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ROOT RESPONSES OF THREE GRAMINEAE SPECIES TO SOIL ACIDITY IN AN OXISOL AND AN ULTISOL[1]

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ABSTRACT

Sorghum roots were highly sensitive to soil solution Al present in acid Ultisols and Oxisols. Corn roots were moderately sensitive and stargrass roots were tolerant. Representative acid soils from the humid region of Puerto Rico contained less soil solution Al than did several selected from the southeastern United States at the same pH level. This confirms the observation that critical soil pH range tends to be lower in soils of Puerto Rico than in those of the southeastern United States. Soil solution Al concentration can be calculated satisfactorily from soil pH and EC of the saturated paste extract using an equation developed from the data presented.

INTRODUCTION

The Gramineae is an extremely important family of crops throughout the humid tropics, with tremendous potential for increasing the high-protein food supply of these areas through use with intensive N fertilization in livestock production (Vicente-Chandler et al. 1964; Caro-Costas et al. 1972a, 1972b). Soils of the humid tropics are usually acid, and the use of residually acid N fertilizers at the high rates required for maximum grass forage yield can rapidly lower soil pH throughout the normal rooting zone (Adams et al. 1967). Although a number of warm climate grasses are relatively tolerant to soil acidity, little is known about their rooting behavior in underlying acid subsoil zones. This characteristic can be of primary importance in determining yield potential during dry seasons and in areas of suboptimal rainfall. Coastal bermudagrass (*Cynodon dactylon*) roots are believed to be highly tolerant, as are those of pearl millet (*Pennisetum typhoides*) (Long 1972), and napiergrass (*Pennisetum purpurem*) (Pearson 1971). Oats (*Avena sativa*) seem to be somewhat less tolerant (Long 1972), and sudangrass (*Sorghum sudanensis*) roots are extremely sensitive (Pearson 1966).

This study was undertaken to compare the effect of acidity in the subsurface zone of a typical Oxisol and Ultisol on root development of three species of Gramineae.

PROCEDURE

Root and top growth of selected test-plant species were measured in a greenhouse experiment, using surface soil material from two soils at three pH levels, overlain by a well-limed and fertilized layer of top soil. The pots were arranged in a complete randomized block with four replications.

The soils selected were Humatas clay—a Typic Tropohumult (Ultisol)—and Coto clay, classified as a Tropeptic Haplorthox (Oxisol). Both soil sampling sites were located in intensively farmed humid regions of Puerto Rico. Preliminary examinations of the soils showed that Al essentially disappeared from the displaced soil solution before soil pH reached 5.0, so that treatment pH levels were chosen to be between 4 and 5. The final pH values were 4.45 and 4.75, in addition to the untreated pH of 3.95 in Humatas and 4.05 in Coto. Buffer curves were determined for each soil for estimating the

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amount of $Ca(OH)_2$ required to adjust soil pH to the desired levels. The limed and check lots of soils were then moistened to the ⅓-atm percentage and incubated in sealed plastic containers for 4 days before potting.

Plastic-lined No. 2 cans were filled to within 3.8 cm of the top with the moistened soil, and discs of coarsely-woven saran mesh material were put in place to separate the treated soil from surface soil to be added. A 2.5-cm layer of uniformly limed and fertilized potting soil was then placed on the surface of each can.

Stargrass (*Cynodon plectostachyus*), corn (*Zea mays*, 'Pioneer' × 306) developed in Jamaica for tropical conditions, and sorghum (*Sorghum vulgare*) were chosen as the test crops. Based on the general knowledge of the relative responsiveness of these species to lime, it was anticipated that roots of stargrass, corn, and sorghum would exhibit high, intermediate, and low tolerance of subsoil acidity, respectively. One rooted node of stargrass was planted per pot. Five and nine seeds of corn and sorghum, respectively, were planted.

Cans were weighed daily and H_2O content was adjusted to the ⅓-atm percentage. After 34 days, plants were harvested and roots washed out of the "subsoil," dried at 75°C, and weighed.

Soil solutions were displaced from samples of soil at ⅓-atm percentage H_2O content taken from each treatment at potting. These solutions were analyzed for Ca, Mg, K, Al, and Mn. The same cations in exchangeable form were also determined. The following analytical procedures were used: Eriochrome Cyanine R method of Jones and Thurmond (1957) for Al; EDTA titration for Ca and Mg; and flame photometry for K. Manganese was determined colorimetrically as $KMnO_4$.

