Reprinted from
AGRONOMY JOURNAL, Volume 65
January-February, 1973, p. 30-34

Response of an Al-Tolerant and an Al-Sensitive Genotype to Lime, P, and K on Three Atlantic Coast Flatwoods Soils[1]

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ABSTRACT

Aluminum toxicity, calcium deficiency, and a complex of other unidentified factors contribute to the poor productivity of Atlantic Coast Flatwoods soils that occupy more than 100,000 km² in the southern U.S. Our objective was to investigate the response of aluminum-sensitive 'Suregrain' oats (*Avena sativa* L.) and aluminum-tolerant 'Starr' pearl millet [*Pennisetum typhoides* (Burm. f)] to lime, phosphorus, and potassium on Bladen, Leon, and Lakeland soils. Results of a series of pot experiments using four or more rates each of dolomitic limestone, monocalcium phosphate, and potassium chloride were used to calculate response surfaces and yield isoquants. Eighty-two to ninety-five percent of the variation in yield was explained by lime, P, and K variables. Phosphorus was the most critical growth-limiting factor for plant growth and response to P depended on lime and K levels.

Additional index words: **Acid soil infertility, Al toxicity, Al tolerance, *Avena sativa* L., *Pennisetum typhoides* (Burm. f.).**

THE Atlantic Coast Flatwoods occupies more than 100,000 km², or about 40,000 square miles, along the southeastern Atlantic Coast. The topography is level to gently rolling, and natural drainage is poor over much of the lower-lying areas. The area is characterized by hot, humid summers, short moderate winters, and long freeze-free seasons, which give it an impressive agricultural potential from a climatic standpoint (3). Recently there has been increased interest in bringing some of the woodland soils of the area, particularly along the Georgia coast, into crop production. A knowledge of fertility status is prerequisite to efficient crop production on these woodland soils.

High rates of both fertilizer and lime are usually required for satisfactory crop yields on such acid, infertile soils, but recent laboratory characterization showed that 18 soil series of the area varied widely in both chemical and physical properties (10). Growth-limiting factors have been attributed to Al toxicity in some of these soils, to Ca deficiency in others, and to a complex of unidentified factors in still others (6).

The purpose of this study was to investigate the responses to and interactions of lime, phosphorus, and potassium in three major soils of the Atlantic Coast Flatwoods region, selected to represent the range in both chemical and physical characteristics found in this area.

EXPERIMENTAL PROCEDURE

The three soils chosen for this study were Bladen loam (typic albaquults), Leon fine sand (aeric haplaquods), and Lakeland sand (typic quartzipsamments)—all extensive soil series of the lower Atlantic Coastal Plain. Some chemical and physical characteristics of these soils are shown in Table 1. Mechanical analysis was made using the Bouyoucos hydrometer method (4). Cation exchange capacity was determined by NH_4OAc (12) and the extracted basic cations were determined by atomic absorption spectrophotometry. Phosphorus was extracted with dilute acid (0.025 *N* H_2SO_4 + 0.05 *N* HCl), using a soil:extracting solution ratio of 1:4 and an extracting time of 5 min, and was determined colorimetrically by the method of Murphy and Riley (11) adapted for use on acid extracts. Soil pH was determined on a 1:1 soil: water suspension. Displaced soil solutions were analyzed for Al using the method of Jones and Thurman (8).

A series of factorial pot experiments was conducted on Al-horizon material of these three soils, using a randomized block design with three replications. Treatments included four or more rates each of 100-mesh dolomitic limestone, monocalcium phosphate, and potassium chloride (Table 2). Polyethylene pails of 8.5-liter capacity were used as containers, with 9.1 kg (20 lb) of soil per container. The test crops were 'Suregrain' oats (*Avena sativa* L.), and 'Starr' pearl millet [*Pennisetum typhoides* (Burm. f.) Stapf and C. E. Hubb]. Three or more clippings were made during the growing season. The plant material was dried at 70 C and weighed.

RESULTS AND DISCUSSION

Multiple regression equations were calculated from oat and millet yields. All equations are based on totals of three or more clippings. The quadratic model used was

$$Y = b_0+b_1L+b_2P+b_3K+b_4L^2+b_5P^2+b_6K^2+b_7LP+b_8LK+b_9PK+b_{10}LPK.$$

In this equation Y is the predicted oven-dry yield of either oats or millet in grams per pot. L is metric tons of dolomitic limestone added per hectare. P and

[1] Contribution of Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with the Alabama Agricultural Experiment Station, Auburn University, Auburn, Ala.; Georgia Agricultural Experiment Station, Athens, Ga.; and Mississippi Agricultural and Forestry Experiment Station, State College, Miss. Received March 13, 1972.

