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N. H. MONTEITH and G. DONALD SHERMAN

INTRODUCTION

Several current field experiments in the Hawaiian sugar industry have shown that liming has increased both yield of sugar and phosphorus uptake by the plant. These results have been of considerable interest to the industry and have brought to focus the whole question of the value of soil amendments in sugar cane production in the Hawaiian Islands.

Early experiments by McGeorge (1924) had shown beneficial results from the application of soluble silicate to sugar cane soils. He attributed the beneficial effect on sugar cane growth to a greater availability of phosphorus in the soil. Sherman *et al.* (1955) obtained similar results using a number of Hawaiian soils. More recently, Clements (1962) and Rixon (1963) reported, respectively, effects beneficial to yield and to soil phosphorus availability, from studies they made on a number of sugar cane soils on the Hamakua coast.

This interest led to the initiation of this study, which had as its objective a comparative study of the effects of application of calcium silicate and calcium carbonate on the growth of plants and on the availability of phosphorus when applied to a soil having aluminum oxides in a fairly good state of crystallinity against a soil in which aluminum exists in a highly hydrated colloidal oxide system.

LITERATURE REVIEW

Effect of Calcium Carbonate on Phosphorus Availability

The effect of calcium carbonate on phosphorus uptake has been studied and recorded for many years. Johnston (1849), Ruffin (1852), and Hilgard (1907) discussed the question at an early stage in the research.

A considerable amount of work has been done in Germany, where Engels (1936) came to the conclusion that lime prevented the formation of insoluble iron and aluminum phosphates. Köttgen and Jung (1941) showed that small amounts of lime increased the phosphorus available in the subsoil and that deficiencies of phosphorus could be corrected by adding lime. Mitscherlich (1947) found that phosphorus fixation decreased with applications of 15 gm. lime per pot. Gericke (1951) reviewed some

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[1] This technical bulletin is part of a thesis submitted by the senior author to the Graduate School of the University of Hawaii in partial fulfillment of the requirements for the Master of Science degree.

of the evidence on liming from work performed in Germany. His investigations showed that liming increased the phosphorus availability on strongly acid soils by 0.7 mg. per 100 gm. but not when the pH of the soils was above 6. He considered that lime corrected "unfavorable" conditions for plant growth and this enabled the plant to utilize the less soluble forms of phosphorus. Several workers have thought that organic phosphorus may be released by lime or by the breakdown of organic matter. Ghani and Aleem (1942), in India, suggested that the increase in phosphorus availability, through the application of lime, was due not to a decrease in the formation of aluminum and iron phosphates, but to the release of phosphorus from organic matter, resulting from a change in reaction which favored microbial action and the breakdown of the organic matter. Salonen (1946), in Finland, reported that liming increased the breakdown of organic phosphorus. Mattson *et al.* (1950), in studying a limed and an unlimed Podsol, thought that the formation of B humus by liming mobilized phosphorus, as more available phosphorus occurred in the subsoil of the limed Podsol than in the subsoil of the unlimed soil.

There is also evidence that under certain circumstances lime applications can decrease phosphorus availability. Máté and Molnár (1956), in Hungary, showed phosphorus fixation increased with liming. Loo, Yu, and Wan (1956), in China, stated that increased fixation is not encountered until liming increased the pH of the soil to 7.5. Lawton and Davis (1956), working on acid organic soils, found increased phosphorus fixation due to liming was apparently caused by a decrease in the proportion of $H_2PO_4^-$ to HPO_4^{--} ions. Phosphorus can be fixed in acid soils by combining with iron and aluminum, and, in alkaline soils, by being precipitated as calcium phosphates.

The increase in phosphorus availability due to liming seems to be associated, then, with soils having a predominating iron-aluminum system. This conjecture appears to be supported by the work of Yudin (1958), in Russia, who found that lime increased the utilization of fertilizer phosphorus by the plant in the Krasnozem soils more than in other types of soils. Similar work with tropical soils is still relatively undeveloped. McGeorge (1924), in Hawaii, suspected that liming increased the phosphorus uptake in sugar cane. Hardy (1934), in Trinidad, by liming, obtained a 39 to 67 percent increase in available phosphorus. Beater (1945) reported a 20 percent greater phosphorus uptake in maize; and nitrogen and calcium uptake were also higher. Monteith *et al.* (1958), in Fiji, found in a study of soil pH and available phosphorus that the expectancy of high soil phosphorus increased as the pH increased to approximately pH 7.5, after which it decreased. They (1959) also recorded liming with coral sand produced an increase in nitrogen uptake in sugar cane, especially at low fertilizer nitrogen levels. Schroo (1954) demonstrated that liming increased the P_2O_5 content of sugar cane juice by 40 percent.

Clements (1962) has found, upon liming Hydrol Humic Latosol soils in Hawaii, that marked increases occur in the phosphorus uptake by sugar cane.

Leaching experiments have shown that liming promotes the leaching of phosphate ions. MacIntire *et al.* (1947) have fully illustrated this in a 12-year leaching experiment. They detected the phosphorus by chemical means; other workers have used radioactive P^{32} to trace the movement of phosphorus in soil columns (Bouldin and Black, 1954; Heslep and Black, 1954).

Effect of Calcium Carbonate on Other Factors

The application of calcium carbonate to soil can affect other factors which can cause growth stimulation. The following effects can be produced in the soil by liming:

1. Reduction of the aluminum or manganese toxicity in a soil (Mulder and Gerretsen, 1952).
2. General increase in the effectiveness of other soil elements in plant nutrition (Truog, 1953).
3. Development of physical conditions more favorable for plant growth in soil (Coleman *et al.*, 1958).
4. Improvement of microbial nitrogen fixation in soils (Black, 1957).
5. Supplying of calcium as a nutrient in very acid leached soils (Ayres, 1961).

Fried and Peech (1946) discussed calcium as a plant nutrient in the introduction of their paper and came to the conclusion that supplying additional calcium to the plant is generally not important. They stated, however, that with soils of equal calcium content lime often gives better results than gypsum.

As indicated above, several workers have reported that liming reduces the "active" aluminum content in the soil and therefore the so-called "toxicity" due to aluminum is correspondingly reduced. Much of this work has been carried out by Russian and German soil scientists. Chizhevskii and Korovkin (1958), Peterburgsky (1941), Peive (1939), and Fatchikina (1953) all found that active aluminum was reduced by the action of lime and that plant growth improved.

It has been observed by Menchikovsky and Puffeles (1938) that calcium salts can be responsible for reducing active aluminum in soils. Chernov and Belyaeva (1946), in their interesting studies on the nature of soil acidity, came to the conclusion that calcium uptake is suppressed completely by $AlCl_3$ at pH 4 to 5. Schmehl, Peech, and Bradfield (1950), Moschler, Jones, and Thomas (1960), and Rixon (1963) have studied the effects of aluminum on other elements and the influence of lime on Al activity. Duthie and Bourne (1939), in British Guiana, and several Japanese workers (Hosoda, Takata, and Ogihara, 1957) have also found a reduction in "active" aluminum occurs due to liming.

Effect of Calcium Silicate on Phosphorus Availability

The effect of calcium silicate (basic slag) on phosphorus availability has also been studied extensively. Even as early as 1906, Hall and Morison, at Rothamsted Experimental Station, England, concluded that sodium silicate responses were similar to phosphorus responses. Scheidt (1917) compared calcium silicate and calcium carbonate treatments and found calcium silicate gave a better response. Conner (1921) also considered that this difference was due to the greater ability of calcium silicate to precipitate active iron and aluminum. McGeorge (1924), in Hawaii, analyzed soils for silica and found that the lower the silica content the more likely a response to phosphorus. High silica meant high phosphorus in the juice of sugar cane. Sherman *et al.* (1955) obtained increased utilization of phosphorus with silicate application, but did not find a relationship to silica content of soils.

Scarseth (1935) obtained a growth increase by the use of silicate compounds which was similar to that obtained by the use of phosphorus compounds. Toth (1939) showed that the soil phosphorus complex broke down with the use of high-pH anions such as SiO_3 and OH; and Low and Black (1948) indicated that the reverse reaction was true when silica was released from clay minerals by the use of phosphorus compounds. This suggested that additions of silica would slow down the release of phosphorus from clay minerals and thus tend to prevent phosphorus from being absorbed by clays. Knickmann (1949), in Germany, found that the loss of phosphorus in the drainage water was less with slag than with lime.

Schollenberger (1922) noted that there was a greater phosphorus uptake with lime and silica than with lime alone, and that the response to lime plus silica was a vegetative response and therefore similar to a nitrogen response. In this regard, Ziemiecka (1929) reported that the phosphorus nutrition of *Azotobacter* is assisted by the addition of colloidal silica.

Effect of Calcium Silicate on Other Factors

It has been pointed out by Fatchikina (1953) that a silicate (dunite), as well as liming, can be effective in reducing “toxic” levels of aluminum.

MacIntire, Winterberg, Dunham, *et al.* (1946) showed that “glassy” slags can be converted to calcium carbonate and that the CO_2 required for the conversion could be derived from bacterial activity. Crystalline calcium silicate, however, is not easily converted to calcium carbonate. The mechanism involved whereby calcium silicate prevents the absorption of phosphorus by clays and precipitates active iron and aluminum, and perhaps even supplies silicon to the plant, is not clear, even though it has been postulated that calcium silicate acts in the same manner as calcium carbonate. Little work has been done on this aspect of the role of calcium silicate in tropical soils.

