolerance in species within the genus Agrostis. J. Ecol. 54:167-178.

Clarkson, D. T. 1966b. Effect of aluminum on the uptake and metabolism of phosphorus by barley seedlings. Plant Physiol. 41:165-172.

Clarkson, D. T. 1967. Interactions between aluminum and phosphorus on root surfaces and cell wall materials. Plant and Soil 27:347-356.

Clarkson, D. T. 1969. Metabolic aspects of aluminum toxicity and some possible mechanism for resistance. In Rorison et al (ed). Ecological aspects of the mineral nutrition of plants. Symp. Brit. Ecol. Soc. No. 9. Sheffield, April 1-5, 1968. Blackwell Scientific Publications, Oxford and Edinburgh, pp. 381-397.

Coleman, N. T., Weed, S. B., and McCracken, R. J. 1959. Cation exchange capacity and exchangeable cations in Piedmont soils of North Carolina. Soil Sci. Soc. Amer. Proc. 23:146-149.

Davies, E. B. 1956. Factors affecting molybdenum availability in soils. Soil Sci. 81:209-221.

DeWard, P.W.F., and Sutton, C. D. 1960. Toxicity of Al to black pepper (Piper nigrium, L.) in Sarawak. Nature 188:1129-1130.

Evans, C. E. 1968. Ion exchange relationships of aluminum and calcium in soils as influenced by organic matter. Ph.D. Thesis. North Carolina State University, Raleigh, N.C. Diss. Abstr. B. 1968 29:(4), 1233.

Evans, C. E. and Kamprath, E. J. 1970. Lime response as related to percent Al saturation, solution Al, and organic matter content. Soil Sci. Soc. Amer. Proc. 34: 893-896.

Fleming, A. L., and Foy, C. D. 1968. Root structure reflects differential aluminum tolerance in wheat varieties. Agro. J. 60:172-176.

Foy, C. D., and Brown, J. C. 1963. Toxic factors in acid soils: I. Characterization of aluminum toxicity in cotton. Soil Sci. Soc. Amer. Proc. 27:403-407.

Foy, C. D., and Brown, J. C. 1964. Toxic factors in acid soils: II. Differential aluminum tolerance of plant species. Soil Sci. Soc. Amer. Proc. 28:27-32.

Foy, C. D., Fleming, A. L. and Armiger, W. H. 1969. Aluminum tolerance of soybean varieties in relation to calcium nutrition. Agro. J. 61:505-511.

Fried, M., and Peech, M. 1946. The comparative effects of lime and gypsum upon plants grown on acid soils. J. Amer. Soc. Agron. 38:614-623.

Gilly, G. 1958. Acidite et aluminium exchangeable. Ann. Agro. 9:679-691.

Greene, H. 1963. Prospects in soil science. Jour. Soil Sci. 14:1-11.

Heald, W. R. 1965. Calcium and Magnesium. In C. A. Black et al. (ed.). Methods of soil analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 999-1010.

Hester, J. B. 1935. The amphoteric nature of three Coastal plains soils: I. In relation to plant growth. Soil Sci. 39:237-243.

Howard, D. D., and Adams, F. 1965. Calcium requirement for penetration of subsoils by primary cotton roots. Soil Sci. Soc. Amer. Proc. 29:558-562.

Jacobson, L., Moore, D. P., and Hannapel, R. J. 1960. Role of Ca in absorption of monovalent cations. Plant Physiol. 35:352-358.

Jenny, H. 1961. Aluminum uptake and toxicity in plants. Plant and Soil 13:297-310.

Johnson, R. E., and Jackson, W. A. 1964. Calcium uptake and transport by wheat seedlings as affected by aluminum. Soil Sci. Soc. Amer. Proc. 28:381-386.

Kamprath, E. J. 1967. Soil acidity and response to liming. International Soil Testing Series.Tech. Bull. No. 4. North Carolina State Univ. Agric. Expt. Stat., Raleigh, N. C.

Kamprath, E. J. 1970a. Exchangeable aluminum as a criterion for liming leached mineral soils. Soil Sci. Soc. Amer. Proc. 34:252-254.

Kamprath, E. J. 1970b. Lime requirements of soils--inactive toxic substances or favorable pH range? Soil Sci. Soc. Amer. Proc. 34:364.

Kamprath, E. J., and Foy, C. D. 1971. Lime-fertilizer-plant interactions in acid soils. In Fertilizer technology and use. Amer. Soc. Agr., Madison, Wisconsin.

