THE COMPARATIVE EFFECTS OF CALCIUM CARBONATE AND CALCIUM SILICATE ON THE YIELD OF SUDAN GRASS GROWN IN A FERRUGINOUS LATOSOL AND A HYDROL HUMIC LATOSOL

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INTRODUCTION

Several current field experiments in the Hawaiian sugar industry have shown that liming has increased yield of sugar and phosphorus uptake by the plant.

The literature contains references to increased phosphorus uptake by silicate compounds, and as there is a possibility of using basic slag (calcium silicate) as a soil amendment in the Hawaiian sugar industry, it was proposed to compare the calcium silicate effect with the liming effect.

The object then was to:

1. Determine if there is an increased yield with the use of these amendments and to determine the mechanism by which this occurs.
2. Provide information which may assist in designing further field tests on the problem.

LITERATURE

Calcium Carbonate

The Effect of Calcium Carbonate on Phosphate Availability

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

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. Kötten 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 15 grams lime per pot. Gericke (1951) reviewed some of the evidence on liming from work in Germany. His investigations showed that liming increased the phosphorus availability on strongly acid soils by .7 mg./100 g. but not with soils above pH 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 lime releases organic phosphorus or that the breakdown of organic matter solubilizes phosphorus. Ghani and Aleem (1942) in India, suggested that the increase in phosphorus availability by the application of lime was due not to less aluminum and iron phosphate formation, but to the release of phosphorus from organic matter. A change in reaction favored microbial action and organic matter breakdown. Salonen (1946) in Finland found that liming increased the organic phosphorus breakdown. Matson et al. (1950) in studying a limed and unlimed podzol thought that the formation of B humus by liming solubilized phosphorus. More available phosphorus occurred in the subsoil of the limed podzol than in the subsoil of the unlimed soil.

There is also evidence that lime applications can decrease phosphorus availability under certain circumstances. Máté and Molnár (1956) in Hungary, showed increased phosphorus fixation with liming. Loo, Yu and Wan (1956) in China, stated that increased fixation is not encountered until liming increases the pH to 7.5. Lawton and Davis (1956) working on acid organic soils found increased phosphorus fixation due to liming apparently caused by a decrease in the proportion of H_2PO_4 to HPO_4 ions. It is apparent that phosphorus can be fixed in acid soils by the formation of iron and aluminum compounds and in alkaline soils by the precipitation of tricalcium phosphate.

The increase in phosphorus availability due to liming seems to be associated then with soils which have an iron, aluminum system predominately. This appears to be supported by Yudin (1958) in Russia. He found that lime increased the utilization of fertilizer phosphorus by the plant in the Krasnozem soils more than in other types. This work is still relatively undeveloped in tropical soils. McGeorge (1924) in Hawaii, suspected that liming increased the phosphorus uptake in sugar cane. Hardy (1934), in Trinidad, increased available phosphorus 39 to 67 percent by liming. Beater (1945) obtained 20 percent greater phosphorus uptake in maize followed by sugar cane. Nitrogen and calcium uptake were also higher. Monteith et al. (1958), in Fiji, found in studying soil pH and available phosphorus that the expectancy of high soil phosphorus increased as the pH increased until about pH 7.5 when it decreased. Also (1959) liming with coral sand produced an increased nitrogen uptake in sugar cane especially at low fertilizer nitrogen levels. Schroo (1954) showed that liming increased the P_2O_5 content of sugar cane juice by 40 percent. Clements (1960) has found marked increases in phosphorus uptake by sugar cane on liming Hydrol Humid Latosol soils in Hawaii.

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

The Effect of Calcium Carbonate on Other Factors

Calcium carbonate can affect other factors, causing growth stimulation by:

1. Reducing aluminum or manganese toxicity (Mulder and Gerretsen, 1952)
2. Generally increasing the effectiveness of other elements (Truog, 1953)
3. Developing more favorable physical conditions (Coleman *et al.*, 1958)
4. Improved microbial N fixation (Black, 1957)
5. Supplying calcium as a nutrient

Fried and Peech (1946) discuss this aspect (5) in the introduction to their paper and come to the conclusion that supplying calcium is generally not important. They state however that often lime gives better results than gypsum with the equivalent calcium content.

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 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 improved growth resulted.

It has been observed by Menchikovsky and Puffeles (1938) that calcium salts can be responsible for reducing aluminum. Chernov and

Belyaneva (1948) 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. Trenel and Schönberg (1959) indicate that the benefit from Mg ions is only obtained if aluminum ions have been removed from the soil solution by liming. Schmekl, Peech and Bradfield (1950), Moschler, Jones and Thomas (1960), Rixon (1960) and Ayres (1960) in the U.S.A. have studied this problem. Duthie and Bourne (1939) in British Guiana and several Japanese workers (Hosoda, Takata and Ogihara, 1957) have also found a reduction in 'active' aluminum due to liming.

Calcium Silicate

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 1905 Hall and Morison at Rothamsted, 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) considered that the 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, the more likely the response to phosphorus. High silica meant high phosphorus in the juice of sugar cane.

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. Low and Black

(1948) indicated that the reverse reaction was true as silica was released from clay minerals by the use of phosphorus compounds. This suggested that silica additions would slow down this release from clay minerals and 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. Also, the response was a vegetative response 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.

<u>The Effect of Calcium Silicate on Other Factors</u>

As in the case of liming, it has been pointed out by Fatchikina (1953) that a silicate (dunite) is effective in reducing 'toxic' levels of aluminum.

MacIntire, Winterberg and Dunham <u>et al</u>. (1946) showed that 'glassy' slags were converted to calcium carbonate and that the CO_2 required for the conversion could be derived from bacterial activity.

Crystalline calcium silicate is not easily converted to calcium carbonate. Therefore, although it has been postulated that calcium silicate acts simply as calcium carbonate, prevents the absorption on clays by phosphorus, precipitates active iron and aluminum or actually supplies silicon to the plant--the mechanism is not clear. Little work has been done on tropical soils.

From assimilation of the problem and a review of the literature several hypotheses on the mechanism of yield increase by liming were formed.

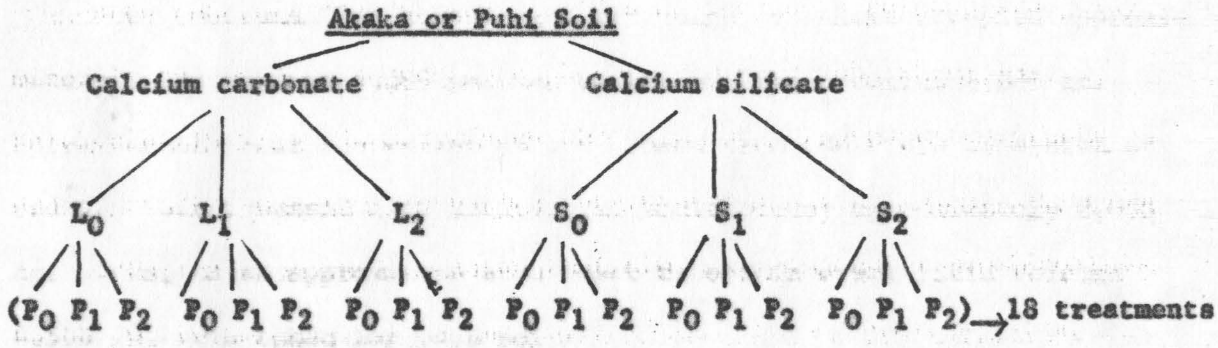
1. The breakdown of organic matter would:
   a. Chelate 'toxic' elements such as aluminum and remove them in the drainage water
   b. Release mineral phosphate and other plant nutrients
2. Calcium could be a limiting factor in growth in these soils.
3. 'Toxic' amounts of aluminum could be reduced by liming, inducing better crystallization in the $Al(OH)_3$ system of the soil. This system is known to exist in at least one of the soils in this study.
4. So-called fixed phosphorus could be released by the action of the OH^- or $SiO_3^{=}$ ion and thus improve growth. This would only occur if phosphorus was a limiting factor, or where phosphorus decreased a 'toxic' factor such as aluminum.
5. Increased microbial activity accompanied by increased nitrification and so on.
6. By increasing the pH of the soil other elements could be reduced in concentration if toxic to the plant, or if some elements had been limiting to plant growth they could be made more available by liming.