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Table 1. Some physical and chemical characteristics of the Al horizon of three Atlantic Coast Flatwoods soils.

Soil series	Depth	Sand	Silt	Clay	OM	pH	CEC	Exchangeable Ca	Exchangeable Mg	Exchangeable K	Soil test P
	cm	%	%	%	%		meq/100 g	meq/100 g	meq/100 g	meq/100 g	
Bladen	0-10	29	46	25	2.5	4.8	13.1	1.69	0.11	0.04	Very low
Leon	0-15	91	7	2	4.6	3.6	17.1	0.44	0.49	0.05	Very low
Lakeland	0-10	89	8	3	2.6	4.8	2.8	0.50	0.16	0.03	Very low

Table 2. Treatments applied to Bladen, Leon, and Lakeland soils in factorial experiments.

Soil	Treatments for millet			Treatments for oats		
	Lime	P	K	Lime	P	K
	mt/ha	kg/ha	kg/ha	mt/ha	kg/ha	kg/ha
Bladen	0.0	0.0	0.0	0.0	0.0	0.0
	4.5	14.5	28.0	4.5	29.0	28.0
	9.0	29.0	56.0	9.0	58.0	56.0
	18.0	58.0	112.0	18.0	116.0	112.0
	36.0	116.0	224.0		232.0	
Leon	0.0	0.0	0.0	0.0	0.0	0.0
	2.2	29.0	28.0	2.2	29.0	28.0
	4.5	58.0	56.0	4.5	58.0	56.0
	9.0	116.0	112.0	9.0	116.0	112.0
Lakeland	0.0	0.0	0.0	0.0	0.0	0.0
	2.2	29.0	28.0	2.2	29.0	28.0
	4.5	58.0	56.0	4.5	58.0	56.0
	9.0	116.0	112.0	9.0	116.0	112.0

All soils received 112 kg N/ha before planting and 56 kg N/ha after each clipping.

Table 3. Partial regression coefficients for the multiple regression equations for plant yields on three soils.

	Bladen loam		Leon fine sand		Lakeland sand	
	Millet	Oats	Millet	Oats	Millet	Oats
bo	5.29×10^{-1}	5.61	4.98	2.01	-2.62×10^{-1}	5.62
L	2.83×10^{-1}**	6.55×10^{-1}**	1.83**	1.58**	3.10×10^{-1}	4.08×10^{-2}
P	7.48×10^{-1}**	4.29×10^{-1}**	2.99×10^{-1}**	2.89×10^{-1}**	6.00×10^{-1}**	3.11×10^{-1}**
K	4.12×10^{-2}**	4.80×10^{-2}**	9.40×10^{-2}**	5.22×10^{-2}**	9.13×10^{-2}**	3.31×10^{-2}**
L^2	-8.80×10^{-3}**	-2.34×10^{-2}**	-1.53×10^{-1}**	-9.64×10^{-2}**	-1.82×10^{-2}	-9.78×10^{-3}
P^2	-4.49×10^{-3}**	-1.40×10^{-3}**	-2.06×10^{-3}**	1.84×10^{-3}**	-3.88×10^{-3}**	-2.04×10^{-3}**
K^2	-1.63×10^{-4}**	-2.52×10^{-4}*	-6.26×10^{-4}**	-2.45×10^{-4}**	-5.93×10^{-4}**	-2.44×10^{-4}**
LP	2.87×10^{-3}**	4.69×10^{-4}	2.59×10^{-3}*	-1.91×10^{-3}	4.71×10^{-3}*	2.58×10^{-3}**
LK	1.40×10^{-4}	1.09×10^{-3}	2.65×10^{-3}*	-2.09×10^{-3}	-3.87×10^{-4}	6.48×10^{-4}
PK	3.67×10^{-4}**	9.10×10^{-5}	4.62×10^{-4}**	1.54×10^{-4}	6.58×10^{-4}**	4.78×10^{-4}**
LPK	-5.55×10^{-6}*	4.04×10^{-6}	-3.33×10^{-5}	2.31×10^{-5}	1.63×10^{-5}	-2.46×10^{-5}
R^2	0.96	0.83	0.90	0.92	0.95	0.92

* Denotes significance at 5% level. ** Denotes significance at 1% level.