Lance, J. C., and Pearson, R. W. 1969. Effect of low concentrations of aluminum on growth and water and nutrient uptake by cotton roots. Soil Sci. Soc. Amer. Proc. 33:95-98.

Lawton, K., and Davis, J. F. 1956. The effects of liming on the utilization of soil and fertilizer phosphorus by several crops grown on acid organic soils. Soil Sci. Soc. Amer. Proc. 20:522-526.

Lefebre-Drouet, E., and Lavielle, G. 1966. Bilan des cations echangeables en divers types de sols acides. Ann. Agro. 17:553-570.

Lund, Z. F. 1970. The effect of calcium and its relation to several cations in soybean root growth. Soil Sci. Soc. Amer. Proc. 34:456-459.

MacLeod, L. B., and Jackson, L. P. 1967. Water-soluble and exchangeable aluminum in acid soils as affected by liming and fertilization. Can. J. Soil Sci. 47:203-210.

Magistad, O. C. 1925. The aluminum content of the soil solution and its relation to soil reaction and plant growth. Soil Sci. 20:181-226.

McCart, G. D., and Kamprath, E. J. 1965. Supplying Ca and Mg for cotton on sandy low cation exchange capacity soils. Agron. J. 57:404-406.

McGeorge, W. T. 1925. The influence of aluminum, manganese and iron salts upon the growth of sugar cane, and their relation to the infertility of acid island soils. Hawaiian Sugar Planters' Assoc. Expt. Sta. Bull., Agr. and Chem. Ser. No. 49.

McIlvaine, T. C., and Pohlman, G. G. 1949. Crop growth and soil reaction. West Virginia Agric. Expt. Sta. Bull. 337.

McLean, E. O. 1965. Aluminum. In C. A. Black et al. (ed.). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 978-998.

McLean, E. O. 1970. Lime requirements of soils--inactive toxic substances or favorable pH range? Soil Sci. Soc. Amer. Proc. 34:363-364.

McLean, F. T., and Gilbert, B. E. 1927. The relative aluminum tolerance of crop plants. Soil Sci. 24:163-175.

Miller, D. F. 1958. Composition of cereal grains and forages. National Academy of Science-National Research Council, Publication 585. Washington.

Munns, D. N. 1965a. Soil acidity and growth of a legume: II. Reactions of aluminum and phosphate in solution and effects of Al, phosphate, Ca and pH on Medicago sativa L. and Trifolium subterraneum L. in solution culture. Aust. J. Agr. Res. 16:743-755.

Munns, D. N. 1965b. Soil acidity and growth of a legume: III. Interaction of lime and phosphate on growth of Medicago sativa L. in relation to aluminum toxicity and phosphate fixation. Aust. J. Agr. Res. 16:757-766.

Norton, G. 1966-1967. Some aspects of aluminum toxicity on plant growth. Univ. Nottingham School of Agriculture Report, pp. 99-103.

Nye, P., Craig, D., Coleman, N. T., and Ragland, J. L. 1961. Ion exchange equilibria involving aluminum. Soil Sci. Soc. Amer. Proc. 25:14-17.

Okruszko, H., Warren, G. F., and Wilcox, G. E. 1962. Influence of calcium on phosphorus availability in muck soil. Soil Sci. Soc. Amer. Proc. 26:68-71.

Paterson, J. W. 1965. The effect of aluminum on the absorption and translocation of calcium and other elements in young corn. Ph.D. Thesis. Penn. State Univ., 1964. Diss. Abstr. 25:(11), 6142-6143.

Pierre, W. H., Pohlman, G. G., and McIlvaine, T. C. 1932. Soluble aluminum studies: I. The concentration of aluminum in the displaced soil solution of naturally acid soils. Soil Sci. 34:145-160.

Pierre, W. H., and Stuart, A. D. 1933. Soluble aluminum studies: IV. The effects of phosphorus in reducing the detrimental effects of soil acidity on plant growth. Soil Sci. 36:211-227.

Pionke, H. B., and Corey, R. B. 1967. Relations between acidic aluminum and soil pH, clay and organic matter. Soil Sci. Soc. Amer. Proc. 31:749-752.

Piper, C. S. 1942. Soil and plant analysis. Interscience publisher Inc., New York, pp. 272-274.