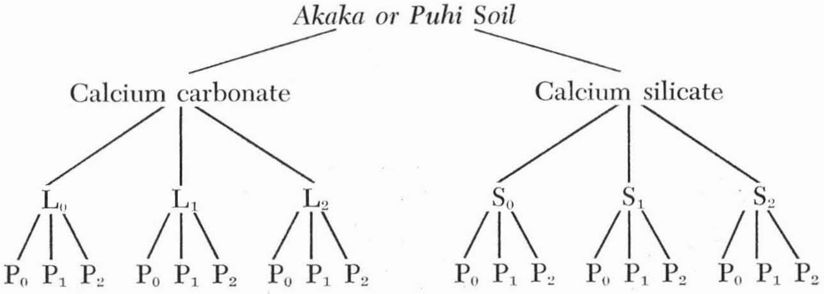
A study of the data and a review of the literature have led to the formation of the following hypotheses relating to the mechanism of yield increase by liming:

1. The breakdown of organic matter
   a. chelates "toxic" elements such as aluminum and removes them in the drainage water.
   b. releases mineral phosphorus and other plant nutrients.
2. Calcium is a limiting factor in growth in lime-treated soils.
3. Liming induces better crystallization in the $Al(OH)_3$ system of the soil, by decreasing "toxic" amounts of aluminum. (This system is known to exist in at least one of the soils used in this study.)
4. Fixed phosphorus is released by the action of an OH^- or SiO_3^{--} ion, and thus growth is improved. This should occur only if phosphorus is a limiting factor, or if phosphorus decreases a "toxic" factor such as aluminum.
5. Increased microbial activity is accompanied by increased nitrification.
6. By increasing the pH of the soil, other elements, if toxic to the plant, are reduced in concentration; or, the lack or insufficiency of some element, which has been limiting plant growth, may be corrected by liming.

An experiment was designed to test some of these hypotheses, and the results are presented in this report.

EXPERIMENTAL PROCEDURES

A pot experiment was designed to obtain results from two different soils. In each soil, half the treatments consisted of 3 levels of calcium carbonate (c.p. grade) and the other half, 3 levels of calcium silicate (c.p. grade). Each of these 12 levels was treated with 3 levels of monocalcium phosphate dihydrate (c.p. grade); there were three replicates of each treatment (108 individuals in all). The layout was a randomized block design.



P = phosphate L = lime S = calcium silicate

Soils

Akaka Silty Clay was collected from the plow layer of field 2 of Laupahoehoe plantation, Hawaii, immediately after the harvest of the sugar cane crop. The other, a Puhi Silt Loam, was collected at Grove Farm plantation, Kauai, likewise from the plow layer and also immediately after the harvest of the sugar cane crop

Akaka soil is a Hydrol Humic Latosol which drastically changes its characteristics on excessive drying; the cation exchange capacity is lowered (Kanehiro and Chang, 1956), and the soil will not rewet to moisture contents found normally in the field. Precautions were therefore taken to prevent excessive drying. This soil has a high content of hydrated colloidal amorphous aluminum, and iron oxide and hydroxide gels. On drying, gibbsite will crystallize with a considerable increase in particle size (Sherman, 1957).

Puhi soil is a Humic Ferruginous Latosol. The characteristics of this soil are altered on drying, but not to the same extent as those of Akaka soil (Trouse, 1960). Precautions were also taken with the Puhi soil to prevent drying. The aluminum and iron oxides exist in these soils in crystalline mineral form as gibbsite, goethite, hematite, and maghemite.

The Akaka soil for this experiment was passed through a ¼-inch-mesh sieve and thoroughly mixed in a mechanical mixer. The Puhi soil was passed through a 5-mm. sieve and mixed. At this point, the moisture content of the Akaka soil was 107 percent and that of the Puhi soil was 42 percent. Volumetrically, 4500 gm. wet weight of Akaka soil occupied approximately 8500 cc.; and a similar wet weight of Puhi soil occupied 4000 cc. Approximately half of the volume of Puhi soil taken from the field consisted of rocks; thus 4500 gm. would occupy approximately 8000 cc., and therefore 4500 gm. were taken for each soil as an approximate adjustment to obtain equal field volumes.

Treatments

In a stainless steel rotary mixer, each of the calcium carbonate and calcium silicate treatments was thoroughly mixed with a 4500-gm. sample of soil and then each mixture was placed in a Mitscherlich pot. The S_1 and L_1 treatments were at 5000 pounds per acre, or 18.12 gm. per pot. The S_2 and L_2 treatments were at 20,000 pounds per acre, or 72.48 gm. per pot. These pots, with proper precautions to prevent moisture loss, were then stored for 7½ weeks to allow time for the pH of the soil to reach equilibrium before planting. At the end of this period, the phosphorus treatments were applied. The chemical was stirred into the top 1½ inches of the soil. The treatments were P_1 at 500 pounds monocalcium phosphate per acre, or 1.81 gm. per pot; and P_2 at 2000 pounds monocalcium phosphate per acre, or 7.24 gm. per pot.

Growth

Pots were planted with Sudan grass seed (California No. 23) and supplied with 0.9 gm. urea and 0.9 gm. potassium chloride per pot at approximately 3-week intervals; they were watered twice a day with tap water.

Harvesting

The Sudan grass was harvested at the first sign of flowering, 6 weeks after planting, and placed in a hot-air oven at 65° C. for 1 week. The dry weight yields were recorded. Plant material was then ground in a Wiley Mill and bottled for analysis.

The root-bound block of soil was removed from the pot and cut in half. The soil from one of these halves was subsampled and bottled in a moist state for soil analysis (pH was taken immediately). Roots were separated from the other half by jetting the soil free with a high-pressure water jet. The roots were then oven-dried at 60° C., weighed, and ground in a Wiley Mill. They were subsequently examined under a binocular microscope at 80× power to determine whether contamination by soil particles had occurred.

Leachates

Although the pots were kept moist, no water passed through the pots into the collecting pan until 3 days after planting, at which time 600 cc. of water had been added to each pot. Twenty-five ml. of the leachate were taken from each collecting pan and the amounts from each of the three replicates for each treatment were combined to give 75 ml. for each treatment. The pH of each combined leachate was recorded, using a Beckman pH meter. Phosphorus analysis was carried out, using the method of Truog (1953).

A week prior to harvesting, all of the collecting pans contained leachate. A total of 150 cc. was taken from two of the replicates and a bulk sample was made up. The pH and phosphorus content of this sample were recorded; and the aluminum content was determined by the aluminon method described by Chenery (1948).

Plant Chemical Analysis

Plant samples which had been previously ground and dried were redried at approximately 70° C. and placed in a desiccator. From these, 2 gm. of plant top samples and 1 to 2 gm. of root samples were taken for chemical analysis. These samples were then ignited in a muffle furnace at 480° C., taken up in concentrated hydrochloric acid, evaporated to dryness, and baked on a hot plate for a period of 4 hours to complete silica crystallization.

Following this, each of these samples was then taken up in 3 N hydrochloric acid and made up to volume. Aliquots were taken for: (1) phosphorus analysis (by the method of Truog and Meyer, 1929); (2) calcium analysis (by the Beckman DU flame photometer with photomultiplier, using a compensated standard developed by the Plant Physiology Department of the University of Hawaii); and (3) aluminum analysis (by the aluminon method of Chenery, 1948). The same methods of analysis were used for both top and root samples.

Soil Chemical Analysis

All samples were in a moist condition and therefore the moisture content of each sample was determined in order to convert all results to an oven-dry weight basis. The pH was determined on the soil as a soil-water paste; the paste was allowed to stand for 1 hour before recording the pH. Extractable phosphorus was determined by using the 0.02 N sulfuric acid extractant (Ayres and Hagihara, 1955) and carrying out the analysis by the method of Truog and Meyer (1929). Extractable aluminum analysis was carried out according to the method of Pratt (Nelson, 1958), using 100 ml. of N ammonium acetate and 0.1 N barium chloride solution ($pH = 4.8$) as the extractant on 10 gm. of moist soil.

Cation exchange capacity was determined on 20 gm. of moist soil by saturating the soil in 250 ml. of N ammonium acetate overnight with intermittent shaking. The soil was filtered, and the filtrate was retained for calcium and potassium determinations. Excess ammonium acetate was washed from the soil with ethanol, and the ammonium was leached out by N potassium chloride solution adjusted to pH 2.5. The leachate was made up to volume, and ammonia was determined by using the Nessler reagent method.

Calcium in the ammonium acetate was analyzed by use of the Beckman DU flame photometer with photomultiplier. This method has been developed by the Hawaiian Sugar Planters' Association (Ayres, 1961). Potassium was also determined by using the Beckman DU flame photometer.