RESULTS AND DISCUSSION

Some physical characteristics of the soils are shown in Table 1. Mineralogically, the chief difference between the soils is the presence of a considerable amount of interlayered 2:1 type material in the Ultisol, and nearly twice as much kaolinite in the Oxisol as in the Ultisol.

Chemical characterization of the soils at each of the three pH levels is listed in Table 2. There are several points of significance in relation to root requirements. One is the low percent base saturation (only 13 percent) in both soils at the lowest pH level. Also, the Ca:total cation ratio is extremely low (<0.1) in the unlimed soils, indicating a definite possibility of Ca deficiency for root growth. Another is the high amounts of

TABLE 1

Some physical characteristics of the Humatas and Coto clays used

Soil	Mechanical, % of soil			Mineralogical, % of clay fraction			
	sand (*mm*) 2.0 – .05	silt (*mm*) .05 – .002	clay (*mm*) <.002	K	C	I	Free Fe_2O_3
Humatas clay (Typic Tropohumult)	3	22	75	56	Tr	10–20	11
Coto clay (Tropeptic Haplorthox)	24	17	60	95	Tr	—	15

TABLE 2

Some chemical characteristics of Humatas and Coto clays

Soil	pH	Exchangeable cations (*me/100 g*)						CEC (*me/100 g*)		Base saturation (%)	Ca/total cations
		Ca	Mg	K	Na	Mn	Al	NH_4OAc	Σ cations		
Humatas clay	3.95	1.13	nil	0.40	0.10	0.02	11.12	14.14	12.77	13	.09
	4.45	2.96	0.74	0.65	0.14	0.02	5.86	12.69	10.37	43	.29
	4.75	3.32	2.10	0.65	0.15	0.02	4.15	12.69	10.39	60	.32
Coto clay	4.05	0.44	0.21	0.20	0.07	0.64	5.35	12.45	6.91	13	.06
	4.45	1.06	0.50	0.20	0.08	0.64	3.73	12.45	6.21	30	.17
	4.75	1.86	0.99	0.23	0.08	0.51	2.88	12.45	6.55	48	.28

exchangeable Al in both soils, even at pH approaching 5. Still another is the discrepancy between Σ cations and CEC by the standard NH_4OAc procedure in the case of Oxisol, but not in the Ultisol. An explanation for the wide difference in CEC, as estimated by the two methods for Coto clay, is not at hand. It is not due to pH-dependent charge, as essentially the same CEC was obtained using NH_4OAc buffered at pH 4.0 as at 7.0. A final point of significance is the similarity in Al saturation between the soils at a given pH level. This is shown graphically in Fig. 1. Several other soils being used in related experiments of lime response are plotted in the same graph to show the similarity in this respect among these soils.

Soil solution analyses (Table 3) show that Ca should be adequate for root growth in all treatments, with the possible exception of Humatas at pH 3.95, in spite of the unusually low exchangeable Ca:total cation ratios (Lund 1970; Howard and Adams 1965). Toxicity due to soil solution Al would range from lethal to low for roots of sensitive species (Adams and Lund, 1966). Soil solution Al had essentially the same relation to pH in each of these two soils. This relationship, which holds only for very low free-salt conditions, is expressed by the equation

$$\text{Log } C_{Al} = 12.2 - 19.05 \log \text{pH} \quad (1)$$

and

$$r^2 = 0.95$$

Root and top growth made by the three grasses at the three pH levels in each soil are shown in Table 4. As had been anticipated, stargrass roots were relatively insensitive to these levels of acidity, whereas sorghum root growth was drastically reduced at the two lower pH values. Corn root development was reduced at