Pratt, P. F. 1965. Potassium. In C. A. Black et al. (ed.). Methods of Soil Analysis. Part II. Chemical and microbiological properties. Agronomy 9. American Society of Agronomy, Wisconsin, pp. 1022-1030.

Pratt, P. F., and Alvahydo, R. 1966. Cation-exchange characteristics of soils of Sao Paulo, Brazil. Bull. 31, IRI Research Institute, New York, N.Y.

Pratt, P. F., and Bair, F. L. 1962. Cation-exchange properties of some acid soils of California. Hilgardia 33:689-706.

Ragland, J. L., and Coleman, N. T. 1959. The effect of soil solution aluminum and calcium on root growth Soil Sci. Soc. Amer. Proc. 23:355-357.

Ragland, J. L., and Coleman, N. T. 1960. The hydrolysis of aluminum salts in clay and soil systems. Soil Sci. Soc. Amer. Proc. 24:457-460.

Randall, P. J., and Vose, P. B. 1963. Effect of aluminum on uptake and translocation of phosphorus by perennial rye grass. Plant Physiol. 38:403-409.

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

Reid, D. A., Fleming, A. L., and Foy, C. D. 1971. A method for determining aluminum response of barley in nutrient solution in comparison to response in Al-toxic soil. Agron. J. 63:600-603.

Rios, M. A., and Pearson, R. W. 1964. The effect of some chemical environmental factors on cotton root behavior. Soil Sci. Soc. Amer. Proc. 28:232-235.

Rorison, I. H. 1958. The effect of aluminum on legume nutrition. In E. G. Hallsworth (ed.). Nutrition of the legumes. Butterworths Scientific Publications, London, pp. 43-61.

Rorison, I. H. 1965. The effect of aluminum on the uptake and incorporation of phosphate by excised sainfoin roots. New Phytol. 64:23-27.

Ross, G. L., Lawton, K., and Ellis, B. G. 1964. Lime requirements related to physical and chemical properties of nine Michigan soils. Soil Sci. Soc. Amer. Proc. 28:209-212.

Sampson, M., Clarkson, D., and Davies, D. D. 1965. DNA synthesis in aluminum treated roots of barley. Sci. 148:1476-1477.

Schnitzer, M., and Skinner, S.I.M. 1963a. Organo-metallic interactions in soils: I. Reactions between a number of metal ions and the organic matter of a podzol Bh horizon. Soil Sci. 96:86-93.

Schnitzer, M., and Skinner, S.I.M. 1963b. Organo-metallic interactions in soils: II. Reactions between different forms of iron and aluminum and the organic matter of a podzol Bh horizon. Soil Sci. 96:181-186.

Schnitzer, M., and Skinner, S.I.M. 1964. Organic-metallic interactions in soils: III. Properties of iron and Al-organic matter complexes, prepared in the laboratory and extracted from a soil. Soil Sci. 98:197-203.

Shoop, G. J., Brooks, C. R., Blaser, R. E., and Thomas, G. W. 1961. Differential responses of grasses and legumes to liming and phosphorus fertilization. Agron. J. 53:111-115.

Sideris, C. P. 1925. Effects of aluminum salts on pineapple plants in water culture. Association of Hawaiian Pineapple Canners. Expt. Stat. Bull. 3.

Soil Survey Investigation Report No. 12. 1967. Puerto Rico and the Virgin Islands. Soil Conservation Service, U.S.D.A. In cooperation with Puerto Rico Agric. Exp. Sta.

Soil Survey Staff. 1970. Soil Taxonomy (selected chapters from the unedited text), U. S. Dept. of Agric. Soil Conservation Service, Washington.

Soileau, J. M., Engelstad, O. P., and Martin, J. B. 1969. Cotton growth in an acid fragipan subsoil: II. Effects of soluble calcium, magnesium and aluminum on roots and tops. Soil Sci. Soc. Amer. Proc. 33:919-924.

Turner, R. C. 1965. A study of the lime potential: 5. Significance of the lime potential in aqueous acid clay systems. Soil Sci. 100:14-19.

Turner, R. C., and Clark, J. S. 1965. Lime potential and degree of base saturation of soils. Soil Sci. 99:194-199.

Villa, F. 1929. Effect on young rice plants of adding aluminum salts to complete culture solutions. Philippine Agr. 17:607-625.