Experiments were designed to test some of these hypotheses.

METHOD

Pot Experiment No. 1

This pot experiment was designed to include two soils. In each soil half the treatments consisted of three levels of calcium carbonate (c.p. grade) and half were three levels of calcium silicate (c.p. grade). Each of these levels was treated with three levels of monocalcium phosphate dihydrate (c.p. grade). There were three replicates of each treatment. The layout was a randomized block design.



18 treatments x 2 soils x 3 replicates = 108 individuals.

Soils

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

The Akaka soil is a Hydrol Humic Latosol which drastically changes its characteristics on drying. The cation exchange capacity is lowered (Kanehiro and Chang, 1956) and it will not rewet to moisture contents found normally in the field. Precautions were taken therefore to prevent excessive drying.

The Puhi soil is a Humic Ferruginous Latosol. The characteristics of this soil are altered on drying although not to the same extent as the Akaka (Trouse, 1960). Precautions to prevent drying were also taken with the Puhi soil.

The Akaka was passed through a 1/4 inch mesh sieve and mixed thoroughly in a mechanical mixer. The Puhi was passed through a 5 mm.

sieve and mixed. Moisture contents were taken: the Akaka was 107 percent and the Puhi was 42 percent.

Four thousand five hundred gm. wet weight of Akaka occupied approximately 8,500 cc. and 4,500 gm. wet weight of Puhi occupied 4,000 cc. Approximately half the volume of soil taken from the field consisted of rocks. Four thousand five hundred gm. would occupy approximately 8,000 cc. Thus, as an approximate adjustment to obtain equal field volumes 4,500 gm. were taken for each soil.

Treatments

Four thousand five hundred gm. of soil were mixed thoroughly with each calcium carbonate and calcium silicate treatment in a stainless steel rotary mixer and placed in a Mitscherlich pot. The S_1 and L_1 treatments were 5,000 lb./acre or 18.12 gm./pot. The S_2 and L_2 treatments were 20,000 lb./acre or 72.48 gm./pot. These pots were then stored in a moist condition for 7½ weeks to allow time for the pH to reach equilibrium before planting. The phosphorus treatments were applied at the end of this period. The chemical was stirred into the top 1½ inches of the pot. Treatments were: P_1 - 500 lb. monocalcium phosphate/acre or 1.81 gm./pot, and P_2 - 2000 lb. monocalcium phosphate/acre or 7.24 gm./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 weeks interval. 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 one 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-half 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 oven dried at 60° C, weighed and ground in a Wiley Mill. They were examined under a binocular microscope at 80X power to detect contamination by soil particles.

Leachates

Although the pots were kept moist no water had passed through the pots into the collecting pan until three days after planting. At this stage 600 cc. of water were added to each pot. Twenty-five ml. was taken from each collecting pan and the three replicates for each treatment bulked to give 75 ml. for each treatment.

pH of the leachate was recorded using a Beckman pH meter. Phosphorus analysis was carried out using the method of Truog. Spot tests for nitrate were carried out on several samples using the Brucine method.

A week prior to harvesting all collecting pans were full of leachate. One hundred fifty cc. were taken from two replicates and a bulk sample made up. pH and phosphorus content were recorded. Aluminum was determined by the aluminon method.

Plant Chemical Analysis

Ground plant samples were redried at approximately 70° C and placed in a desiccator. Two grams of plant top samples were weighed out and between 1 and 2 grams of roots were weighed for chemical analysis. Samples were ignited in a muffle furnace at 480° C, taken up in concentrated hydrochloric acid, evaporated to dryness and baked on a hot plate for 4 hours for silica crystallization.

The sample was then taken up in 3N hydrochloric acid and made up to volume. Aliquots were taken for: (1) phosphorus analysis--by the method of Truog and Meyer, (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 analyses (by the aluminon method - Chenery, 1948).

Methods were the same for both roots and tops.

Soil Chemical Analysis

All samples were in a moist condition and therefore the moisture content of each sample was determined to convert all results to an oven dry weight basis.

pH was determined on the soil as a paste. The paste was allowed to stand for 1 hour before recording the pH.

Extractable phosphorus was determined by using the 0.02N sulfuric acid extractant (Ayres and Hagihara, 1955) and carrying out the analysis by the method of Truog and Meyer.

Extractable aluminum analysis was carried out according to the method of Pratt (Nelson, 1958), using 100 ml. of N ammonium acetate and 0.1N 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, the filtrate being retained for calcium and potassium determinations. Excess ammonium acetate was washed from the soil with ethanol and the ammonium leached out by N potassium chloride solution adjusted to pH 2.5. The leachate was made up to volume and ammonia determined by using the Nessler reagent method.

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

Pot Experiment No. 2

This experiment was designed to test the liming materials which would be used in field trials against those used in pot experiment No. 1. In addition a calcium sulfate treatment was included to test the addition of calcium without altering the pH and a chelating agent was added to see if aluminum ions were removed by this treatment with a subsequent increase in yield.

Soils

The same soils, preparation, and amounts per pot were used as for pot experiment No. 1.

Treatments

1. Pacific Chemical and Fertilizer Company crushed coral rock @ 10,000 lb./acre or 36.22 gm./pot.
2. Calcium carbonate (c.p.) @ 10,000 lb./acre or 36.22 gm./pot.
3. Basic slag from Birmingham (U.S.A.) @ 36.22 gm./pot.

4. Calcium silicate (c.p.) @ 36.22 gm./pot.

5. Calcium sulfate (c.p.) (equivalent rates of Ca as 1 and 2) @ 62.30 gm./pot.

6. Ethylene dinitrilo tetraacetic acid @ 500 lb./acre or .90 gm./pot.

7. Nil.

Each treatment was split so that one had zero phosphorus and the other had 3,000 lb. monocalcium phosphate per acre (10.86 gm./pot).

As with pot experiment No. 1 all treatments except the phosphorus treatment were allowed to 'reach equilibrium' for 11 weeks prior to phosphorus applications and planting.

Two replicates were used in a randomized replicate trial with: 7 x 2 = 14 treatments x 2 replicates = 28 x 2 soils = 56 units.

<u>Growth</u>

Pots were sown with sudan grass and grown for seven weeks. Nitrogen and potassium were supplied in the same manner as pot experiment No. 1.

<u>Harvesting</u>

The same procedure as in pot experiment No. 1 was followed.

<u>Ratoons</u>

The experiment was ratooned and harvested again at six weeks after ratooning. Dry weights of sudan grass were recorded and the plant material discarded.

<u>Plant Analysis</u>

The material has been stored for future projects.

<u>Soil Analysis</u>

Only the pH and extractable aluminum were determined.

Mineralogical Examinations

X-ray and DTA

Subsamples of the soil from each pot were bulked, air dried and passed through a 60 mesh sieve. Samples from major treatments were subjected to X-ray diffraction analysis and differential thermal analysis.

For X-ray analysis samples were ground to a fine powder and placed in a planchette on an automatic chart recording Phillips-Norelco X-ray diffraction machine using an iron tube, a manganese filter and a silicon standard.

For differential thermal analysis a heating rate of 15° C per minute was used. Galvanometer and temperature readings were manually recorded at one minute intervals.

Thin Section Radioautographs

It would be an advantage if thin sections of soils could be studied, and if phosphorus compounds formed under various treatments could be identified. With this in mind blocks of impregnated soil were cut from the P^{32} zone of several of the pots in the P^{32} leaching experiment (described in this thesis). Thin soil sections were made from the block. Radioautographs were taken of the thin section slides in the same manner as the radioautographs in the main P^{32} experiment.

Radioactive decay had weakened the activity of the P^{32} in the blocks so that if the slide was thin enough for examination under a mineralogical microscope the radioautograph was not distinct with a 16-hour exposure. If the radioautograph was distinct then, under these conditions, the slide was too thick for satisfactory mineralogical examination. However, by superimposing the radioautograph onto the slide, areas on the peds where radioactivity occurred, could be distinguished.

Radioactive Phosphorus Leaching Experiment

Chemical studies on the leachates from pot experiment No. 1 showed that there was a tendency for phosphorus to increase in the leachate from the limed pots at the medium and high phosphorus levels. To further examine this aspect, a leaching experiment was set up using radioactive monocalcium phosphate.