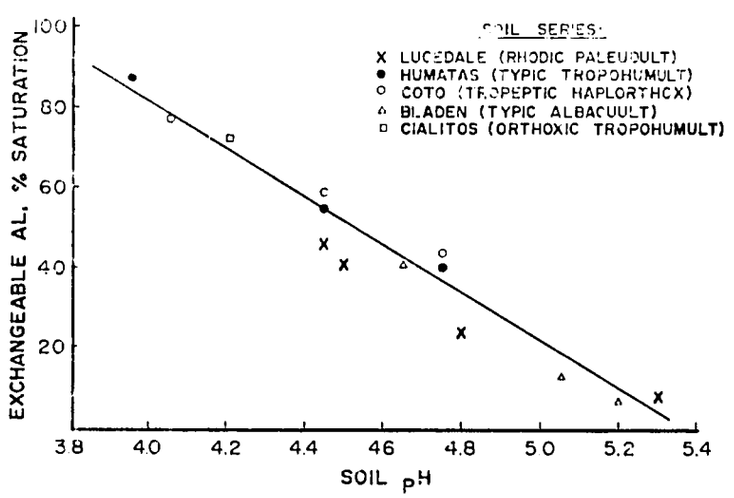

FIG. 1. Relation of exchangeable Al saturation to soil pH among selected soils of Puerto Rico and the southeastern United States.

TABLE 3

Composition of displaced soil solutions of Humatas and Coto clays at various pH levels

Soil	pH	Cation concentration (*me/liter*)					Ca/total cations	Activity of Al (*mM*)
		Ca	Mg	K	Al	Mn		
Humatas clay	3.95	1.00	2.00	0.59	1.03	0.00	0.20	0.1134
	4.45	2.10	1.50	0.54	0.08	0.05	0.36	0.0074
	4.75	4.30	4.32	0.77	0.04	0.03	0.40	0.0009
Coto clay	4.05	3.24	2.58	0.46	0.31	3.28	0.30	0.0342
	4.45	3.50	2.66	0.36	0.09	2.44	0.35	0.0086
	4.75	5.84	4.16	0.31	0.01	2.17	0.44	0.0037

TABLE 4

Root and top yield of three plant species in an Ultisol and an Oxisol at three pH levels

Soil series	Soil pH	Dry weight of tissue per pot (*mg*)					
		Corn		Sorghum		Stargrass	
		roots	tops	roots	tops	roots	tops
Humatas	3.95	209a[1]	1560a	19a	613a	154	350
	4.45	874b	2220a	296b	1360a	267	545
	4.75	931b	2070b	400c	1130b	230_{NS}	605_{NS}
Coto	4.05	389a	2045	128a	1070a	194	335
	4.45	630b	1940	126a	1300a	117	325
	4.75	687b	1880_{NS}	345b	1390b	176_{NS}	390_{NS}

[1] Numbers followed by the same letter are not significantly different at the 1% probability level.

the lowest pH level only. Yield of tops was generally a less sensitive indicator of subsoil pH than was root yield. This would be expected in pot tests, where moisture stress resulting from restricted root development would be minimized.

Previous research has clearly shown that whereas soil pH is related to plant root growth in a general way (Pearson 1971), the level of Al in the soil solution is usually the specific factor responsible for reduced root development in acid soils (Adams and Lund 1965). Even so, soil solution Al and percent Al saturation of mineral soils are related (Evans and Kamprath, 1970), as are percentage Al saturation and overall plant response (Abruña-Rodriguez et al. 1970). The relationship found in this study between root growth and exchangeable Al, expressed as percent saturation of effective CEC, is indicated graphically in Figs. 2 and 3. Values for a given crop species fall on the same curve, regardless of soil, but the sorghum shows considerable scatter of points. Nevertheless, root growth in these soils was not seriously inhibited by acidity until

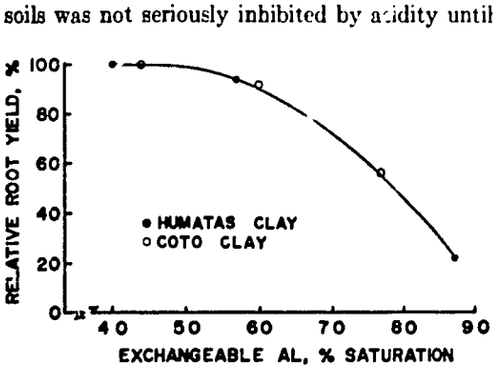

FIG. 2. Relative root growth of corn as influenced by percent Al saturation of CEC.

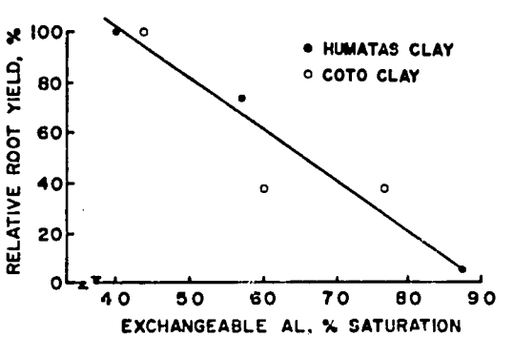

FIG. 3. Relative root growth of sorghum as influenced by percent Al saturation of the CEC.