EXPERIMENTAL RESULTS

Yield

The yield results for the pot experiment are shown in tables 1 and 1A. Analysis of variance for the yield is shown in table 2. In both soils, the yields of Sudan grass were significantly increased by each increment of phosphorus. In the Akaka soil the effect of rates shows a linear relationship, whereas in the Puhi soil the relationship is curvilinear. Lime and calcium silicate applied separately at the rate of 5000 pounds per acre increased the yield in the Akaka soil but did not increase yield in the Puhi soil. Lime at the 20,000-pound-per-acre rate tended to decrease yield in the Akaka soil and did significantly decrease yield in the Puhi soil; however, calcium silicate at the 20,000-pound-per-acre rate increased yield in both the Akaka and Puhi soils.

TABLE 1. Effect of applications of liming materials and monocalcium phosphate on yields (in grams of dry matter) of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	19.8	33.7	28.3	19.8	25.7	41.7
500	26.2	46.3	42.7	26.2	41.7	63.7
2000	38.3	64.7	58.0	38.3	59.7	83.3
		PUHI SOIL				
0	35.8	28.6	24.0	35.8	35.6	49.0
500	72.8	69.0	35.6	72.8	66.3	85.3
2000	85.8	93.3	53.6	85.8	84.3	92.0

TABLE 1A. Effect of applications of liming materials and monocalcium phosphate on yields (in grams of dry matter) of roots of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	3.0	3.9	4.4	3.0	3.4	5.1
500	2.6	6.1	7.5	2.6	3.8	8.1
2000	4.6	12.6	10.1	4.6	9.2	13.9
		PUHI SOIL				
0	5.6	4.3	2.9	5.6	4.5	8.7
500	12.1	10.9	4.8	12.1	10.9	12.9
2000	13.9	14.5	7.0	13.9	13.6	17.2

The over-all interaction of phosphorus × calcium rates is not significant, but it is important to note that the soil's phosphorus × calcium interaction is significant; this interaction is evident in the Akaka soil but not in the Puhi soil.

TABLE 2. Significance of F values in the analysis of variance of various factors in pot experiments with Sudan grass on Akaka and Puhi soils

SOURCE	TOPS				ROOTS
	Yield	% P	% Ca	ppm Al	ppm Al
Soils	**				*
Phosphorus (P)	**	**	*		
Rates of calcium (Ca)	**		**		
Source of calcium (CS)	**	*	**	**	
S × P	**	**			
S × Ca	**				
S × CS	**		**	**	
P × Ca					
P × CS					
Ca × CS	**		**	**	
S × P × Ca	**				
S × P × CS		*			
S × Ca × CS	*	**			
P × Ca × CS	*	**			
S × P × Ca × CS		*	*		
Mean	51.8	0.111	0.93	130.6	2404
Coefficient of variation	13.46%	9.82%	10.56%	27.98%	29.82%
$S_{\bar{x}}$	4.028	0.0065	0.057	21.11	717
Approximate L.S.D.	12 gm.	0.020%	0.170%	63.0 ppm	2150 ppm

** Significant at 1% level.
* Significant at 5% level.

Inasmuch as a study of the depressed yield at the L_2 level is considered outside the scope of this investigation, the results will be only briefly discussed, and those for the L_2 and S_2 levels have been omitted from all graphical relationships. The results of the root chemical analysis in the Puhi series are considered unreliable because there was a possibility of root contamination due to soil particles. Contamination in the Akaka series, however, is considered unlikely, as high-yielding plants showed a low aluminum content.

Root yield is presented in table 1A. In both soils, there was a definite response in root growth to applications of phosphorus and also to the application of calcium silicate. In the Puhi soil, application of high amounts of lime caused a decrease in root growth.

Plant and Soil Analysis

Phosphorus: Phosphorus was extracted from the soil by using 0.02 N sulfuric acid, and the results show a significant increase in P with each level of added phosphorus (table 3). The nil P level value of the Puhi soil indicates that there may have been insufficient phosphorus for optimum plant growth. The nil P level of the Akaka soil indicates that there should be sufficient phosphorus for growth in this soil. For the Puhi soil, the available phosphorus ranged from an average of 8 ppm for nil P to 46 ppm for soil receiving the highest P application, while for the Akaka soil the same treatments gave 33 ppm and 98 ppm, respectively.

TABLE 3. Effect of applications of liming materials and monocalcium phosphate on the amount of available phosphorus (as ppm P) extracted from Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	41	37	25	41	26	32
500	49	61	45	49	54	42
2000	82	107	106	82	78	94
		PUHI SOIL				
0	9	8	10	9	7	9
500	17	20	23	17	15	15
2000	40	50	50	40	39	47

The Puhi soil studies show phosphorus content in the roots (table 4) increased with added phosphorus; but the Akaka soil studies show no significant increase in phosphorus concentration occurred when phosphorus was added, and, moreover, a decrease occurred when lime or calcium silicate was added.

The phosphorus content of tops of Sudan grass is presented in table 5. The significance of the interactions presented in table 2 indicates that the percentage of phosphorus generally increased with added phosphorus. In the Akaka soil series, compared with the Puhi series, there was little increase in phosphorus content from the application of phosphorus at the rate of 2000 pounds per acre. Both lime and calcium silicate increased the percentage of phosphorus uptake in the Puhi series, but only at the high

TABLE 4. Effect of applications of liming materials and monocalcium phosphate on the phosphorus content (as percent P) of roots of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
			AKAKA SOIL			
0	0.125	0.092	0.106	0.125	0.111	0.101
500	.135	.109	.124	.135	.098	.097
2000	.119	.104	.089	.119	.113	.089
			PUHI SOIL			
0	.091	.079	.111	.091	.085	.069
500	.074	.080	.102	.074	.079	.086
2000	.105	.124	.138	.105	.114	.148

level of phosphorus; there was no marked increase in the uptake of phosphorus by plants grown under identical treatments on the Akaka soil. The phosphorus content of the plants receiving nil P on the Akaka soil was higher than the phosphorus content in plants grown under identical treatments on the Puhi soil, thus presenting further evidence that the plants grown in the Akaka series nil P treatment pots received sufficient phosphorus from the soil, whereas those in the Puhi series did not.

The analysis of the yield data and chemical composition of the Sudan grass and soils is presented in figure 1. There is a significant relationship between yields of Sudan grass grown on the Puhi soil and the phosphorus content of the tops and the roots of the plants and also the amount of available phosphorus in the soil. There is no relationship between yield of Sudan grass grown on the Akaka soil and the chemical composition of the plant tops; but there is a negative relationship with the phosphorus content of the plant roots and a positive one with the available phosphorus in the soil.

Calcium: In both soils, application of lime or calcium silicate increased the exchangeable calcium content. The data obtained are presented in table 6. The highest content of exchangeable calcium was obtained from the application of lime to the Akaka soils, and ranged from 1.2 milliequivalents per 100 gm. for the soil of the control to 24.2 milliequivalents per 100 gm. for the soils receiving 10 tons of lime per acre; the range for the same treatments on the Puhi soil was from 0.9 milliequivalent per 100 gm. to 13.9 milliequivalents per 100 gm., respectively. The content of exchangeable calcium of the soils receiving calcium silicate was also increased, but