Bouldin and Black (1954) analyzed P^{32} in a soil column by pushing thin sections successively out of the sampling tube, cutting them off and counting the activity of the sections with G.M. equipment. Heslep and Black (1954) constructed the soil column in sections and removed the sections after the experiment was completed. They also manufactured a tube with two 'windows' running the length of the tube. The activity of the P^{32} was measured by taking radioautographs at the windows.

Radioautographs appear to be a suitable technique as ion-mobility effects can be dramatically illustrated. However, there is a contact zone between the window and the soil which may distort movement of solutions. Obviously investigating cross sections of the columns would provide a more precise illustration of P^{32} movement.

Leaching Columns

Two 6-oz. waxed paper cups were fitted together, the bottom being removed from the top cup. Drainage holes were punched in the bottom of the lower cup. The purpose of the two cups was to accommodate a longer soil column.

Treatments

Soils stored from pot experiment No. 1 were used. They were Akaka with nil lime, with medium lime level, and with high lime level; and Puhi with nil lime level, with medium lime level, and with high lime level. Duplicate treatments were used. Thus, there were 2 x 6 = 12 treatments.

A saturated solution (200 cc) of monocalcium phosphate was made up and a solution of P^{32} added. It remained for 22 hours to enable equilibrium to be reached. The activity of the stock solution was 2 μc/cc on December 18, 1960. This is equivalent to 4.44×10^9 disintegrations/minute/cc. With 10 percent efficiency it is equivalent to 4.44×10^8 disintegrations/c.p.m./cc. 0.05 cc. of P^{32} solution was added to 200 cc. of Ca phosphate; thus, the dilution was 1 in 4000. The P^{32} strength is therefore $\frac{4.44 \times 10^8}{4000} = 1.11 \times 10^5$ c.p.m./cc.

= 110,000 c.p.m./cc

on December 18, 1960.

Four cc. of this tagged solution was added to the surface of the soils in the cups. A fine pipette was used to obtain an even distribution of the solution over the surface. The surface was covered with 1/2 inch of vermiculite to prevent evaporation and to enable leaching water to be added to the soil without directly disturbing the P treated zone.

The test cups were placed inside larger cups to collect the leachate. The whole unit was placed in a tray in the glasshouse. This was completed on December 9, 1960.

<u>Fertilizer Solution</u>

Since no P^{32} was detected in the leachate it was thought that the addition of fertilizer may be a factor. Five ml. of a 5 percent urea, and 5 percent KCl solution was added to one of each duplicate pairs on December 15, 1960.

Leaching Schedule

December 9, 1960 - treated with P^{32} solution

December 10, 1960 - 25 cc. water added to each pot

December 12, 1960 - 50 cc. water added to Akaka soils

100 cc. water added to Puhi soils

December 17, 1960 - 100 cc. water added

Total - Akaka, 175 cc; Puhi, 225 cc.

The pots were then allowed to dry.

Impregnation

A solution of 'Laminac', acetone (50:50) and 2 cc. of a catylst was made up and added slowly to saturate the dry soil columns until the solution appeared as a thin layer in the leachate collecting cup. This was done on December 22, 1960 and allowed to harden. It was repeated on the 24th. By the 27th the bottom of the columns had been sealed and the 'Laminac' solution was added until it reached 1/4 inch above the surface of the soil. This was hardened until the 29th.

Cutting

The dry columns appeared hard enough to cut. A circular diamond faced, water lubricated saw was used. As the study included the movement of P^{32} down the column the saw cuts were made from the bottom upwards. This prevented the downward spread of P^{32} by the saw. The cut 'face' of the column was dried and by using a fine pointed knife a fresh 'face' was made. This excluded contamination of non-P^{32} areas by the 'smearing' action of the saw.

Radioautographs

On the 28th a trial exposure of 16 hours was made with one soil block. The result was satisfactory and the remainder were exposed for 16 hours on the 28th and 29th.

The 'cleaned' cut columns were wrapped in one layer of 'Saran Wrap' and labelled. Twelve, 5 x 7" Kodak, no-screen X-ray films were set out on a bench in the darkroom in complete darkness. The columns (which had been arranged in order previously) were placed, face down onto the film and the film numbered with a chinagraph pencil. This was also in complete darkness.

After 16 hours the films were developed in Kodak X-ray film developer for 4.5 minutes, fixed for 5 minutes, then washed thoroughly and dried. (NB: This could have been accomplished also by inserting the film in black paper envelopes and placing the blocks in the light.)

RESULTS

Pot Experiment No. 1

Yield

The yield results for pot experiment No. 1 are shown in page 1 of Appendix A1. Analysis of variance for the yield is shown in Table 1.

The yields of sudan grass are significantly increased by each increment of phosphorus in both soils. In the Akaka soil the effect of rates show a linear relationship; whereas, in the Puhi soil the relationship is curvilinear.

The L_1 and S_1 levels of lime and calcium silicate increase the yield in the Akaka but not in the Puhi soil.

TABLE I. SIGNIFICANCE OF F VALUES IN THE ANALYSIS OF VARIANCE OF VARIOUS FACTORS IN POT EXPERIMENTS WITH SUDAN GRASS ON PUHI AND AKAKA SOILS

Source	Tops				Roots
	Yield	% P	% Ca	ppm. A	ppm. Al
Soils	X X				X
Phosphorus (P)	X X	X X	X		
Rates of calcium (Ca)	X X		X X		
Source of calcium (CS)	X X	X	X X	X X	
S x P	X X	X X			
S x Ca	X X				
S x CS	X X		X X	X X	
P x Ca					
P x CS					
Ca x CS	X X		X X	X X	
S x P x Ca	X X				
S x P x CS		X			
S x Ca x CS	X	X X			
P x Ca x CS	X	X X			
S x P x Ca x CS		X	X		
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.	.020%	.170%	63.0 ppm.	2150 ppm.

X X - significant at 1% level.

X - significant at 5% level.

TABLE II. CORRELATION COEFFICIENTS CALCULATED FROM THE RELATIONSHIPS BETWEEN DRY MATTER YIELD OF SUDAN GRASS AND THE FOLLOWING FACTORS

Factor	Soil	r	Signi-ficance	Coefficient of determination
Yield Vs.				
In Plant Tops				
% phosphorus	Akaka	+.03	N.S.	-
Log % phosphorus	Puhi	+.87	X X	75.7%
% calcium	Akaka	+.66	X X	43.6%
% calcium	Puhi	+.35	N.S.	-
ppm. aluminum	Akaka	-.48	X	23.0%
ppm. aluminum	Puhi	+.38	N.S.	-
In Plant Roots				
% phosphorus	Akaka	+.56	X	31.4%
Log % phosphorus	Puhi	+.77	X X	59.3%
% calcium	Akaka	+.56	X	31.4%
% calcium	Puhi	-.71	X X	50.4%
ppm. aluminum	Akaka	-.64	X X	41.0%
ppm. aluminum	Puhi	+.70	X X	49.0%
In The Soil				
ppm. phosphorus	Akaka	+.63	X X	39.7%
Log ppm. phosphorus	Puhi	+.91	X X	82.8%
Exchangeable calcium	Akaka	+.78	X X	60.8%
Exchangeable calcium	Puhi	+.11	N.S.	-
pH	Akaka	+.70	X X	49.0%
pH	Puhi	+.03	N.S.	-
Extractable aluminum	Akaka	-.86	X X	74.0%
Extractable aluminum	Puhi	-.26	N.S.	-
Cation exchange capacity	Akaka	+.47	N.S.	22.1%
Cation exchange capacity	Puhi	+.23	N.S.	-

TABLE III. CORRELATION COEFFICIENTS CALCULATED FROM RELATIONSHIPS WITHIN SOIL ANALYSIS VALUES AND ROOT ANALYSIS VALUES

Factor a vs. Factor b	Soil	r	Signi-cance	Coefficient of determination
Roots				
Aluminum vs. calcium	Akaka	-.64	X X	41.0%
" "	Puhi	-.55	X	27.8%
Aluminum vs. phosphorus	Akaka	+.75	X X	56.2%
" "	Puhi	+.60	X	36.0%
Soil				
Aluminum vs. calcium	Akaka	-.95	X X	90.2%
" "	Puhi	-.91	X X	82.8%
Aluminum vs. phosphorus	Akaka	-.28	N.S.	-
" "	Puhi	-.22	N.S.	-
Aluminum vs. CEC	Akaka	-.61	X X	37.2%
" "	Puhi	-.45	N.S.	-

The L_2 level of lime tends to decrease the yield in the Akaka soil and significantly decreases the yield in the Puhi soil. The S_2 level of calcium silicate however increases yields in both the Akaka and Puhi soils.