Al saturation exceeded around 60 percent. About 80 percent Al saturation was required to reduce corn root growth to 50 percent maximum. Sorghum root growth, on the other hand, was sharply reduced by any increase in exchangeable Al above the lowest level tested. The data suggest that sorghum root growth might have increased more from a further reduction in exchangeable Al level if such treatments had been included.

Soil solution Al content or, more precisely, the chemical activity of soil solution Al, provides the real measure of Al toxicity potential for plant roots growing in acid soil (Adams and Lund 1966). Aluminum activity in the Humatas and Coto soil solutions ranged from 0.113 mM at the lowest pH to only 0.0009 at the highest pH in Humatas clay. Adams and Lund (1966) found a clear reduction in cotton root elongation rate at Al activity levels even less than 0.0009 mM. Our results, plotted in Fig. 4, show that sorghum root growth dropped sharply with the first in-

crement of soil solution Al. As Al activity increased, corn root growth was also restricted, but about twice as much Al was required to cause the same reduction in corn root growth as in sorghum.

Although both soil pH and Al saturation percentage provide general indications of soil solution Al level, especially among closely related soils, other factors play strongly modifying roles. This is illustrated by the scatter diagram of Fig. 5. For example, the presence of only traces of electrolyte in the soil, such as would result from fertilizer application, can increase soil solution Al concentration and activity at the same soil pH and exchangeable Al level. Treatments used are listed in Table 5.

Electrical conductivity (EC) is easily measured and is a sensitive indicator of free electrolytes at low concentration levels in the soil solution. When data from Tables 3 and 5 were used to relate soil pH to soil solution Al and EC, the curve of Fig. 6 was obtained. Thus, with soil pH and solution conductivity measurements, soil solution Al concentration for these two dissimilar soils can be calculated with considerable precision ($r^2 = 0.95$) by use of the equation

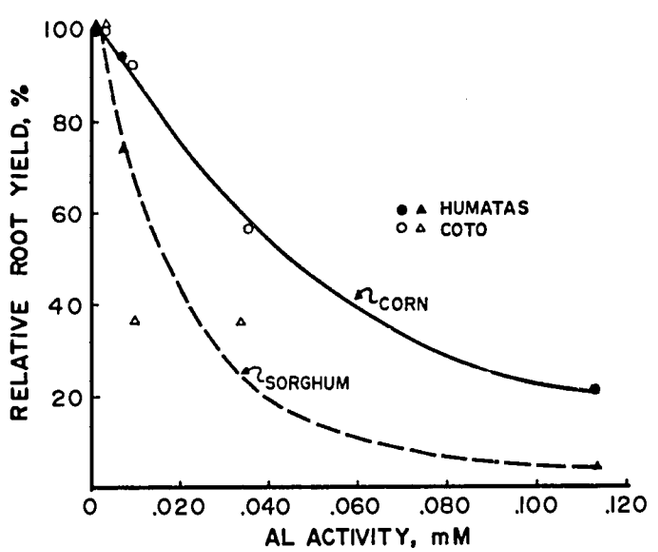

FIG. 4. Effect of soil solution Al on corn and sorghum root growth.

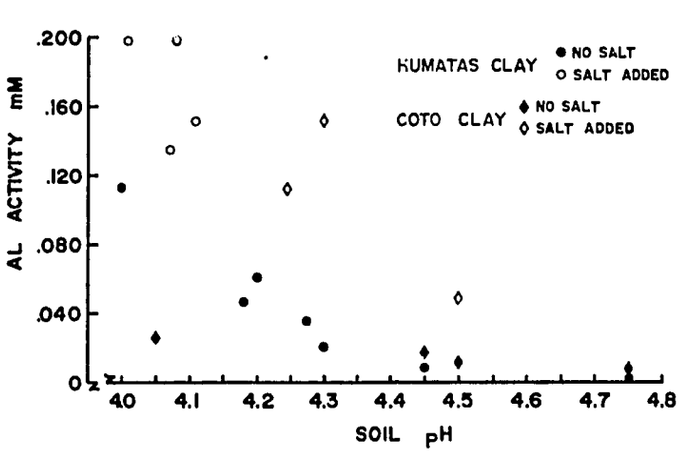

FIG. 5. Effect of presence of free electrolyte on Al level in the displaced soil solution.

$$\text{Al conc.} = \text{EC}\,(176.612 - 109.098\ \text{pH} + 22.528\ \text{pH}^2 - 1.555\ \text{pH}^3) \quad (2)$$

where EC is expressed as mmhos/cm at 25°C.