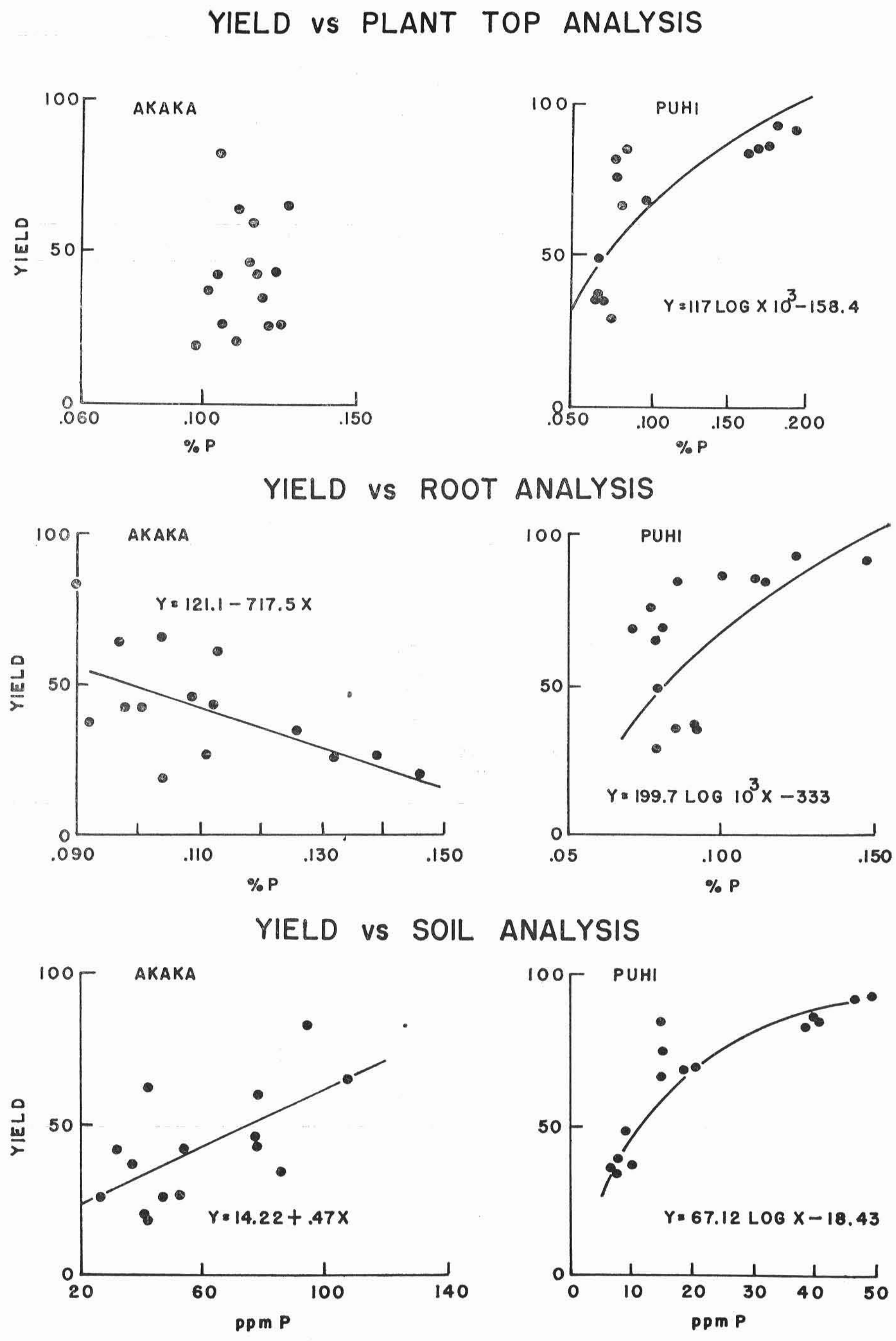


FIGURE 1. Relationships between yield and phosphorus contents of plant material and soil extracts.

TABLE 5. Effect of applications of liming materials and monocalcium phosphate on the phosphorus content (as percent P) of tops of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	0.103	0.101	0.124	0.103	0.105	0.104
500	.123	.114	.157	.123	.117	.110
2000	.120	.127	.124	.120	.115	.105
		PUHI SOIL				
0	.068	.075	.110	.068	.069	.069
500	.081	.096	.082	.081	.085	.085
2000	.073	.184	.129	.073	.167	.195

TABLE 6. Effect of applications of liming materials and monocalcium phosphate on the exchangeable calcium content (as milliequivalents per 100 gm. of dry soil) in soils of the Akaka and Puhi series

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	1.2	7.7	23.4	1.2	3.5	11.5
500	1.4	9.4	24.2	1.4	3.8	12.2
2000	1.8	8.8	24.0	1.2	4.3	13.2
		PUHI SOIL				
0	.9	6.6	13.9	.9	1.9	6.7
500	1.1	5.3	11.3	1.1	2.1	6.6
2000	1.3	5.2	10.1	1.3	2.8	7.1

only about half the magnitude of the increase registered for the lime applications.

The calcium content of the Sudan grass tops is given in table 7. The calcium content of tops was increased more by the application of lime than by the application of calcium silicate. The application of phosphate fertilizer gave a small increase in calcium content of the tops in most cases.

TABLE 7. Effect of applications of liming materials and monocalcium phosphate on the calcium content (as percent Ca) of the tops of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	0.75	0.92	1.25	0.75	1.00	0.92
500	.79	.94	1.15	.79	.87	1.00
2000	.81	1.01	1.30	.81	.96	.96
		PUHI SOIL				
0	.75	.96	1.16	.75	.64	.91
500	.75	1.00	1.38	.75	.88	.95
2000	.87	.94	1.36	.87	.86	.86

The calcium content was determined in the roots and the data are presented in table 8. The application of both amendments increased the calcium content in the roots; but the application of lime gave a much greater increase than the application of silicate. A most remarkable and unexpected effect was produced by the application of phosphorus on the calcium content of the roots of plants grown on the Puhi soil in that the application of phosphorus decreased the calcium concentration in the roots.

TABLE 8. Effect of applications of liming materials and monocalcium phosphate on the calcium content (as percent Ca) of roots of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	0.21	0.29	0.56	0.21	0.24	0.33
500	.22	.28	.61	.22	.29	.35
2000	.22	.33	.62	.22	.24	.26
		PUHI SOIL				
0	.17	.40	.54	.17	.43	.28
500	.12	.20	.77	.12	.18	.15
2000	.09	.18	.48	.09	.13	.13

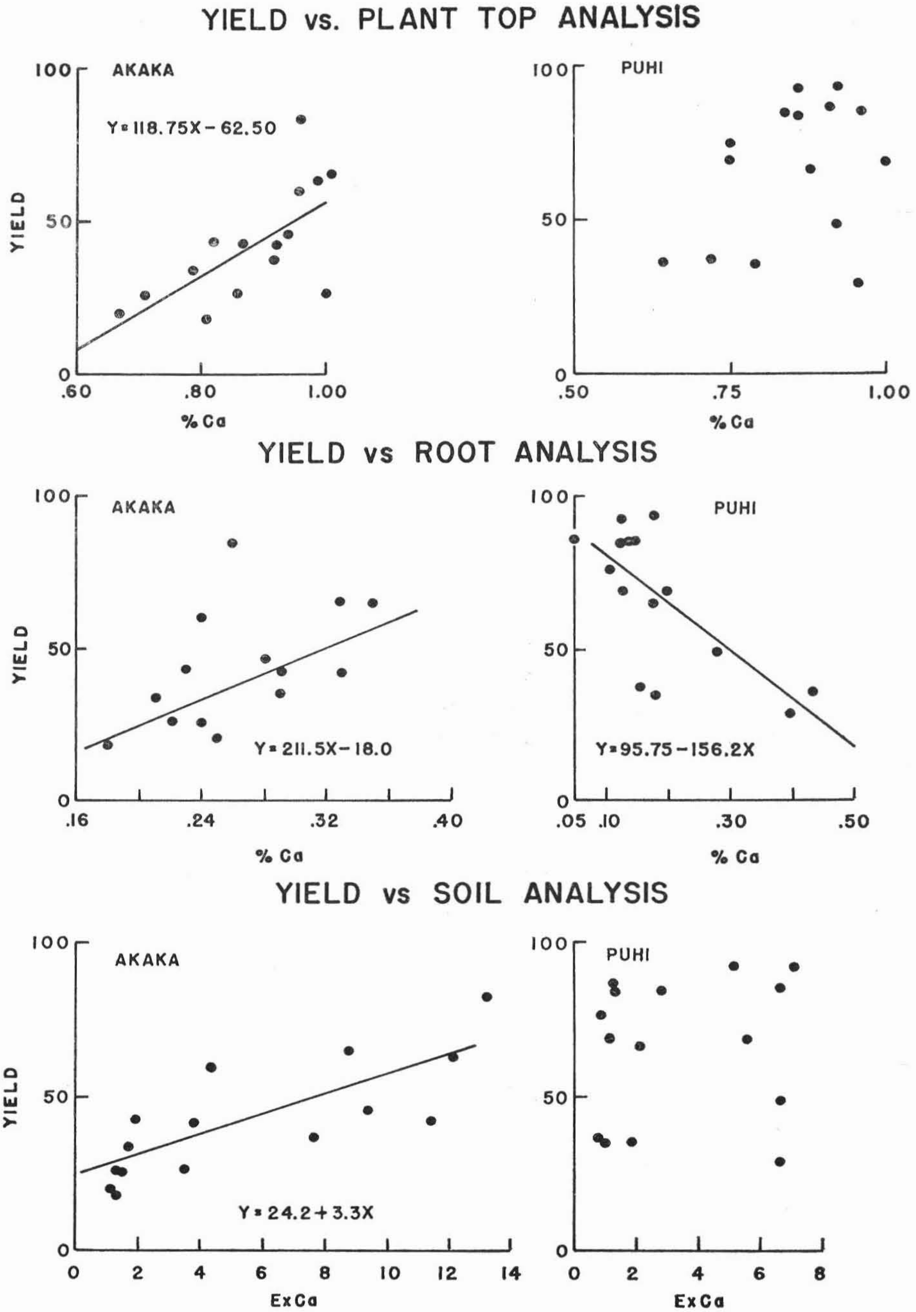


FIGURE 2. Relationships between yield and calcium contents of plant material and soil extracts.

The analysis of the tops reveals a similar situation in both soils in that the uptake due to lime was considerably greater than that due to calcium silicate. The analysis of variance (table 2) confirms that an over-all increase in calcium uptake occurs with increases in phosphorus levels.

When the calcium content of soil, roots, or tops is compared with the yield (fig. 2), the Akaka series shows a positive correlation in all cases; namely, yield vs. calcium content of plant tops, yield vs. calcium content of roots, and yield vs. exchangeable calcium in soil. This would indicate a shortage of calcium by the plant in untreated soils but for the fact that the Puhi results are within the same range of calcium values as the Akaka series; therefore, it is more likely that calcium is acting upon another factor which is in turn affecting yield. In contrast, there is no positive correlation between yield and calcium status of plants or soils in the Puhi experiments; and a negative correlation is evident between yield and calcium content of the plant roots.

Aluminum: The amount of aluminum which can be extracted from the soil is given in table 9. The data show a reduction in extractable aluminum occurred through the addition of lime or calcium silicate and also upon the application of monocalcium phosphate. The Akaka soil contains considerably more extractable aluminum than the Puhi soil.