The over-all phosphorus x calcium rates interaction is not significant but it is important to note that the phosphorus x calcium x soils interaction is significant. This means that the phosphorus x calcium rates interaction is apparent in the Akaka soil but not in the Puhi.

As a study of the depression due to the L_2 level was considered outside the scope of this investigation the results will only be briefly discussed. Results for the L_2 and S_2 levels have been omitted from all graphical relationships. Root chemical analysis results in the Puhi series are considered unreliable because of the possibility of soil contamination. Contamination in the Akaka series is unlikely as high yielding plants show a low aluminum content.

Plant and Soil Analysis

Phosphorus - ppm. phosphorus extracted from the soil by 0.02N sulfuric acid shows a significant increase with each level of added phosphorus (see page 10, Appendix A1). The nil P level value of the Puhi soil indicates the possibility of a lack of phosphorus for optimum plant growth. The nil P level of the Akaka soil shows that there should be sufficient phosphorus for growth in this soil.

In the roots (page 6, Appendix A1), the Puhi soil studies show increased percent phosphorus with added phosphorus. The Akaka soil shows no significant increase with added phosphorus but rather a decrease with added lime or calcium silicate.

In the tops (page 2, Appendix A1), the significance of the interactions in Table 1 indicate that percent phosphorus generally increased with added phosphorus. There is little increase from the P_2 level of phosphorus in the Akaka soil compared with the Puhi soil series. Both lime and calcium silicate increase the percent phosphorus uptake in the Puhi series but only at the high level of phosphorus. Leachate studies show a similar trend.

There is no marked increase in the uptake of P in the Akaka series with these materials. The zero treatment values of the Akaka plants are higher than the Puhi values, presenting further evidence that the plants grown in the Akaka series nil treatment pots received sufficient phosphorus from the soil whereas those in the Puhi series did not.

An examination of the relationship between phosphorus and yield (page 5, Appendix A2) in the soil and the plant shows that there is no relationship between yield and phosphorus in the Akaka series but there is a significant relationship in the Puhi series.

<u>Calcium</u> - The exchangeable calcium in the soil (page 9, Appendix A1) was increased by increasing levels of lime and levels of calcium silicate. Lime gave higher values than calcium silicate in both soils. In the Akaka soil, phosphorus additions increased the exchangeable calcium, especially in conjunction with calcium silicate.

In the roots however (page 7, Appendix A1) calcium uptake increased with the use of lime but only to a slight extent with calcium silicate. What is more surprising is that increased phosphorus lowers the calcium uptake in the roots with the Puhi series.

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

When the calcium content of soil, roots or tops is compared with the yield (pages 1,2,4, Appendix A2) the Akaka series shows a positive correlation in all cases. This would indicate a shortage of calcium by the plant in untreated soils except 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. This will be discussed further. It is noted that there is a negative correlation in the roots with the Puhi series.

Aluminum - Extractable aluminum in the soil (page 10, Appendix A1) shows a reduction by the addition of lime or calcium silicate and also monocalcium phosphate. The Akaka soil contains considerably more extractable aluminum than the Puhi soil.

In spite of the large variation in the root analysis values it appears that lime and calcium silicate reduce aluminum in the roots of the Akaka series and that monocalcium phosphate increases the aluminum content of the Puhi series roots. The increase in the Puhi series could be due to contamination by soil particles.

In the tops, calcium silicate suppresses aluminum uptake whereas lime increases uptake, at least at the L_2 level.

Yield relationships (pages 1,2,4, Appendix A2) show that in the soil, roots, and tops, a reduction in aluminum level is accompanied by an increase in yield. There is no relationship with yield in the Puhi series except in the root content of aluminum.

pH - The pH is increased by lime to a greater extent than by calcium silicate. The general increase is higher in the Puhi soils than in the Akaka. pH of the soil is related to exchangeable calcium and to yield (page 4, Appendix A2).

Cation exchange capacity - (Page 6, Appendix A2) shows the effect of aluminum on cation exchange capacity. The reduction in aluminum is accompanied by an increase in the cation exchange capacity. This was also pointed out by Magistad (1928). Monocalcium phosphate levels also affect cation exchange capacity probably through the effect of increasing calcium and reducing aluminum.

Potassium - Results show that in general high yielding plants have removed more potassium from the soil solution than the low yielding plants.

Leachate Studies

Although the results were not statistically analyzed it is obvious that the aluminum content of the nil treatment in the Akaka soil is extremely high. The concentration is reduced by lime and calcium silicate and by monocalcium phosphate. This appears to be in keeping with results of plant and soil analysis. Hester (1935) stated that growth was directly correlated with the appearance of aluminum in the drainage waters.

With the Puhi soil the results are normally low. However, monocalcium phosphate increased the aluminum content in the leachate at the S_0 and L_0 levels. This was accompanied apparently by a drastic lowering of the pH of the leachate solution.

The graph of the relationship between aluminum content and pH (page 7, Appendix A2) illustrates clearly the reduction in soluble aluminum as the pH increases. At approximately pH 5.6 the aluminum content remains constant with increasing pH. It is completely soluble at pH 3.5. The activity of aluminum in this pH range corresponds to the activity of aluminum on decreasing the pH of a $Al_2O_3(P_2O_5)$.980 colloidal complex (Miller, 1956). Magistad (1925) pointed out that when the acidity became greater than pH 5 the aluminum solubility increased until pH 4.5 was reached, at which point it increased rapidly.

Although the concentration of phosphorus is variable the L_1 level in the Puhi soil increases phosphorus when phosphorus is added. This occurs in both the first and second leachate. The L_2 level however is responsible for a much smaller increase due probably to the formation of tricalcium phosphate. The uptake in the plant tops reflects this increase.

The increase in phosphorus concentration with the Akaka soil leachates is small and variable.

Preliminary spot tests for nitrate on the first leachate showed the following results:

Treatment	Akaka Soil	Puhi Soil
L_2	100 NO_3 ppm.	100 NO_3 ppm.
L_1	--	100 " "
S_2	40 " "	--
S_1	10 " "	--
Nil	6 " "	30 " "

Many other workers including those of the Hawaiian Sugar Planters' Association have found a high NO_3 concentration with liming. This phenomenon was considered outside the scope of this work although it is probably of considerable importance.

No tests were carried out for calcium, but in all cases $CaCO_3$ precipitated out in the leachate pans of the L_2 treatments.

Pot Experiment No. 2

Yield results (Appendix B) show a marked increase with added phosphorus in both soils. In the Akaka soil (when considering both the +P and the -P treatments together) the $CaCO_3$, coral sand, $CaSiO_3$ and gypsum treatments were significantly higher than the nil and the chelate treatments. The slag treatment was much higher than the check in the -P treatment. The significant treatments have one factor in common--they each contain calcium and they each reduce the extractable aluminum to some extent. Slag has the additional factor of containing phosphorus.

The results appear to generally confirm the indications in pot experiment No. 1--that yield in the Akaka soil can be related to an increase in soil calcium and phosphorus acting together. These factors can be related in turn to a reduction in the high aluminum levels. Yield in the Puhi series is related principally to the availability of phosphorus to the plant.

It is apparent that the action of calcium phosphate on the Akaka soil is different in this pot experiment. In addition the general yield is higher than pot experiment No. 1. This would indicate that the nature of soil environment has changed. The experiment was carried out 6 months after the soil was collected and while an attempt was made to keep the soil moist, it is possible that some drying out and shrinkage did occur. It has been shown (King, 1961) that the yield is generally increased as this soil is dried out. No explanation is offered for the increased phosphorus response as no soil or plant analyses were carried out in this series.

Mineralogical Examinations

X-Ray and DTA

X-ray and DTA patterns are shown in Appendix C. These patterns illustrate that the Akaka soil is amorphous to X-rays except for indications of a small amount of quartz. The DTA pattern is similar to allophane patterns reported by Fieldes (1957). The exothermic peaks in the 800° to 1000° C. zones vary markedly from sample to sample. It was not possible to reproduce the same position of this peak in duplicate samples.