It may be that this or a similar relationship will apply to broad soil categories. In that case, a useful and timesaving tool would be at hand for characterizing Al status of soils, particularly if EC could be estimated without actual soil solution displacement. With this possibility in mind, values for EC of the saturated paste extract were measured for comparison with those of the soil solution. The results, plotted in Fig. 7, show that $EC_{soil\ solution}$ was predicted with a high degree of accuracy from the EC of the saturated paste extract ($r^2 = .98$). This simple and rapid measurement, together with the soil pH, could thus be substituted for soil solution displacement and analysis in estimating soil solution Al concentration level. The expression for calculating Al concentration in me/liter would then become

$$C_{Al} = 1.725\ \text{EC} - 0.1184\,(176.612 - 109.098\ \text{pH} + 22.528\ \text{pH}^2 - 1.555\ \text{pH}^3) \quad (3)$$

Of course, this approach must be tested on a wide range of soils to establish its limits of application.

A given level of soil acidity does not appear to

TABLE 5

Soil pH, conductivity, and aluminum content of solutions displaced from Humatas and Coto clays treated with varying amounts of $Ca(OH)_2$ and KCl

	Treatment		Soil pH	Conductivity of soil solution	Soil solution Al	
	$Ca(OH)_2$	KCl			Concentration	Chemical activity
	(me/100 g)	*(me/100 g)*		*(mmhos/cm at 25°C)*	*(mM)*	*(mM)*
Humatas	None	None	4.18	0.63	0.141	0.047
	0.50	None	4.20	0.70	0.185	0.061
	1.00	None	4.28	0.79	0.118	0.036
	1.25	None	4.30	0.80	0.070	0.021
	0.50	0.50	4.01	1.55	0.626	0.188
	1.00	0.50	4.07	1.69	0.474	0.135
	1.25	0.50	4.11	1.70	0.555	0.154
	1.75	1.00	4.08	2.90	0.804	0.199
Coto	None	None	4.45	1.55	0.111	0.029
	None	0.25	4.50	2.55	0.207	0.049
	None	0.50	4.24	3.55	0.485	0.112
	None	1.00	4.30	5.80	0.785	0.152

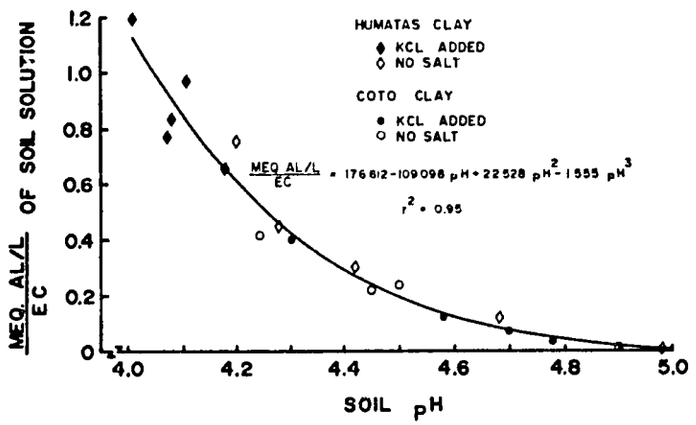

FIG. 6. Relationship of soil pH of an Oxisol and an Ultisol to soil solution Al concentration and electrical conductivity.