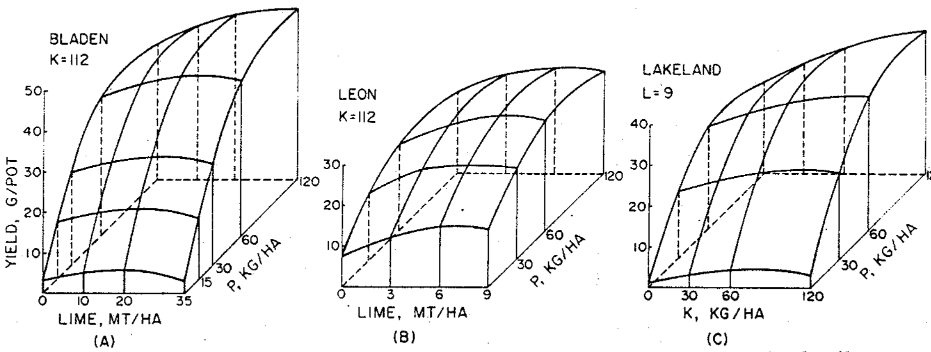

Fig. 1. Yield response surfaces for millet on Bladen, Leon, and Lakeland soils.

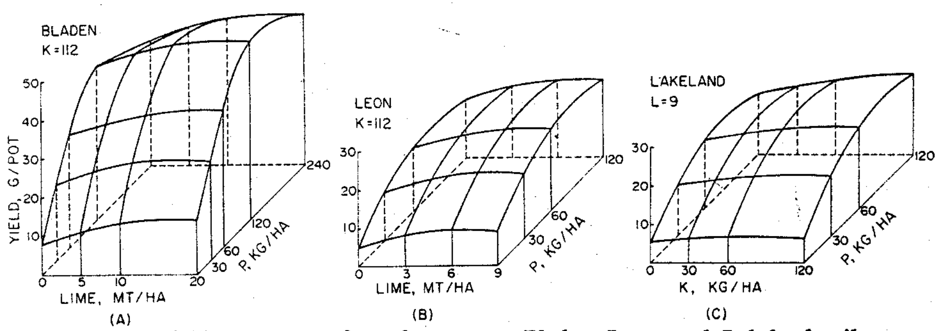

Fig. 2. Yield response surfaces for oats on Bladen, Leon, and Lakeland soils.

K are kilograms of phosphorus and potassium added per hectare, respectively.

The b values and R^2 for the multiple regression equations are presented in Table 3. The R^2 values for the equations range from 0.83 to 0.96. Thus, from 83 to 96% of the variation in yield was accounted for by the different rates of L, P, and K added. Because such a high percentage of the variation in yields was accounted for by the fertilizer variables, no attempt was made to evaluate any statistical model other than the quadratic.

The positive coefficients for the L, P, and K terms denote that yields were increased by these treatments. The negative coefficients for the L^2, P^2, and K^2 terms indicate that the yield increase from each increment of the variable decreased as the rate of the variable increased.

Yield response surfaces prepared from the yields predicted by the multiple regression equation are shown in Fig. 1 and 2. These response surfaces show the effect on yield of varying two of the nutrients with the third held constant. The least-responsive nutrient was held constant at a rate considered adequate to remove it as a growth-limiting factor, and yield was plotted vs the other two nutrients.

In Bladen soil the major response was to P (Fig. 1A). At the 0 and 10 metric tons/ha rates of L, there was P response through 60 kg/ha, and at the 20 and 35 metric tons/ha rates of L there was P response through 120 kg/ha. Lime gave a significant response through 20 metric tons/ha. At 0 P, there was a significant decrease in yield at a L rate of 35 metric tons/ha compared to the 20-metric-tons/ha rate. However, such decreases did not occur at the 120 kg/ha rate of P. Soil pH ranged from 4.3 to 0 L to 7.0 at 35-metric-tons/ha, and was 6.5 at the 20-metric-tons/ha rate.

The response surface for millet on Leon soil is shown in Fig. 1B. The millet responded to L through 6 metric tons/ha, with a tendency for response to L to decrease with increasing rates of P. There was response to P through 60 kg/ha at all levels of L. Soil pH ranged from 3.3 at 0 L to 4.6 at 6 metric tons/ha of L, and was 5.1 at the 9-metric-ton/ha rate.