TABLE 9. Effect of applications of liming materials and monocalcium phosphate on the amount of extractable aluminum (as milliequivalents per 100 gm. of dry soil) in soils of the Akaka and Puhi series

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
			AKAKA SOIL			
0	18.5	12.0	5.4	18.5	15.2	7.2
500	16.8	11.7	5.5	16.8	13.4	6.7
2000	15.2	10.2	4.7	15.2	12.1	5.6
			PUHI SOIL			
0	3.1	1.0	.4	3.1	1.9	.5
500	3.5	.8	.4	3.5	1.4	.4
2000	2.5	.6	.4	2.5	1.5	.4

In spite of the large variation in the root analysis values (table 10), it appears that lime and calcium silicate reduced the aluminum content in the roots of plants grown on soils of the Akaka series, and that monocal-

TABLE 10. Effect of applications of liming materials and monocalcium phosphate on the aluminum content (as ppm dry matter) of roots of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	3470	1670	1400	3470	2030	1780
500	2940	1780	1370	2940	1070	980
2000	2110	2080	1330	2110	2130	1540
		PUHI SOIL				
0	1610	950	2600	1610	1260	3000
500	2950	2870	2560	2950	2760	2200
2000	4080	4370	1000	4080	4540	5960

cium phosphate increased the aluminum content of roots in the Puhi series. As previously noted, the increase of aluminum content in the Puhi series was possibly due to contamination by soil particles.

In the plant tops, calcium silicate suppressed aluminum uptake; but lime appeared to increase uptake at the L_2 level in the Puhi series (table 11). The differences were not large.

TABLE 11. Effect of applications of liming materials and monocalcium phosphate on the aluminum content (as ppm dry matter) of tops of Sudan grass grown on Akaka and Puhi soils

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	136	118	132	136	125	113
500	138	121	137	138	101	119
2000	148	129	167	148	111	102
		PUHI SOIL				
0	115	121	199	115	96	90
500	130	149	176	130	104	105
2000	143	151	181	143	137	99

Yield relationships presented in figure 3 show that in the Akaka series a reduction in aluminum level in the soil, roots, and tops was accompanied by an increase in yield; in the Puhi series there was no relationship with yield except in the aluminum content of the roots.

Figure 3A shows that as the aluminum content of the root increased the phosphorus content increased but the calcium content decreased. These correlations occurred for both soils.

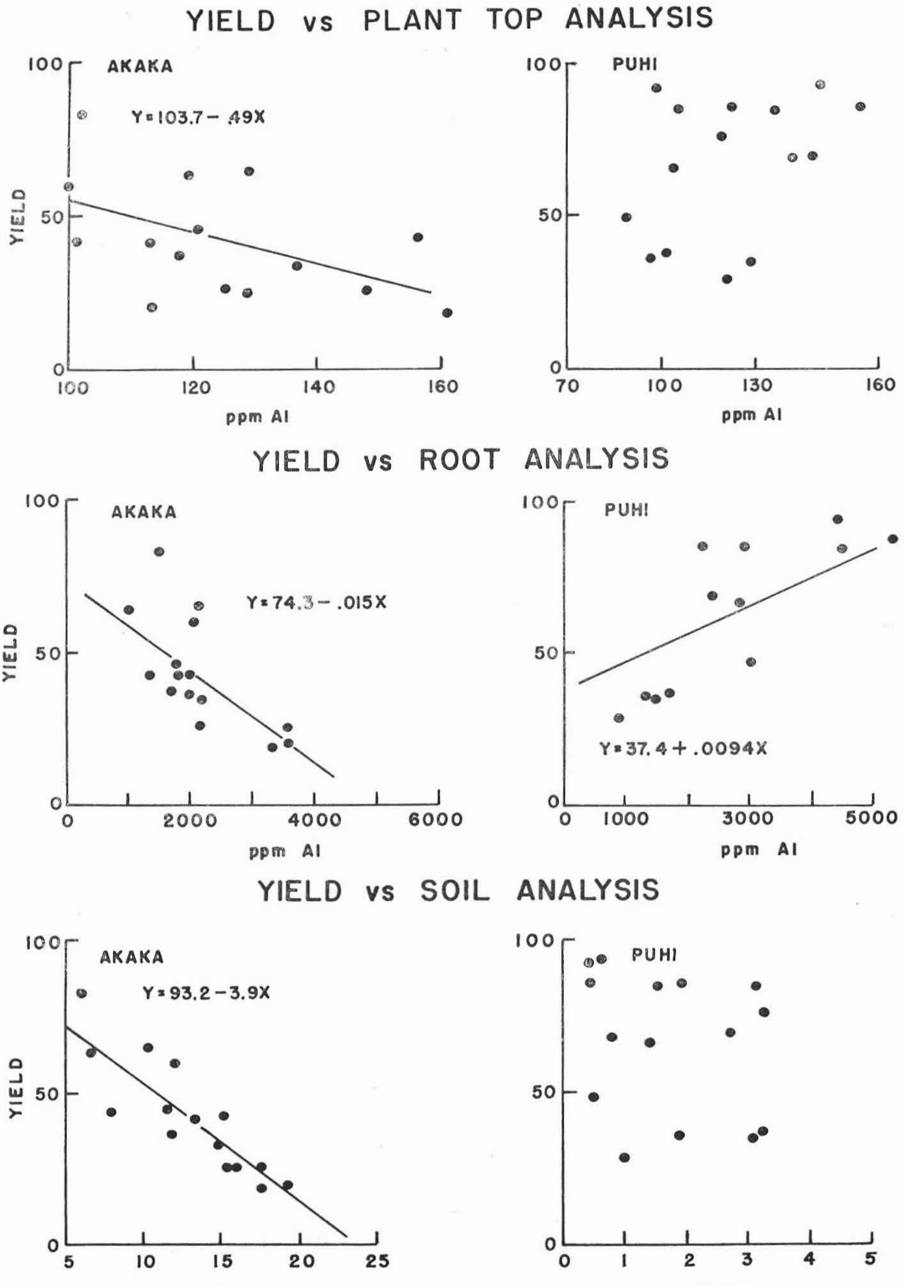
pH: As shown in data presented in table 12, the pH of the soil was increased to a greater extent by lime than by calcium silicate. The general increase was higher in the Puhi soils than in the Akaka soils, reflecting the difference between their buffering capacities. The reaction of the soil was related to exchangeable calcium and to yield (fig. 4).

TABLE 12. Effect of applications of liming materials and monocalcium phosphate on the pH of the soils of the Akaka and Puhi series

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	4.5	5.5	7.0	4.5	4.9	5.4
500	4.6	5.6	6.8	4.6	5.0	5.5
2000	4.6	5.6	7.0	4.6	5.0	5.4
		PUHI SOIL				
0	4.5	5.9	7.4	4.5	4.9	5.9
500	4.5	5.5	7.4	4.5	4.9	5.9
2000	4.5	5.9	7.4	4.5	4.9	5.8

Cation Exchange Capacity: Data presented in figure 5 show the effect of aluminum on cation exchange capacity, and indicate a reduction in aluminum was accompanied by an increase in cation exchange capacity. Magistad (1928) had previously pointed out this phenomenon. It is also of interest to note that in the Akaka soil there appeared to be a relationship between yield and cation exchange capacity; this relationship is shown in figure 6. No such relationship existed in the Puhi soils.

Exchangeable Calcium and Extractable Aluminum Relationships: The data presented in figure 7 indicate a definite relationship existed between exchangeable calcium and extractable aluminum in both the Akaka and Puhi soils. This relationship appeared to be associated with yields in the case of the Akaka soils, but not in the Puhi soils.


YIELD vs PLANT TOP ANALYSIS

YIELD vs ROOT ANALYSIS

YIELD vs SOIL ANALYSIS

FIGURE 3. Relationships between yield and aluminum contents of plant material and soil extracts.