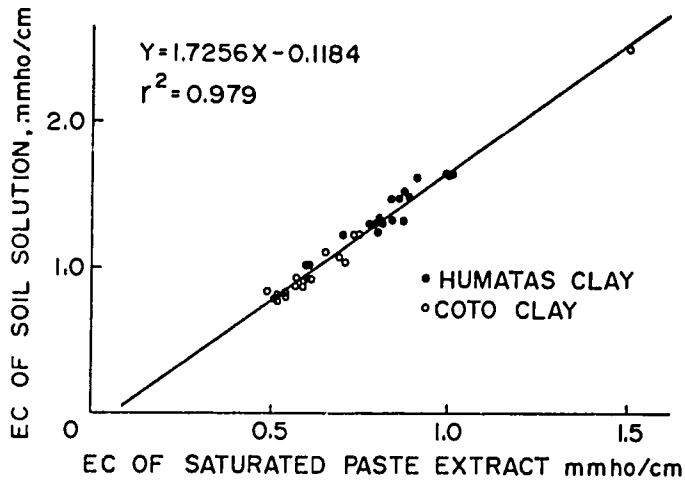

FIG. 7. Relationship between conductivities of displaced soil solutions and of saturated paste extracts of a Coto and a Humatas clay.

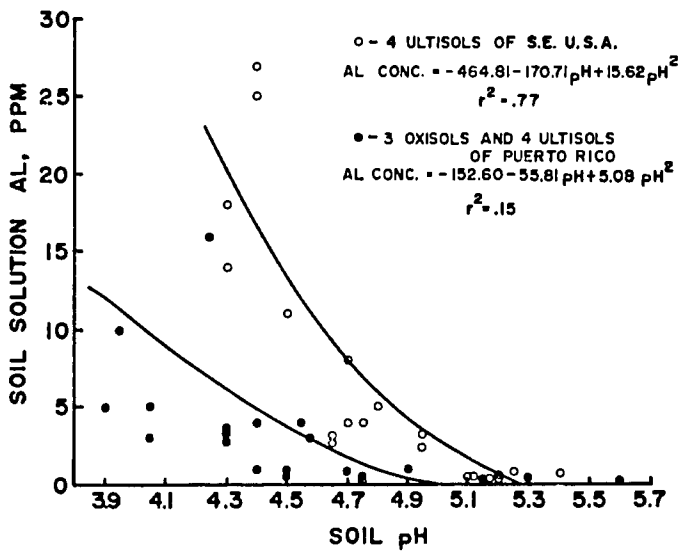

FIG. 8. Soil solution Al concentration in randomly chosen mineral soils of humid-tropical Puerto Rico and of the humid-temperate southeastern United States as influenced by soil pH.

be as unfavorable to plant growth in soils of the humid areas of Puerto Rico as in those of the southeastern United States. If true, this could be due either to higher tolerance to acidity on the part of the adapted genotypes found in Puerto Rico, or to a lower level of toxic ions, particularly of Al, in soils developed under humid tropical conditions. Large differences in soil solution Al-soil pH relationship have been shown to exist among closely related soils (Richburg and Adams 1970), but no connection between this relationship and climatic environment has been suggested.

To test whether such a relationship does exist, soil solution Al and soil pH were determined on a number of soils from both Puerto Rico and the southeastern United States. All samples were taken from cultivated fields during the growing season at least a month after any fertilizer addition. The results plotted in Fig. 8 show a clear difference in soil solution Al content, with the soils from the humid tropical region having a

lower level than those from temperate areas throughout the normal acid soil pH range. This difference is large enough to account for the apparently lower "critical" soil pH for plant growth often observed in Puerto Rico as compared to soils in the humid-temperate areas of the mainland United States.

SUMMARY

Root growth of both corn and sorghum in an Oxisol and in an Ultisol was restricted by soil acidity, but that of stargrass was not affected even at pH 4.0. Corn root development was reduced only above 50 percent saturation of CEC with Al, although root growth decreased sharply with the first increment in chemical activity of soil solution Al. Sorghum roots were highly sensitive to Al, with essentially zero growth at 0.113 mM Al activity in the soil solution. There was no difference in root growth of either species in the Oxisol or Ultisol at the same soil solution Al level, which supports the premise that root inhibition in acid humid-tropical soils is primarily a result of soil-solution Al toxicity.

Soil solution Al concentration could not be predicted satisfactorily from pH alone, even for the same soil, when free electrolyte content was varied. However, by including EC as a measure of free electrolyte content, Al level was calculated with acceptable accuracy using an equation developed from the data presented. Electrical conductivity of the saturated paste was closely related to, and could be used in calculating, that of the displaced soil solution.

Representative acid soils from the humid region of Puerto Rico, both Ultisols and Oxisols, had considerably lower soil-solution Al levels than did those from the southeastern United States. This is consistent with the observation that "critical" soil pH for plant growth is often lower in the soils of Puerto Rico than in those of the southeastern United States.

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