In the Lakeland soil, L produced the least response of the added variables and was held constant at 9 metric tons/ha. Here, the major response was to P (Fig. 1C). At a K rate of 60 kg/ha or less, there was P response through 60 kg/ha, but at the 120-kg/ha rate of K there was P response through 120 kg/ha. Although K response was small, it was highly significant. At the 0 and 30-kg/ha rate of P, there was K response through 60 kg/ha, but at the 60- and 120-kg/ha rate of P there was K response through 120 kg/ha.

Oat yield response surfaces for the three soils are shown in Fig. 2. In the Bladen soil (Fig. 2A), response was much greater to P than to L, but both responses were highly significant. There was response to P through 120 kg/ha, regardless of the rate of L, and there was response to L through 10 metric tons/ha, regardless of the rate of P. In most cases, yields were higher at the 20-metric-ton/ha rate of L than at the 10-metric-ton/ha rate, but the increase was not significant at the 5% level. Soil pH values were 4.3, 5.0, 6.5, and 7.0 at 0, 10, 20, and 35 metric tons/ha of L, respectively.

Oat yields on the Leon soil (Fig. 2B) were only about 50% of those of the Bladen, but L and P responses were similar. However, highest yields on the Leon occurred at lower L and P levels. There was P response through 60 kg/ha, regardless of the rate of L. There was response to L through 6 metric tons/ha. Soil pH values were 3.3, 4.0, 4.6, and 5.1 at 0, 3, 6, and 9 metric tons/ha of L, respectively.

On the Lakeland soil, there was oat yield response to P through 60 kg/ha, regardless of the rate of K (Fig. 2C). Response to K, however, was affected by the rate of P. There was little response to K at 0 P, but at 120 kg/ha of P there was response to K through 120 kg/ha.

Analysis of variance showed that the interaction of P × K was significant with both crops on all three soils. The interaction of L × P was significant in all cases except with millet on the Leon soil. In no case was the interaction of L × K or L × P × K significant.

Yield isoquants for millet and oats on the three soils are presented in Fig. 3 and 4. The multiple regression equation, which was used in calculating predicted yields, is the basic equation from which the isoquant equations were derived. These isoquants represent the combinations of rates of two variables that will result in a specified yield with the third variable fixed. Because of the interactions present in this experiment, the isoquant curves for two variables are dependent on the rate of the fixed third variable. The curves shown in Fig. 3 and 4 fix the least-responsive variable at a level considered adequate to remove it as a limiting factor. In Bladen and Leon soils K was the least responsive, and was fixed at 9 112 kg/ha. In the Lakeland, L was least responsive and was fixed at metric tons/ha. The Y values shown are in grams/pot.

The phenomenon of an increase in one variable decreasing the required quantity of a second variable in order to maintain a specified yield has been referred to as "replacement" or "substitution" of one variable for another (5). The use of "replacement" or "substitution" does not imply physiological substitution of one element for another. The isoquant curves show that such replacement occurred in this experiment. With the possible exception of Bladen, the magnitude of the replacement appeared to be related more to the soil than to crop requirement, as evidenced by the similarity of the curves within soils, regardless of the crop.

The least replacement of L and P occurred in the Bladen with millet (Fig. 3A). However, the replacement effect tended to increase with increasing yield. With oats on Bladen, replacement was of considerable magnitude. At a 40-g/pot yield and 16 metric tons/ha of L, approximately 80 kg/ha of P was required, whereas with no L approximately 115 kg/ha of P was required (Fig. 4A) to produce the same yield.

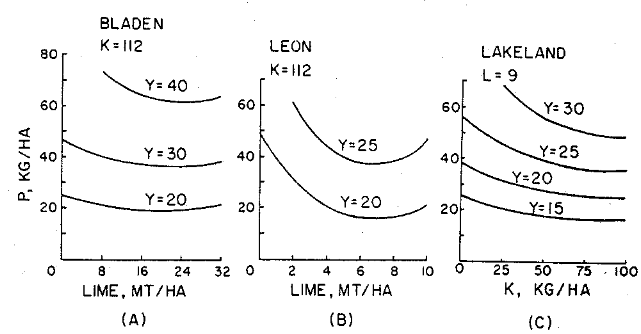

Fig. 3. Yield isoquants for millet on Bladen, Leon, and Lakeland soils.