Vitosh, M. L. 1968. Interrelationships of Al and organic matter with regard to lime requirements of high organic matter soils. Ph.D. Thesis, North Carolina State University, Raleigh, N. C.

Vlamis, J. 1949. Growth of lettuce and barley as influenced by degree of calcium saturation of soil. Soil Sci. 67: 453-466.

Vlamis, J. 1953. Acid soils infertility as related to soil-solution and solid-phase effects. Soil Sci. 75:383-394.

Watanabe, F. S., and Olsen, S. R. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Amer. Proc. 29:677-678.

Welch, C. D., and Nelson, W. L. 1950. Calcium and magnesium requirements of soybeans as related to the degree of base saturation of the soil. Agron. J. 42:9-13.

Woodruff, C. M. 1967. Crop response to lime in the Midwestern United States. In R. W. Pearson and F. Adams (ed.). Soil acidity and liming. Agronomy 12. American Society of Agronomy, Wisconsin, pp. 207-231.

Wright, K. E. 1937. Effects of lime and phosphorus in reducing aluminum toxicity of acid soils. Plant Physiol. 12:173.

Wright, K. E. 1943. Internal precipitation on phosphorus in relation to aluminum toxicity. Plant Physiol. 18:708-712.

Wright, K. E., and Donahue, B. A. 1953. Aluminum toxicity studies with radioactive phosphorus. Plant Physiol. 28:674-680.

Zandstra, H. G. 1971. Aluminum toxicity in some highly weathered soils of the tropics. Ph.D. Thesis, Cornell University, Ithaca, N.Y.

APPENDIX

Appendix Table 1. Amount of $Ca(OH)_2$ and organic matter applied to each treatment

Treatment				
No.	Organic matter	Calculated Al neutralized with lime	Organic matter	$Ca(OH)_2$
	%	%	g/pot	
1	0	0	0	0.000
2	0	25	0	0.962
3	0	50	0	1.924
4	0	75	0	2.886
5	0	100	0	3.848
6	0	150	0	5.772
7	2	0	26	0.000
8	2	25	26	0.962
9	2	50	26	1.924
10	2	75	26	2.886
11	2	100	26	3.848
12	2	150	26	5.772
13	4	0	52	0.000
14	4	25	52	0.962
15	4	50	52	1.924
16	4	75	52	2.886
17	4	100	52	3.848
18	4	150	52	5.772
19	6	0	78	0.000
20	6	25	78	0.962
21	6	50	78	1.924
22	6	75	78	2.886
23	6	100	78	3.848
24	6	150	78	5.772
25	8	0	104	0.000
26	8	25	104	0.962
27	8	50	104	1.924
28	8	75	104	2.886
29	8	100	104	3.848
30	8	150	104	5.772

Appendix Table 2. Dry matter yields of sorghum for different rates of lime and organic matter applied to a Humatas soil

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime 0	25	50	75	100	150
	%	g/pot					
1	0	0.0900	0.3868	0.3480	0.7683	3.7500	2.8615
2	0	0.0314	0.2230	0.3378	0.6996	3.8000	2.4375
3	0	0.0620	0.1757	0.2171	0.6898	3.4716	2.5387
4	0	0.0672	0.2070	0.2538	0.6158	3.7910	2.4347
1	2	0.4212	0.7043	1.7780	5.7113	5.8543	4.7750
2	2	0.2993	0.6784	1.7666	6.0698	5.8572	4.6913
3	2	0.4551	0.6845	2.0690	5.5130	5.3278	5.7520
4	2	0.4149	0.7674	1.9395	5.8670	6.5624	5.6920
1	4	0.9493	3.9480	5.9530	5.5893	4.0813	4.6095
2	4	0.8545	3.6165	6.3530	5.5400	3.5648	3.9280
3	4	0.9828	4.4170	5.9818	4.9720	5.7540	5.9057
4	4	0.9908	4.2270	5.5500	5.2280	6.0658	4.9080
1	6	4.4461	5.8260	5.3170	4.2740	2.9923	3.1370
2	6	5.6622	5.4560	4.6920	5.0964	3.4223	3.7605
3	6	4.8970	6.8280	4.7510	4.3580	4.0917	3.9940
4	6	4.1212	4.7994	5.1735	4.4512	3.8400	2.4700
1	8	4.1703	3.3382	4.0660	2.6530	2.4163	2.2170
2	8	4.5725	4.0800	3.9738	3.2363	2.7276	1.8675
3	8	3.6230	3.5227	3.1907	3.1270	2.1510	1.5723
4	8	4.5330	3.4800	4.0450	4.2100	2.7150	1.8400