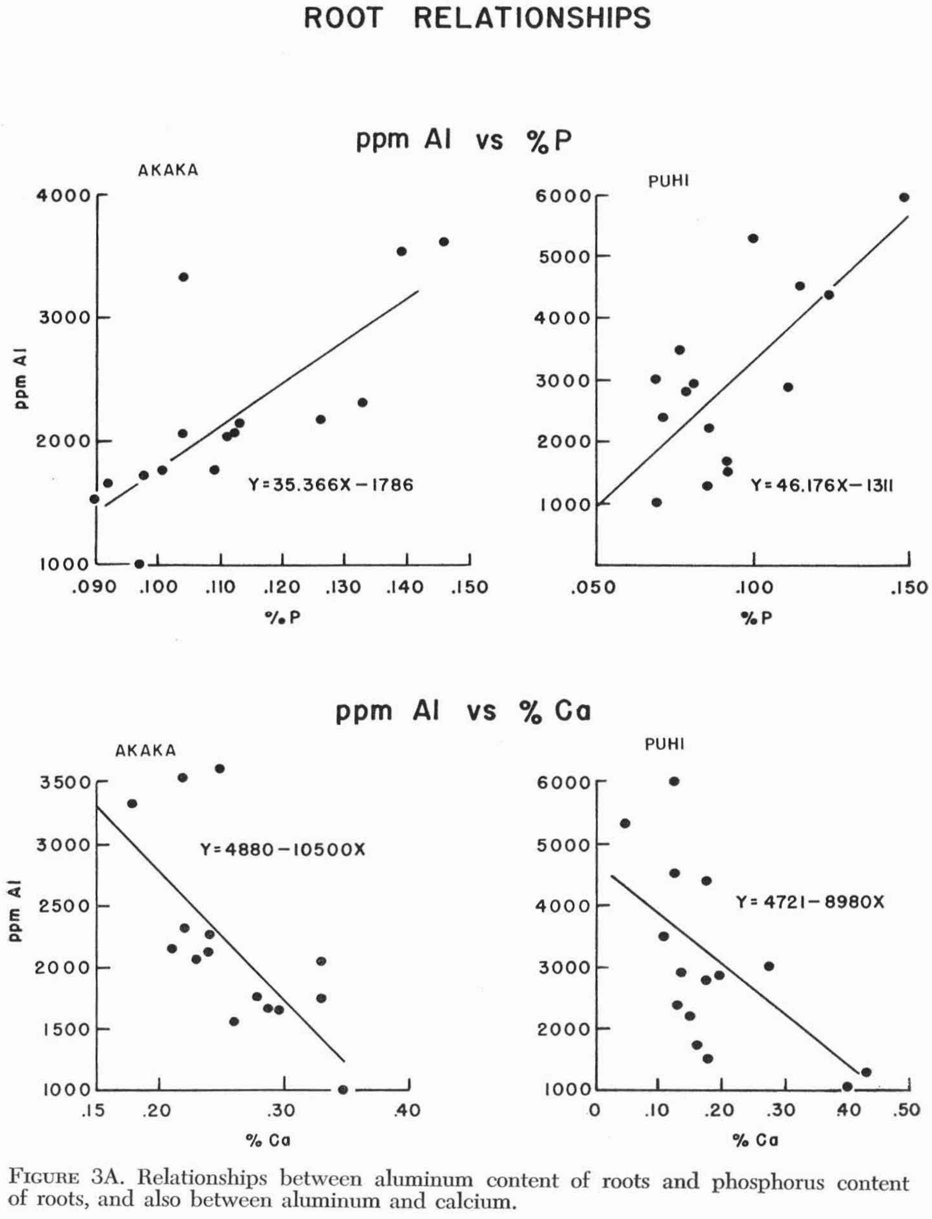


FIGURE 3A. Relationships between aluminum content of roots and phosphorus content of roots, and also between aluminum and calcium.

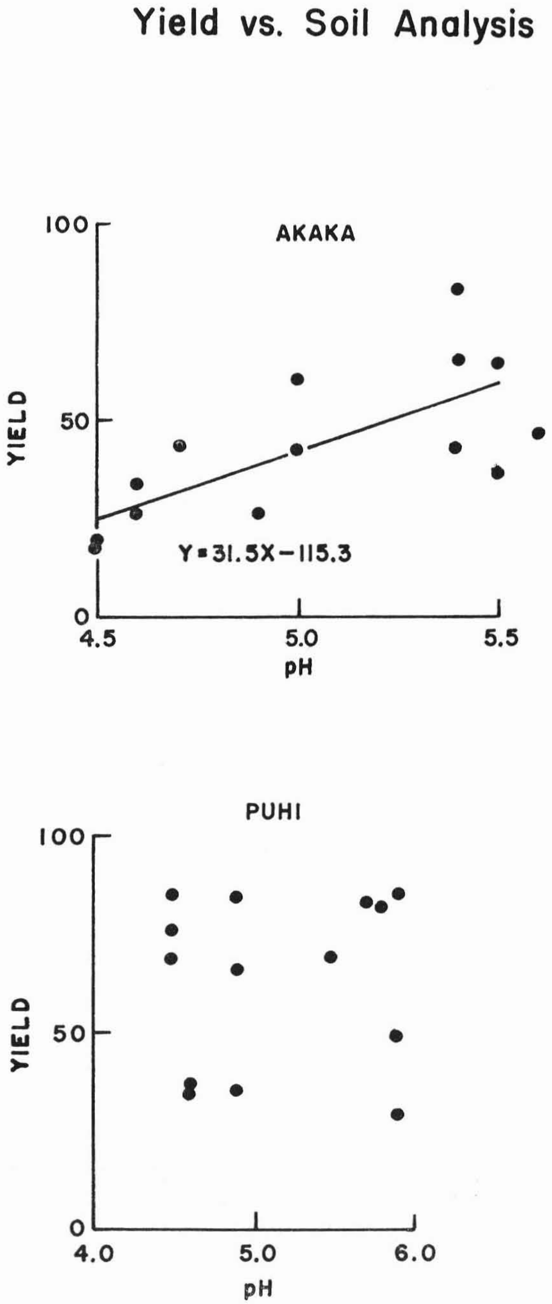


FIGURE 4. Relationships between yield and pH of the soil.

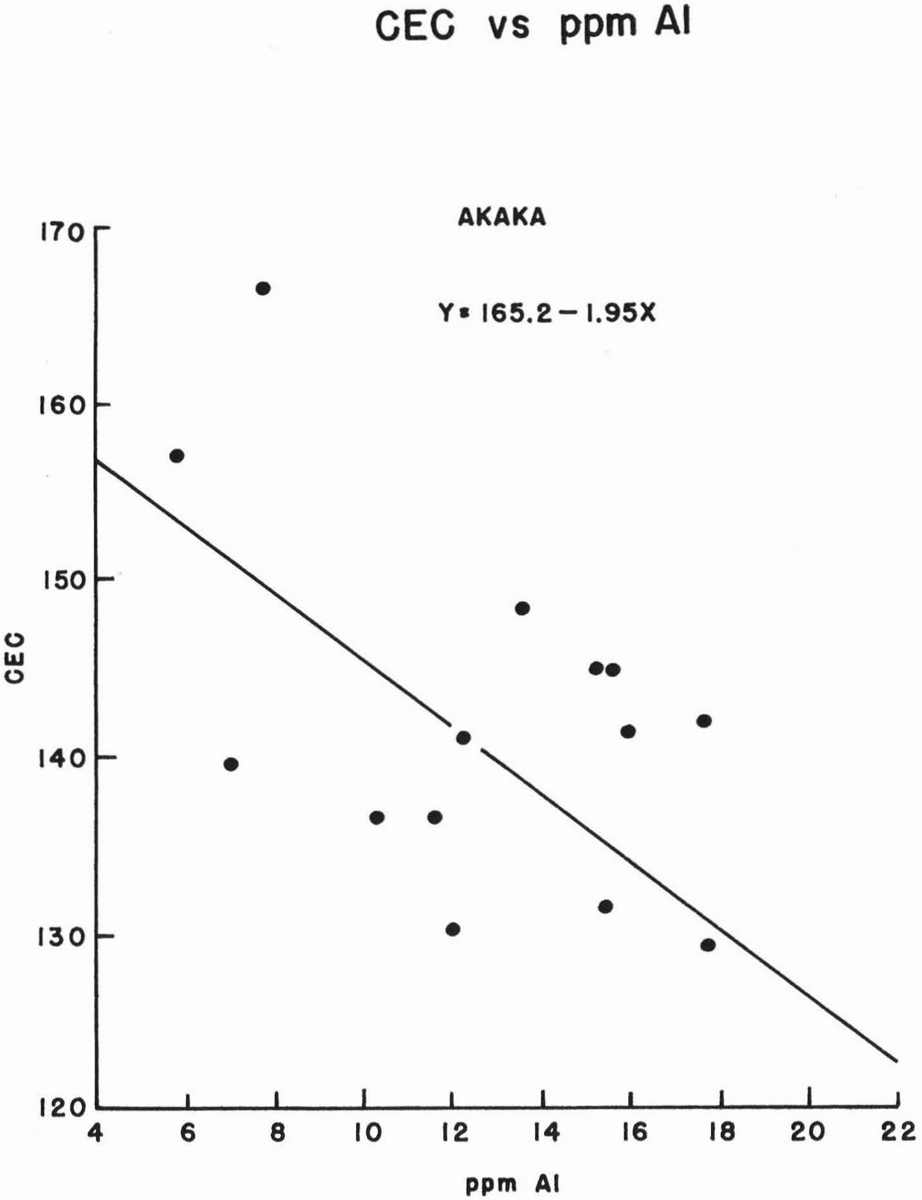


FIGURE 5. Relationship between cation exchange capacity and aluminum content of the soil extract.