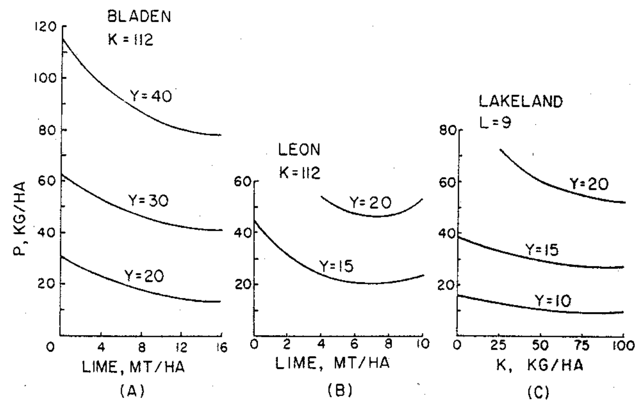

Fig. 4. Yield isoquants for oats on Bladen, Leon, and Lakeland soils.

On the Leon soil the replacement effect was more pronounced. With millet (Fig. 3B) a 20-g yield was obtained with 6 metric tons/ha of L and 15 kg/ha of P. To maintain the same yield with no L required approximately 50 kg/ha of P. The same relationship existed with oats, where yields were slightly lower (Fig. 4B). The relationship between L and P is not expressed by a single constant applicable to all rates. This is evident because the slope of the isoquant curves is not the same at all rates. For example, at a 20-g yield of millet (Fig. 3B), the first 2 metric tons/ha of L replaced about 20 kg/ha of P, but the next 2 metric tons/ha of L replaced about 10 kg/ha of P. In some cases, at the higher rates of L, an increase in L required an increase in P to maintain a given yield, as shown by the upturn of the curve.

On the Lakeland soil L was held constant at 9 metric tons/ha, and the isoquant curves are shown vs P and K. The curves show some replacement effect of P and K with both crops (Fig. 3C, 4C), with the effect more pronounced at the higher than at the lower yields.

On soils with initial pH as low as these, one would expect a greater response to L than was obtained. Trace element deficiency was eliminated as a possible growth-limiting factor based on the results of a companion study, which showed no significant response to B, Zn, Cu, Mn, Mo, or Fe. Since there was a consistent interaction of L and P throughout the study, an experiment was conducted to determine the effect of L *per se* on the root system, without the addition of P to the soil, but with the P being supplied from an outside source. The need for supplying the P requirements from a source outside the soil is obvious, due to the interrelationship of L, P, and soluble Al in the soil solution. The apparatus used is shown in Fig. 5. All three soils were used with and without L, using millet as the test crop. The rate of 100-mesh dolomitic limestone (L) used was 18, 9, and 9 metric tons/ha for the Bladen, Leon, and Lakeland soils, respectively. One millet root was threaded through the tube into the side container, where it grew into the sand culture through which there was a continuous flow of nutrient solution containing P. Mean root weight was greater with L in the Leon and Lakeland soils, but not in the Bladen soil. There was, however, a marked difference in appearance of roots with and without L in all cases (Fig. 6). With L, the roots were light in color, fibrous, and had considerable branching. Without L, they were very dark, short, stubby, and had very little branching. Thus, the roots with L obviously were much more desirable with a much greater specific surface than those without L.

Aluminum Studies

The possibility of soluble Al being a growth-limiting factor in these soils at low pH was considered. The maximum amount of Al in solution would have occurred with no L and with the maximum amount of added N and K salts. After adding these salts, the soil solution was displaced and analyzed for Al. The Bladen, Leon, and Lakeland soil solutions contained 22.3, 6.0, and 2.8 ppm Al, respectively. The amount of Al in the Bladen was extremely high, and that in the Leon and Lakeland was high enough to be toxic to most plants (1, 2, 7, 9, 13).

An Al tolerance test was conducted on the millet and oats using solution culture. The criterion used was mean daily root elongation rate. Although there was considerable variation in the millet results, there was no indication of any adverse effect of Al on millet root elongation rate up to 16 ppm, indicating an unexpectedly high tolerance to Al (Fig. 7).

The oat roots were much less tolerant of Al than were the millet roots (Fig. 7). Two ppm Al reduced oat root elongation rate to less than 50% that at 0 Al. This plant, however, is not as sensitive to Al as some other plants. For example, 0.5 ppm Al drastically reduced root development of 'Empire' cotton (*Gossypium hirsutum* L.) (14).