Appendix Table 3. Analysis of variance for dry matter yields of sorghum of Appendix Table 2

Source of variation	Degrees of freedom d.f.	Sum of squares SS	Mean square MS	Observed F
Organic matter	4	159.66	39.92	187.00**
Lime	5	56.13	11.23	52.59**
Organic matter x lime	20	219.10	10.95	51.32**
Error	90	19.21	0.21	
Total	119	454.09		

**Significant at the 1% level.

Appendix Table 4. N content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime 0	25	50	75	100	150
	%	%					
1	0					3.18	3.55
2	0					3.41	3.47
3	0					2.98	
4	0						
1	2			3.18	1.84	1.46	2.00
2	2			3.23	2.11	1.89	2.29
3	2				2.08	1.82	2.48
4	2				2.08	1.97	2.21
1	4		1.87	1.66	1.49	1.44	1.28
2	4		2.40	1.58	1.54	1.44	1.44
3	4		2.24	1.71	1.49	1.52	1.22
4	4		1.86	1.61	1.44		1.44
1	6	1.34	1.26	0.99	0.90	0.96	0.94
2	6	1.28	1.18	1.04	0.84	0.82	0.88
3	6	1.31	1.19	1.14	0.95	0.88	
4	6		1.24	1.07	0.90	0.93	
1	8	0.85	0.80	0.77	0.77	0.70	0.70
2	8	0.80	0.78	0.82	0.75	0.75	
3	8	0.93	0.83	0.75	0.82		
4	8	0.80	0.82		0.80		

Data for treatments that were not included in this table was due to insufficient plant material.

Appendix Table 5. P content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime 0	25	50	75	100	150
	%	%					
1	0	0.19	0.12	0.12	0.15	0.20	0.22
2	0		0.17	0.10	0.17	0.21	0.19
3	0				0.19	0.21	0.18
4	0				0.22	0.19	0.19
1	2	0.15	0.20	0.28	0.18	0.15	0.19
2	2	0.08	0.19	0.24	0.20	0.17	0.22
3	2	0.12	0.18	0.24	0.18	0.15	0.19
4	2		0.17	0.23	0.20	0.15	0.17
1	4	0.20	0.20	0.13	0.15	0.16	0.13
2	4	0.20	0.24	0.13	0.14	0.18	0.17
3	4	0.18	0.28	0.15	0.15	0.15	0.13
4	4	0.18	0.20	0.13	0.16	0.15	0.11
1	6	0.16	0.14	0.16	0.16	0.14	0.12
2	6	0.14	0.13	0.18	0.17	0.11	0.11
3	6	0.17	0.11	0.13	0.15	0.13	0.11
4	6	0.21	0.19	0.14	0.15	0.10	0.13
1	8	0.17	0.19	0.12	0.13	0.13	0.11
2	8	0.18	0.15	0.15	0.16	0.11	0.13
3	8	0.20	0.19	0.19	0.14	0.15	0.15
4	8	0.13	0.13	0.13	0.10	0.15	0.15

* Data for treatments that were not included in this table was due to insufficient plant material.

Appendix Table 6. K content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime 0	25	50	75	100	150
	%	%					
1	0	2.30	1.84	2.08	3.26	4.56	4.66
2	0		2.80	2.08	2.08	4.10	4.30
3	0				2.30	4.38	3.94
4	0				1.83	3.34	4.00
1	2	2.10	2.35	3.86	4.56	4.48	4.20
2	2	1.93	2.15	3.86	4.30	4.00	4.56
3	2	2.10	2.28	3.86	3.86	3.56	3.34
4	2		2.01	3.78	4.30	4.30	3.94
1	4	2.63	4.66	4.00	3.86	3.86	3.68
2	4	3.00	4.48	3.86	4.66	4.10	4.00
3	4	2.78	4.66	3.94	4.20	3.60	3.78
4	4	2.85	4.20	3.78	3.86	3.68	3.16
1	6	3.78	2.82	3.94	3.86	3.78	3.50
2	6	3.86	3.26	3.94	3.68	4.00	3.42
3	6	3.86	3.08	3.78	3.86	3.26	3.34
4	6	4.84	4.00	3.68	3.50	3.26	3.34
1	8	3.50	3.34	4.00	3.16	3.68	3.26
2	8	3.50	3.42	3.00	3.50	3.60	3.34
3	8	4.20	3.68	3.60	3.34	3.60	3.16
4	8	3.34	4.00	3.26	2.90	3.60	3.42

* Data for treatments that were not included in this table was due to insufficient plant material.