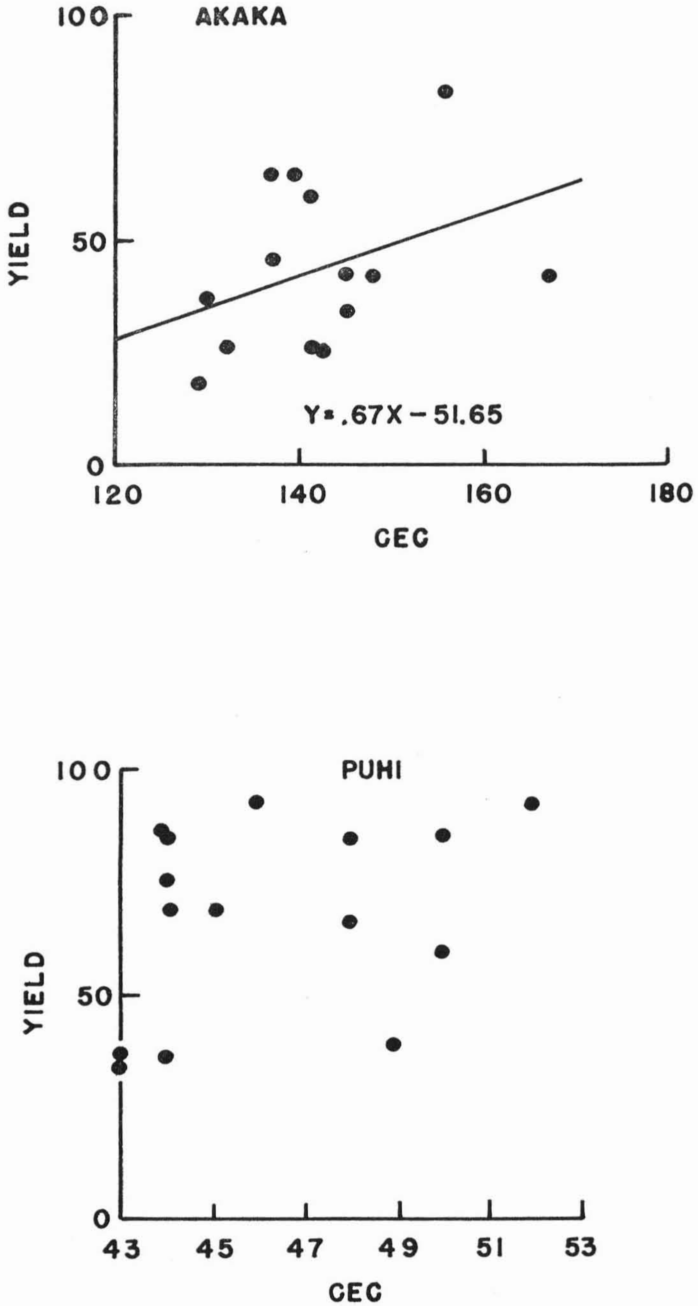
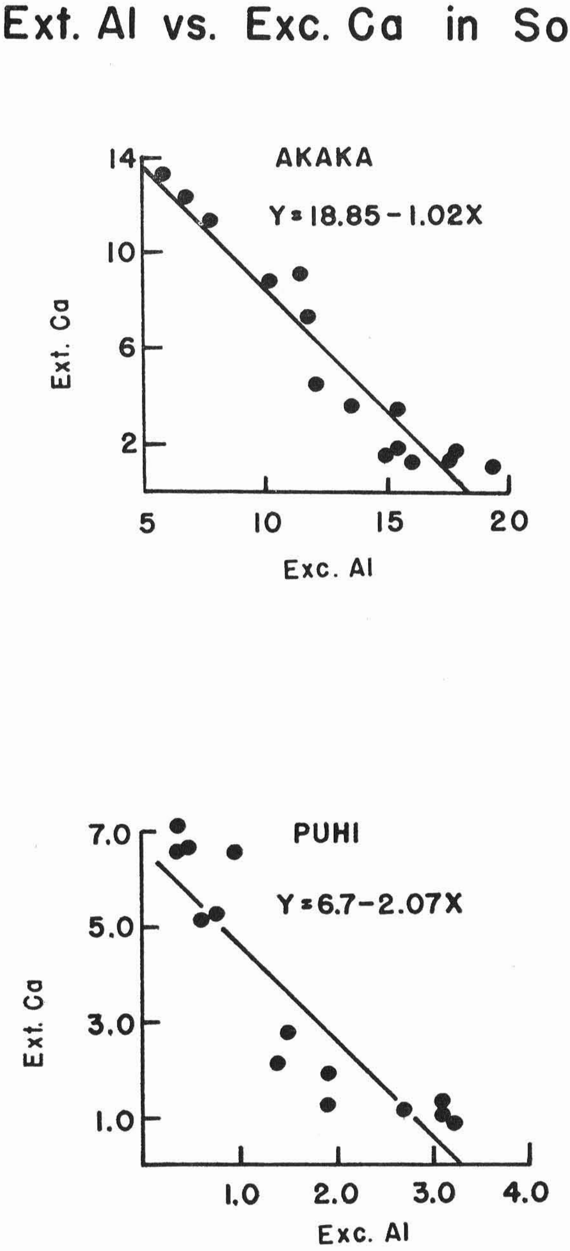


FIGURE 6. Relationships between yield and cation exchange capacity of the soil.



Ext. Al vs. Exc. Ca in Soil

AKAKA

PUHI

FIGURE 7. Relationships between extractable aluminum and exchangeable calcium in the soil.

Results of Correlation Coefficients: Tables 13 and 14 present the correlation coefficients which have been calculated from the relationship of yields to various soil and plant factors and the relationships between vari-

TABLE 13. Correlation coefficients calculated from the relationships between dry matter yield of Sudan grass and various factors

FACTOR	SOIL	r	SIGNIFICANCE	COEFFICIENT OF DETERMINATION
Yield vs.				
In Plant Tops				
% phosphorus	Akaka	+.03	N.S.	—
Log % phosphorus	Puhi	+.87	**	75.7%
% calcium	Akaka	+.66	**	43.6%
% calcium	Puhi	+.35	N.S.	—
ppm aluminum	Akaka	—.48	*	23.0%
ppm aluminum	Puhi	+.38	N.S.	—
In Plant Roots				
% phosphorus	Akaka	+.56	*	31.4%
Log % phosphorus	Puhi	+.77	**	59.3%
% calcium	Akaka	+.56	*	31.4%
% calcium	Puhi	—.71	**	50.4%
ppm aluminum	Akaka	—.64	**	41.0%
ppm aluminum	Puhi	+.70	**	49.0%
In the Soil				
ppm phosphorus	Akaka	+.63	**	39.7%
Log ppm phosphorus	Puhi	+.91	**	82.8%
Exchangeable calcium	Akaka	+.78	**	60.8%
Exchangeable calcium	Puhi	+.11	N.S.	—
pH	Akaka	+.70	**	49.0%
pH	Puhi	+.03	N.S.	—
Extractable aluminum	Akaka	—.86	**	74.0%
Extractable aluminum	Puhi	—.26	N.S.	—
Cation exchange capacity	Akaka	+.47	N.S.	22.1%
Cation exchange capacity	Puhi	+.23	N.S.	—

** Significant at 1% level.
* Significant at 5% level.
N.S. Not significant.

TABLE 14. Correlation coefficients calculated from relationships within soil analysis values and root analysis values

FACTOR a VS. FACTOR b	SOIL	r	SIGNIFICANCE	COEFFICIENT OF DETERMINATION
Roots				
Aluminum vs. calcium	Akaka	—.64	**	41.0%
Aluminum vs. calcium	Puhi	—.55	*	27.8%
Aluminum vs. phosphorus	Akaka	+.75	**	56.2%
Aluminum vs. phosphorus	Puhi	+.60	*	36.0%
Soil				
Aluminum vs. calcium	Akaka	—.95	**	90.2%
Aluminum vs. calcium	Puhi	—.91	**	82.8%
Aluminum vs. phosphorus	Akaka	—.28	N.S.	—
Aluminum vs. phosphorus	Puhi	—.22	N.S.	—
Aluminum vs. CEC	Akaka	—.61	**	37.2%
Aluminum vs. CEC	Puhi	—.45	N.S.	—

** Significant at 1% level.
* Significant at 5% level.
N.S. Not significant.

ous factors in soil and root analysis. These data reveal that there was a significant relationship between yields and the log percent phosphorus in plant tops grown on Puhi soil, and also between yield and calcium content of plant tops grown on Akaka soil. In addition, they indicate significant relationships between yield and the calcium, aluminum, and phosphorus content of roots of plants grown on both soils. In the Akaka soil, there also were significant relationships between yield and the phosphorus, exchangeable calcium, soil reaction, and extractable aluminum of the soil; but, in the Puhi soil, only the relationship between yield and phosphorus content was significant.

In both soils, there was a significant negative correlation between the aluminum and the calcium content of the roots, and a significant positive correlation between the aluminum and the phosphorus content of the roots. Also, in both soils, the relationship between aluminum and calcium content of the soil was highly significant.

Leachate Studies

Although the results were not statistically analyzed, it is obvious from table 15 that the aluminum content of the nil treatment in the Akaka soil was extremely high, and that this concentration was reduced by applications of lime and calcium silicate and by monocalcium phosphate. Hester (1935) stated that plant growth was directly correlated with the appearance of aluminum in drainage waters. In the case of the Puhi soil, the results were generally low; however, monocalcium phosphate increased the aluminum content in the leachate at the S_0 and L_0 levels, and this was accompanied, apparently, by a drastic lowering of the pH of the leachate solution.