X-ray studies on the Puhi soil show the presence of a small amount of crystalline gibbsite, goethite, and quartz. However, gibbsite is more predominant in the DTA patterns than in the X-ray patterns, indicating that perhaps the majority of the gibbsite is in a crypto-crystalline state. This state is not amorphous yet not oriented enough for detection by X-rays. The cation exchange capacity, and the buffering characteristics of this soil support this statement. A crystalline oxide soil would not have cation exchange capacity values as high as 40 to 50 me./100 gms. and the rate of pH increase with liming should be higher with a crystalline oxide soil. It is interesting to note that Russell (1950) in discussing Schofield's work showed that the buffer curve of an acid soil was dependent on the aluminum content. Therefore, several comparisons can be drawn between these two soils based on the mineralogical studies. These comparisons may assist in explaining yield responses.

1. Soils in an amorphous state would have both Fe and Al in a more 'reactive' form.

2. They could be imagined as having a loose 'open weave' structure, such that ions can move to internal areas as well as surfaces. Orchiston (1959) has stated from water vapor and nitrogen studies that some allophanes are shown to possess an 'internal' surface. This would explain the high cation exchange capacity possessed by these soils. In this loose configuration these would be both positive and negative sites.

3. OH^- ions would be attached to the negative sites giving the amorphous soil a high buffering capacity.

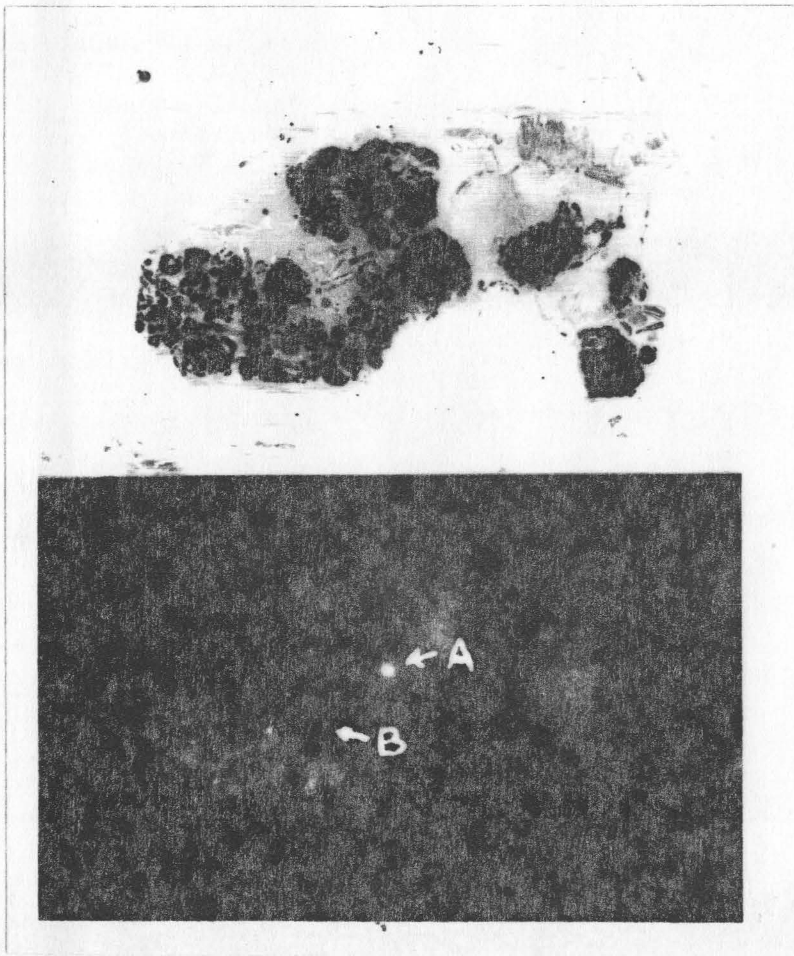
In these examinations there was no evidence to support the hypothesis that liming increased the order of the crystalline state. It probably requires the use of more sensitive instruments such as the electron microscope to detect such changes.

Thin Section Radioautographs

Thin section radioautographs failed to reveal the identity of the precipitated phosphorus minerals as the slides were too thick to examine the optical properties with certainty. However, there is no doubt that with practice radioautographs can be used to locate the phosphorus minerals in thin sections. In any case the radioautographs showed that the phosphorus compounds were distributed in at least two types of patterns. Firstly, a diffuse form on the outer section of the ped and secondly, a reprecipitated form at several points on the slide. This is

Figure 1.

Top - Thin section slide of Akaka soil.



Bottom - Radioautograph taken from thin section shown above.

Note: A. Reprecipitated P compounds.

B. P in a diffuse 'shell' surrounding a ped.

shown in Figure 1. This method may be a useful tool for investigating the micro distribution of certain minerals in the soil and to aid in the identification of minerals.

Radioactive Phosphorus Leaching Experiment

Radioautographs in Appendix D present little evidence to show that liming treatments increase the movement of added phosphorus through the profile of either the Akaka or the Puhi soil. This is in contrast to the leaching studies in pot experiment No. 1 where it was shown that added phosphorus was more mobile with the addition of liming materials in both soils.

No satisfactory explanation can be offered for the difference between these two experiments. The added phosphorus in the P^{32} experiment was in solution whereas in pot experiment No. 1, the phosphorus was in solid form. 'Fixation' may therefore have been more rapid in the P^{32} experiment.

It may be significant that the pH of the first leachate of pot experiment No. 1 shows that the leaching solution had not reached equilibrium with the soil solution. Equilibrium had been reached to some extent in the second leachate. In general, the second leachate showed lower phosphorus values than the first leachate. The soluble phosphorus was therefore decreasing with time.

DISCUSSION

A considerable amount of data has been collected during this investigation. It should be kept in mind however that the main problem is to explain differences in response to lime and calcium silicate on the Akaka soil and the Puhi soil.

From the yield results it has been shown that lime and calcium silicate increase the yield on the Akaka soil to the same extent and that the yield is also increased with monocalcium phosphate in a linear manner. On the Puhi soil only the S_2 level appears to increase yield slightly. The main increase comes from monocalcium phosphate.

The reduction in yield due to L_2 has been omitted from the discussion.

In the introduction section of this thesis several hypotheses were suggested. These can be analyzed using the evidence above.

1. a.) The breakdown of organic matter (if any) has not released soluble aluminum to the drainage waters. This can be shown in the leaching studies.

b.) Phosphorus has only been released by lime or calcium silicate where monocalcium phosphate has been added.

2. Although calcium uptake correlates with yield in the Akaka soil series the range of calcium values are not lower than the Puhi soil which shows no relationship with yield. Therefore, it is likely that calcium is acting with another factor which is, in turn, affecting yield and is not a limiting factor in itself. Evidence shows that this factor may be aluminum. Mechikovsky and Puffeles (1938) reached a similar conclusion.

3. Aluminum is certainly a major factor in the Akaka soil but appears to have little importance in the Puhi soil. Aluminum is negatively correlated with yield in the tops, roots and soil in the Akaka series but shows no relationship in the Puhi studies. Leachate studies also show extremely high concentration of aluminum in the untreated pots.

It appears likely that aluminum is acting as a 'toxic' factor in the Akaka soil and is reduced by high calcium ion concentration, high pH and by a high phosphorus content. King (1961) has shown that high amounts of aluminum phosphate are formed in this soil type upon adding phosphorus, 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 the Akaka series indicate that aluminum phosphate could be 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 is adequate in the tops of the Akaka series. It is more likely that aluminum affects the metabolic functions of the cell at these concentrations. Ruth Addoms (1927) 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. The coagulation finally became irreversible and death of the cell resulted. The fate of aluminum is interesting. The so-called 'active' aluminum is certainly lowered in the soil but is not lost through the drainage waters. It has been speculated therefore that the aluminum enters a cryptocrystalline state. As shown in the X-ray and DTA results, there is no evidence for this occurrence.

4. There is evidence that added phosphorus is released to the soil solution by lime and calcium silicate (analysis of the leachates). With the S_2 level in the second leachate of the Puhi series P_0 and P_1 levels show an increase in soluble phosphorus. The increase is reflected in a yield increase. The increase does not show in the plant uptake or the Truog extractant.