Thus, whereas the low yield response of millet to lime applied to these very acid soils may reflect, at least in part, the extreme tolerance of millet roots to Al, the relatively small lime effects on oat yield cannot be explained in the same way. A more likely explanation could be that reduced root growth due to Al toxicity in the unlimed acid soils did not seriously limit the water and nutrient supplies of the plants under pot culture where near-ideal moisture conditions were maintained. Other workers have clearly shown that cotton root development, for example, can be restricted by Al, under such conditions, without a proportionate reduction in top growth (15). This rationalization, of course, implies extreme caution in extrapolating pot-test lime response results to field situations where moisture stress would be accentuated by restricted root systems.

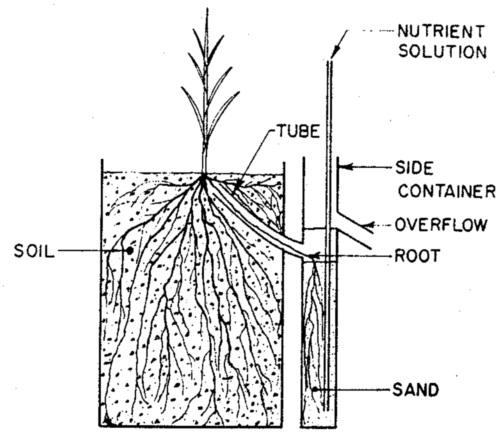

Fig. 5. Apparatus used to isolate effect of lime on root development.

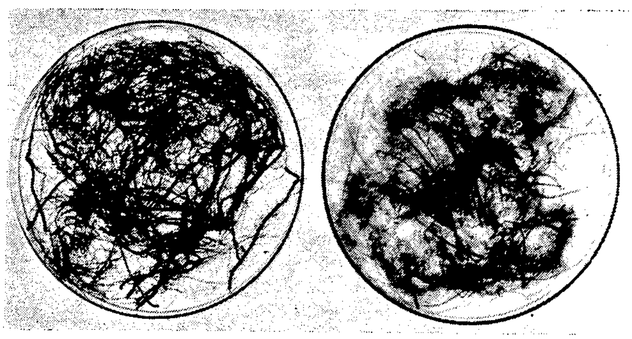

Fig. 6. Character of millet roots without lime (pH 4.0) (left) and with lime (pH 5.3) (right).

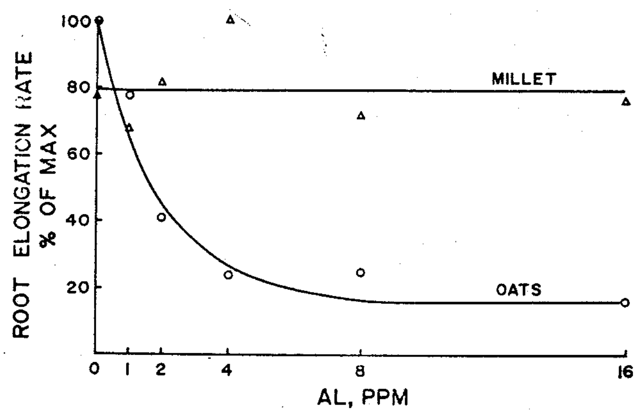

Fig. 7. Millet and oat root elongation rates as affected by Al in solution.

SUMMARY AND CONCLUSIONS

The responses of oats and millet to applications of L, P, and K were determined on three soils typical of the Atlantic Coast Flatwoods region. Phosphorus was, by far, the most critically growth-limiting factor on all soils for both crops. Both crops responded to

L and K applications in all soils, however, and interactions of L $\times$ P and P $\times$ K were significant in all but one case. Multiple regression yield equations fit the results to the extent that 83 to 96% of the variation in yield was explained by the treatments.

Response to lime was less than was expected, in view of the very low soil pH values and the high soil solution Al levels. Possible explanations are (i) that millet roots are unusually tolerant of Al; and (ii) that even though oats was fairly sensitive to Al, in pot tests root damage by Al toxicity could be largely offset by the favorable moisture and nutrient levels maintained, thus reducing the importance of root proliferation into a large volume of soil. Even though the millet was extremely tolerant to Al in nutrient solution, there was a definite beneficial effect on the root system by L, with P being supplied from a source outside the soil.

Yield response surfaces, prepared from the yields predicted by the multiple regression equations, show the effect on yield of varying rates of two variables, while the third is held constant.

Yield isoquants show that there are many combinations of L and P that result in a specified yield with K held constant at an optimum value.

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