TABLE 15. Effect of applications of liming materials and monocalcium phosphate on the aluminum content (in ppm) of the second leachates

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	5.1	0.3	0.3	5.1	0.3	0.4
500	1.4	.3	.5	1.4	.4	.5
2000	1.4	.5	.5	1.4	.6	.5
		PUHI SOIL				
0	.4	.3	.3	.4	.9	.5
500	3.1	.9	.2	3.1	1.7	.3
2000	2.7	.3	.2	2.7	.4	.4

The graph presented in figure 8 shows the relationship between aluminum content and pH and illustrates clearly the reduction in soluble aluminum which occurred as the pH increased. At approximately pH 5.6, the aluminum content remained constant with increasing pH. It was completely soluble at pH 3.5. The activity of aluminum in the 3.5 to 5.6 range corresponded to the activity of aluminum on decreasing the pH of an $Al_2O_3(P_2O_5)\cdot H_2O$ colloidal complex (Miller, 1956). Magistad (1925) pointed out that when the acidity became greater than pH 5, the aluminum solubility began to increase until pH 4.5 was reached, at which point it then proceeded to increase rapidly.

Although the concentration of phosphorus was variable, the L_1 level in the Puhi soil increased the phosphorus content when phosphorus was

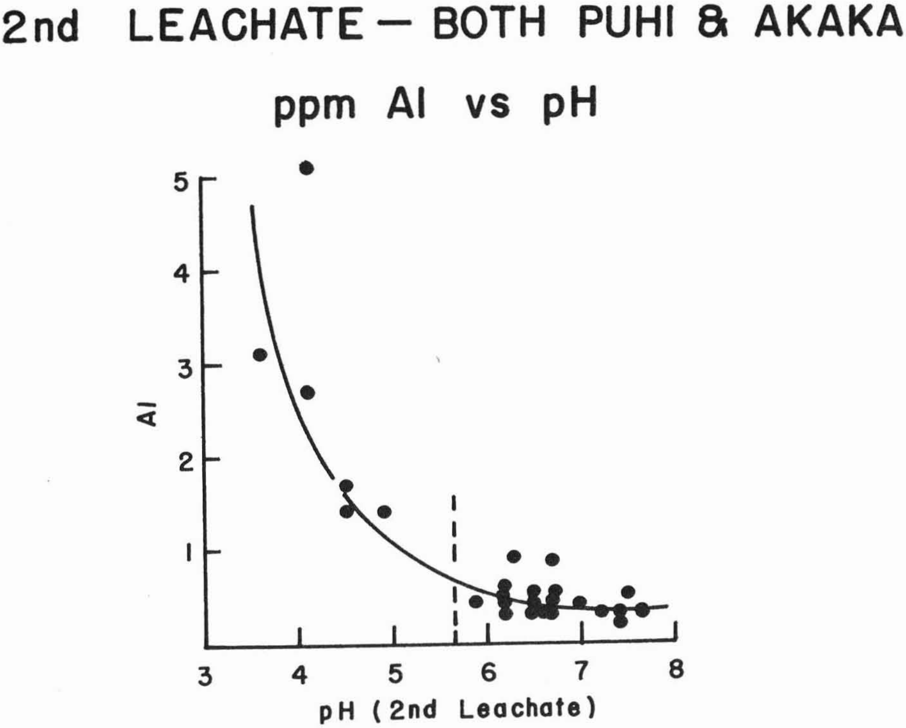


FIGURE 8. Relationship between aluminum content and pH of the second leachate.

added; this occurred in both the first and second leachates (tables 16, 17). However, at the L_2 level, the increase was much smaller, due probably to the formation of tricalcium phosphate at this level. The uptake in the plant tops reflected this increase.

TABLE 16. Effect of applications of liming materials and monocalcium phosphate on the phosphorus content (in ppm) of the first leachates

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	0.09	0.07	0.09	0.09	0.03	0.02
500	.07	.05	.10	.07	.05	.16
2000	.03	.26	.16	.03	.05	.13
		PUHI SOIL				
0	.08	.13	.33	.08	.05	.10
500	.08	.27	.26	.08	.05	.10
2000	.08	1.42	.41	.08	.06	.63

TABLE 17. Effect of applications of liming materials and monocalcium phosphate on the phosphorus content (in ppm) of the second leachates

PHOSPHATE APPLIED, lb/acre	LIME APPLIED, lb/acre			CALCIUM SILICATE APPLIED, lb/acre		
	0	5,000	20,000	0	5,000	20,000
		AKAKA SOIL				
0	0.05	0.08	0.05	0.05	0.05	0.07
500	.06	.11	.09	.06	.05	.17
2000	.06	.14	.09	.06	.11	.21
		PUHI SOIL				
0	.06	.05	.08	.06	.14	.18
500	.06	.22	.08	.06	.05	.14
2000	.08	.65	.11	.08	.08	.09

DISCUSSION

A considerable amount of data was collected during this investigation; however, it should be kept in mind that the main objective of this study was to explain differences in response to lime and calcium silicate on Akaka soil and on Puhi soil.

It has been shown from the yield results that both lime and calcium silicate increased yield to the same extent in the Akaka soil and that monocalcium phosphate also increased yield and in a linear manner. On the Puhi soil, only the highest application level of calcium silicate appeared to increase yield, and then but slightly. The main increase in yield came from the use of monocalcium phosphate.

The reduction in yield caused by the highest lime application has been omitted from this discussion.

Several hypotheses were outlined at the end of the foregoing literature review section of this bulletin; these are now analyzed, using the evidence cited above.

1. a. The breakdown of organic matter (if any) did not release soluble aluminum to the drainage waters. This is shown in the leaching studies.
   b. Phosphorus was released by lime or calcium silicate only when monocalcium phosphate was added.
2. Although calcium uptake correlated with yield in the Akaka soil series, the range of calcium values was not lower than the Puhi series, which showed no relationship with yield. Therefore, it is likely that calcium was acting with another factor which was, in turn, affecting yield and was not a limiting factor in itself. Evidence shows that this factor may have been aluminum. Menchikovsky and Puffeles (1938) reached a similar conclusion.
3. Aluminum is certainly a major factor in the Akaka soil but appears to be of little importance in the Puhi soil. Aluminum can be negatively correlated with yield in the tops, roots, and soil in the Akaka series, but no correlation is indicated in the Puhi studies. Leachate studies also showed extremely high concentrations of aluminum in the untreated pots in the Akaka series.

   It appears likely that aluminum acts as a "toxic" factor in the Akaka soil and is reduced by either high calcium ion concentration, high pH, or high phosphorus content, or by combinations of these three conditions. King (1961) has shown that upon adding phosphorus, high amounts of aluminum phosphate are formed in this soil type, whereas relatively smaller amounts are formed in a soil similar to the Puhi soil. Hartwell and Pember (1918), and others, also found that the addition of phosphate reduces "active" aluminum. They stated: "The practical advantage of phosphating and liming may often prove to be due to the precipitation of active aluminum." Reasons for the action of aluminum in reducing yield are purely speculative. Relationships between aluminum and phosphorus in the roots of plants grown on Akaka soil indicate the possibility that aluminum phosphate is formed in the root. Pierre and Stuart (1933), and others, have placed importance on this occurrence, which is said to prevent phosphorus uptake by the plant tops; however, phosphorus was adequate in the plant tops of the Akaka series. It is more likely then that aluminum affects the metabolic functions of the plant cell at the aluminum concentrations found in Akaka soils. Evidence for this supposition is found in the work of Ruth Addoms (1927), who examined the root hair cells of the wheat plant while immersing them in salt solutions. She found that aluminum and zinc penetrated the cell rapidly and produced a severe flocculation of the protoplasm; coagulation finally became irreversible and death of the cell resulted.

4. There is evidence (analysis of the leachates) that added phosphorus is released to the soil solution by the addition of lime or calcium silicate. With the highest application of calcium silicate, the second leachate of the Puhi series at the P_0 and P_1 levels showed an increase in soluble phosphorus. This increase in soluble phosphorus was reflected in an increase in yield; it was not evident in either plant uptake or soil tests. Inasmuch as Puhi soil appears to lack the ability to supply adequate phosphorus to the plant, any increase in available phosphorus should therefore cause an increase in yield. This is not the case, however, in the Akaka soil, where its phosphorus supply to the plant appears adequate and would not of itself be limiting to growth; here, monocalcium phosphate may be acting indirectly on the yield by reducing aluminum and thereby causing an increase in yield.

5. Only the effects of phosphorus, calcium, and aluminum have been investigated in this study; and it is realized that other factors could be involved and that there is much more work to be done in this field. For example, manganese may be present in toxic concentrations and may be reduced by the action of liming materials; or, molybdenum may be made more available.

CONCLUSION

In a Hydrol Humic Latosol, both calcium carbonate and calcium silicate appear to increase the yield of Sudan grass, provided the pH remains below approximately 6.8; above this value, yield is depressed. Increased yield is probably due to the reduction of "toxic" aluminum brought about by the action of calcium ions and increasing pH.

In a Humic Ferruginous Latosol, lime does not increase yield but depresses it at high pH values. Calcium silicate slightly increases yield at higher values; such increase is probably due to increased available phosphorus and not to a decrease in the "active" aluminum. Aluminum does not appear to be a toxic factor in this soil.

Monocalcium phosphate increases yield in both cases—in the Hydrol Humic Latosol by reducing "toxic" aluminum, and in the Humic Ferruginous Latosol by supplying phosphorus as a nutrient.

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