As the Puhi soil appears to lack the ability to supply adequate phosphorus to the plant, any increase in available phosphorus would effect yield. This is not the case in the Akaka soil where the phosphorus supply to the plant is not limiting for growth. In this case monocalcium phosphate could act on the yield indirectly by reducing aluminum.

5. The action of increased nitrification and general microbial activity was not investigated to any extent.

6. Only phosphorus, calcium, and aluminum have been investigated in this study. However, 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 reduced by the action of liming materials or molybdenum may be made more available, etc.

CONCLUSION

In a Hydrol Humic Latosol both calcium carbonate and calcium silicate increase the yield of sudan grass provided the pH remains below about pH 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 Ferruginous Latosol lime does not increase yield but depresses it at high pH values. Calcium silicate slightly increases yield at higher values. This increase is probably due to increased available phosphorus and not to decreasing 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 soil by reducing 'toxic' aluminum, in the Ferruginous Latosol by supplying phosphorus as a nutrient.

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APPENDIX A

POT EXPERIMENT NO. 1

1. Results of yield and soil, plant and leachate analysis.

LEACHATES

pH

	S_1	S_2
	.6	6.7
	.0	6.5
	.3	6.1

2nd Leachate

	L_0	L_1	L_2
P_2	4.5	6.7	7.5
P_1	4.9	6.7	7.5
P_0	4.2	6.6	7.6

	S_0	S_1	S
P_2	4.5	6.2	6.
P_1	4.9	6.5	6
P_0	4.2	6.2	6

	S_1	S_2
	.0	6.6
	.8	6.2
	.6	6.1

	L_0	L_1	L_2
P_2	4.1	6.5	7.4
P_1	3.6	6.7	7.4
P_0	6.2	7.2	7.4

	S_0	S_1	S
P_2	4.1	5.9	7
P_1	3.6	4.5	6
P_0	6.2	6.3	7

LEACHATES

Phosphorus

ppm SOLUTION

2nd Leachate

	S_2
P_2	.13
P_1	.16
P_0	.02

	L_0	L_1	L_2
P_2	.06	.14	.09
P_1	.06	.11	.09
P_0	.05	.08	.05

	S_0	S_1	S_2
P_2	.06	.11	.21
P_1	.06	.05	.17
P_0	.05	.05	.07

	S_2
P_2	.63
P_1	.10
P_0	.10

	L_0	L_1	L_2
P_2	.08	.65	.11
P_1	.06	.22	.08
P_0	.06	.05	.08

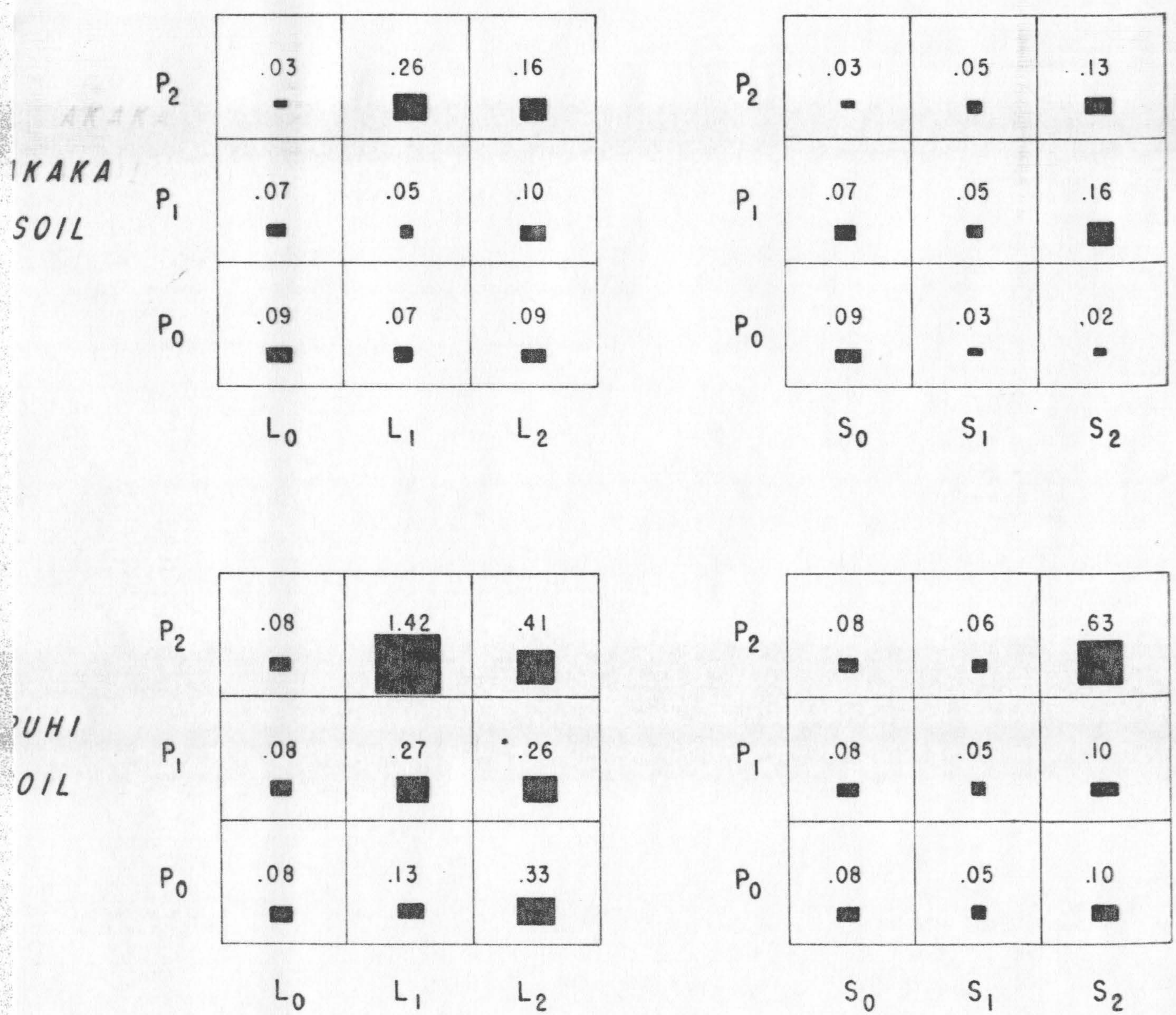
	S_0	S_1	S_2
P_2	.08	.08	.09
P_1	.06	.05	.14
P_0	.06	.14	.18