Appendix Table 7. Ca content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime 0	25	50	75	100	150
	%	%					
1	0	0.62	0.51	0.87	0.80	0.71	0.82
2	0		0.88	0.92	0.88	0.77	0.77
3	0				0.74	0.70	0.84
4	0				1.04	0.68	0.70
1	2	0.47	0.59	0.89	0.55	0.49	0.68
2	2	0.48	0.59	0.82	0.53	0.55	0.58
3	2	0.41	0.59	0.80	0.51	0.53	0.56
4	2		0.50	0.80	0.55	0.47	0.70
1	4	0.76	0.60	0.40	0.50	0.46	0.57
2	4	0.62	0.58	0.44	0.46	0.63	0.63
3	4	0.62	0.60	0.42	0.46	0.46	0.48
4	4	0.70	0.57	0.40	0.46	0.44	0.55
1	6	0.43	0.33	0.39	0.42	0.45	0.50
2	6	0.45	0.35	0.42	0.44	0.43	0.46
3	6	0.44	0.30	0.40	0.41	0.39	0.51
4	6	0.49	0.41	0.40	0.41	0.44	0.56
1	8	0.40	0.34	0.33	0.44	0.40	0.52
2	8	0.37	0.32	0.38	0.39	0.42	0.60
3	8	0.37	0.38	0.39	0.40	0.39	0.60
4	8	0.39	0.31	0.37	0.35	0.44	0.61

* Data for treatments that were not included in this table was due to insufficient plant material.

Appendix Table 8. Mg content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime					
		0	25	50	75	100	150
	%	%					
1	0	0.22	0.21	0.20	0.20	0.20	0.26
2	0		0.33	0.19	0.18	0.21	0.25
3	0				0.20	0.21	0.23
4	0				0.30	0.20	0.20
1	2	0.21	0.19	0.22	0.21	0.20	0.26
2	2	0.19	0.19	0.21	0.22	0.22	0.27
3	2	0.23	0.19	0.22	0.20	0.23	0.27
4	2		0.16	0.20	0.22	0.21	0.25
1	4	0.28	0.22	0.16	0.19	0.20	0.19
2	4	0.24	0.24	0.17	0.20	0.22	0.22
3	4	0.21	0.24	0.18	0.22	0.21	0.19
4	4	0.23	0.22	0.16	0.22	0.22	0.20
1	6	0.18	0.18	0.17	0.17	0.20	0.18
2	6	0.19	0.18	0.20	0.17	0.19	0.18
3	6	0.21	0.17	0.17	0.19	0.18	0.19
4	6	0.25	0.22	0.20	0.17	0.17	0.18
1	8	0.18	0.14	0.16	0.17	0.16	0.14
2	8	0.18	0.15	0.18	0.17	0.17	0.16
3	8	0.19	0.18	0.17	0.17	0.18	0.18
4	8	0.15	0.15	0.17	0.16	0.20	0.18

* Data for treatments that were not included in this table was due to insufficient plant material.

Appendix Table 9. Mn content of sorghum plants with different rates of lime and organic matter applied to a Humatas soil*

Replication number	Organic matter	Treatment: Calculated % Al neutralized with lime					
		0	25	50	75	100	150
	%	ppm					
1	0	80	32	32	32	136	80
2	0		32	64	32	116	56
3	0				40	100	80
4	0				53	100	80
1	2	40	133	100	136	116	32
2	2	27	27	172	152	116	32
3	2	40	53	188	152	116	56
4	2		80	172	136	116	56
1	4	287	232	136	136	56	16
2	4	232	212	172	136	80	32
3	4	227	172	152	100	56	32
4	4	287	232	116	100	32	32
1	6	188	152	136	116	80	32
2	6	212	136	136	116	80	16
3	6	188	136	116	100	32	32
4	6	232	172	100	100	56	32
1	8	188	136	100	100	56	188
2	8	172	116	136	116	56	56
3	8	188	172	116	100	116	80
4	8	172	116	80	80	100	56

* Data for treatments that were not included in this table was due to insufficient plant material.

END