LEACH

Phosp

ppm SO

1st Leachate



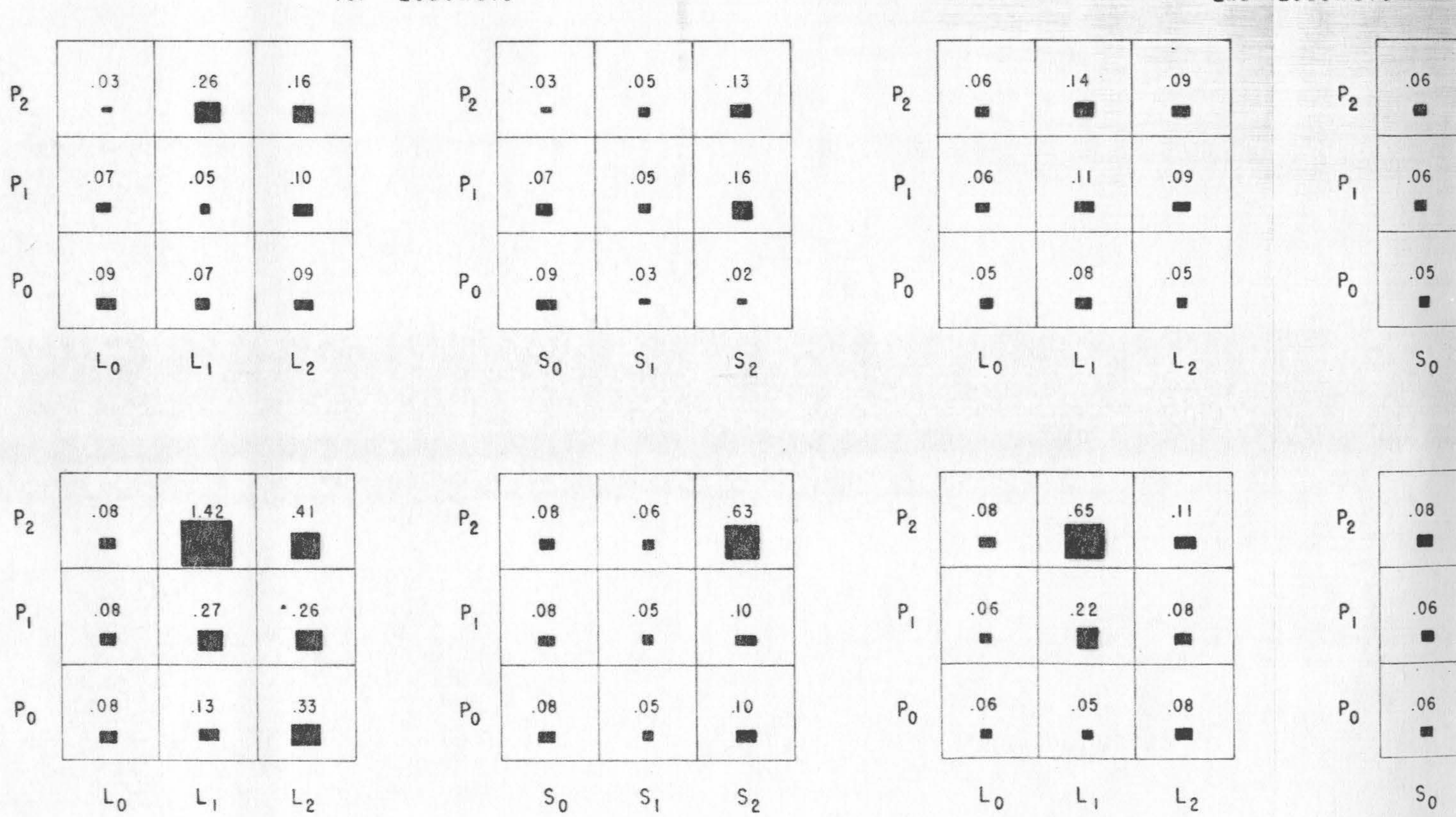
LEACHATES

Phosphorus

ppm SOLUTION

1st Leachate

2nd Leachate



LEACHATES

Aluminum

ppm SOLUTION

2nd Leachate

AKAKA SOIL

	L_0	L_1	L_2
P_2	1.4	.5	.5
P_1	1.4	.3	.5
P_0	5.1	.3	.3

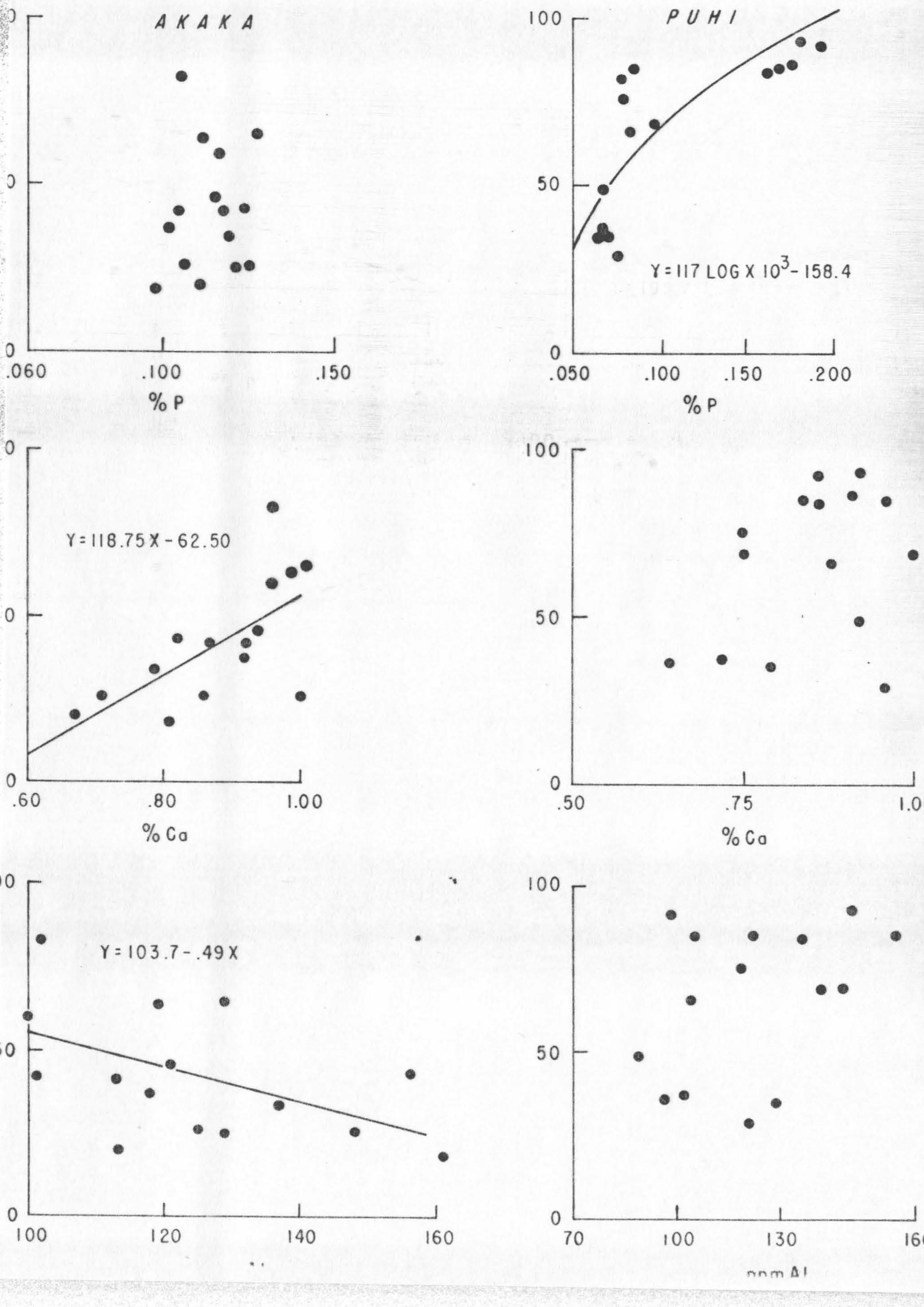
	S_0	S_1	S_2
P_2	1.4	.6	.5
P_1	1.4	.4	.5
P_0	5.1	.3	.4

PUHI SOIL

	L_0	L_1	L_2
P_2	2.7	.3	.2
P_1	3.1	.9	.2
P_0	.4	.3	.3

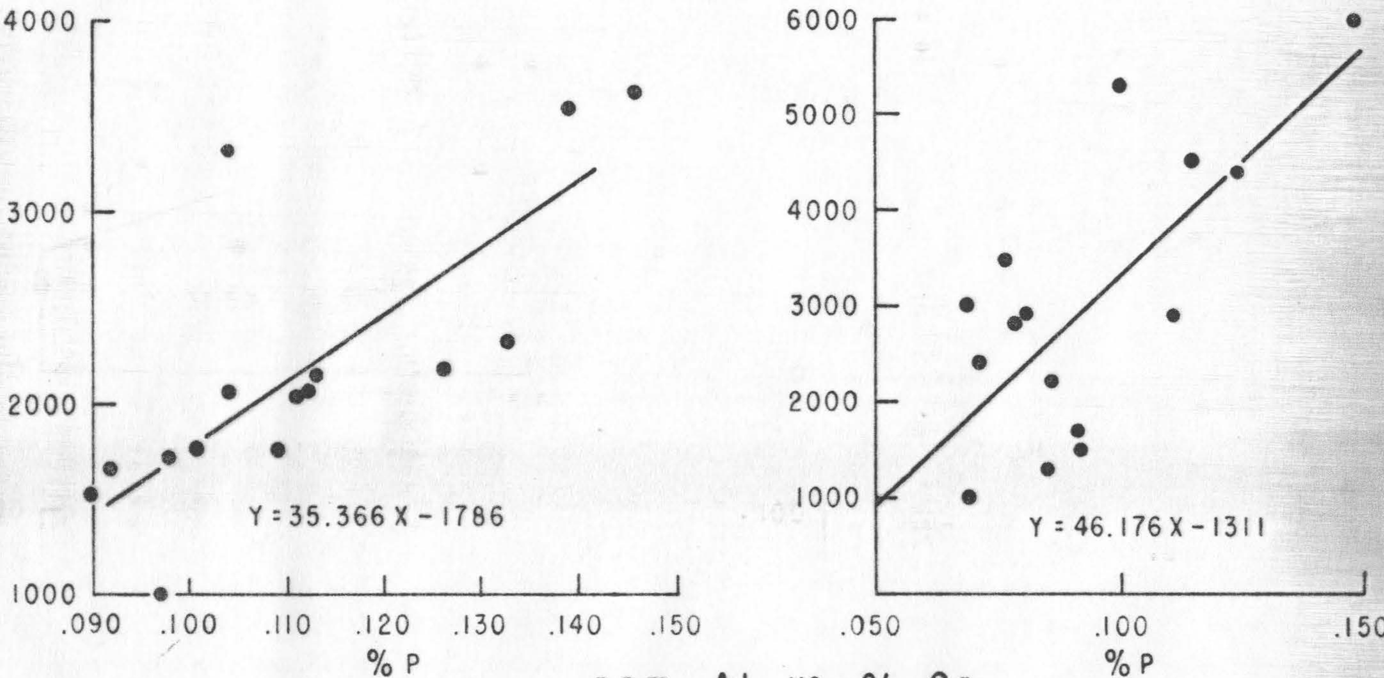
	S_0	S_1	S_2
P_2	2.7	.4	.4
P_1	3.1	1.7	.3
P_0	.4	.9	.5

POT EXPERIMENT No. 1
Yield vs Plant Top Analysis

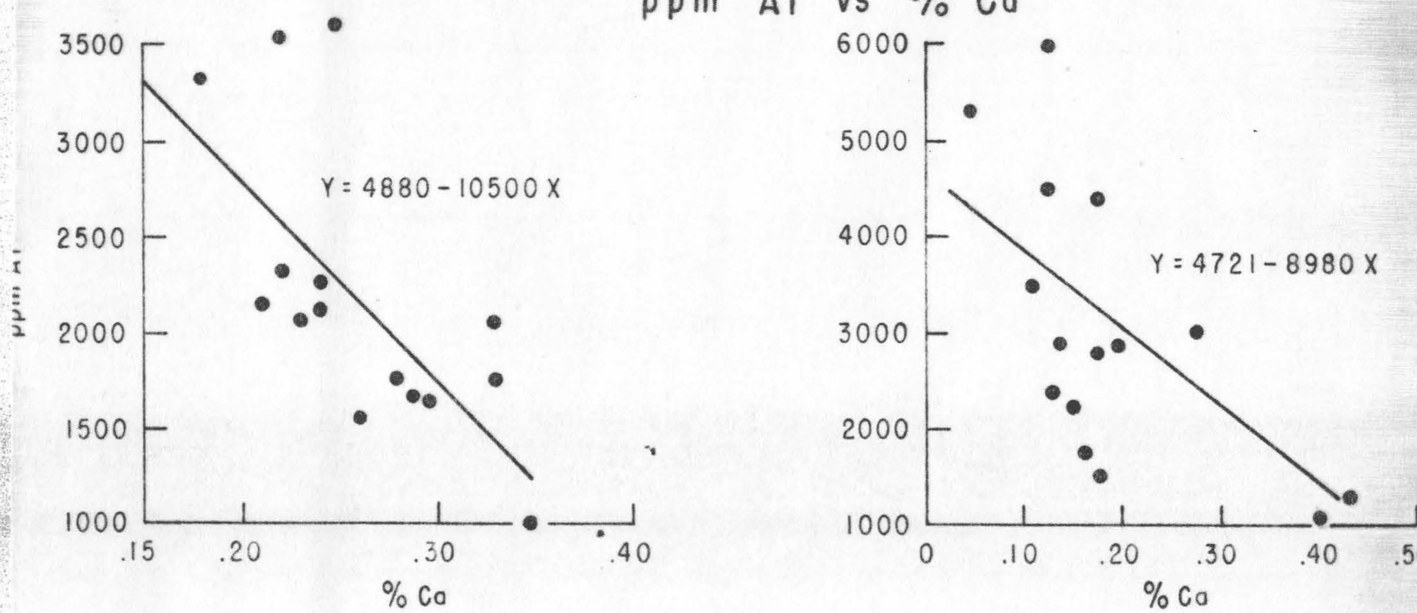


ROOT RELATIONSHIPS

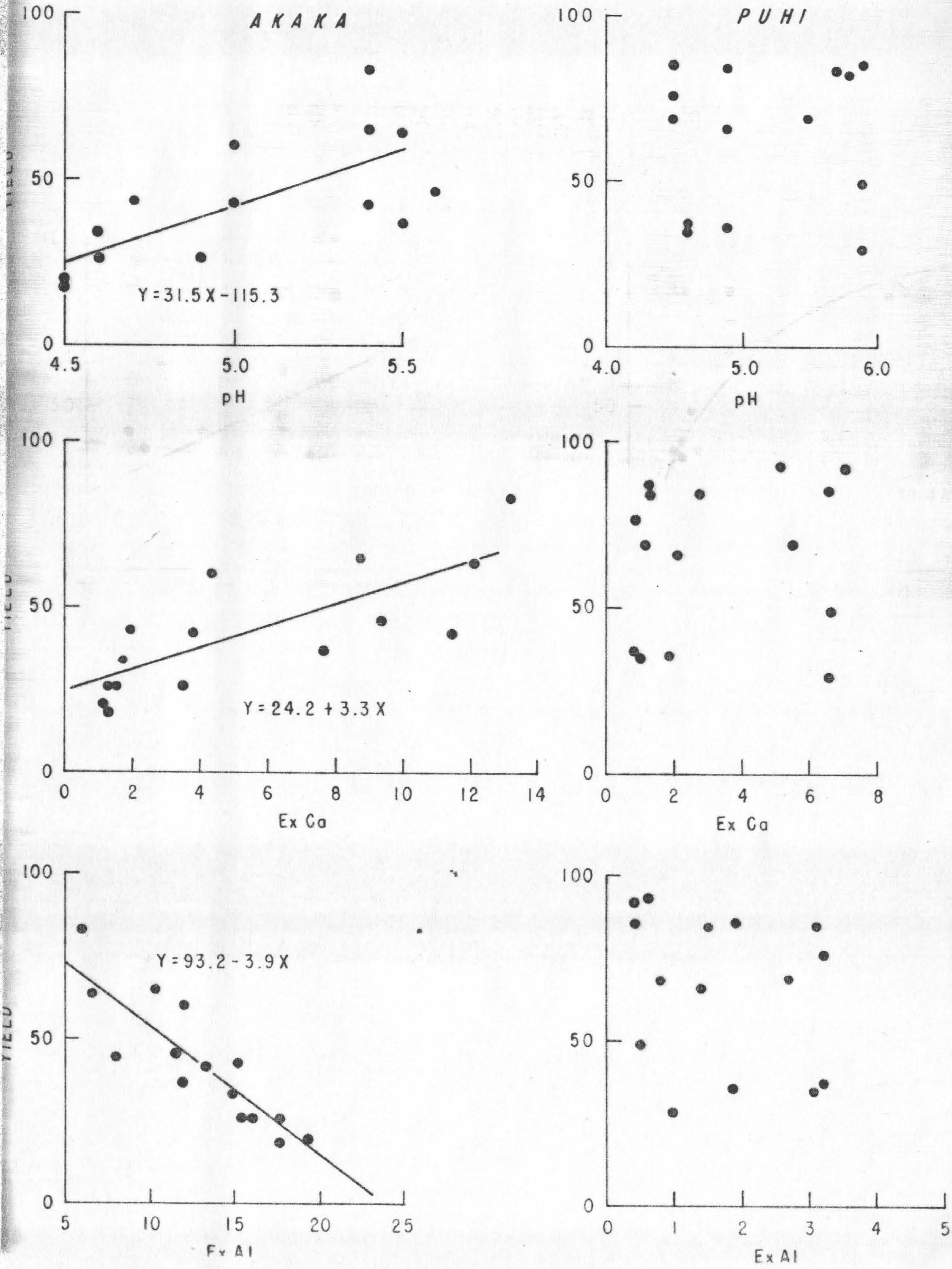
ppm Al vs %P



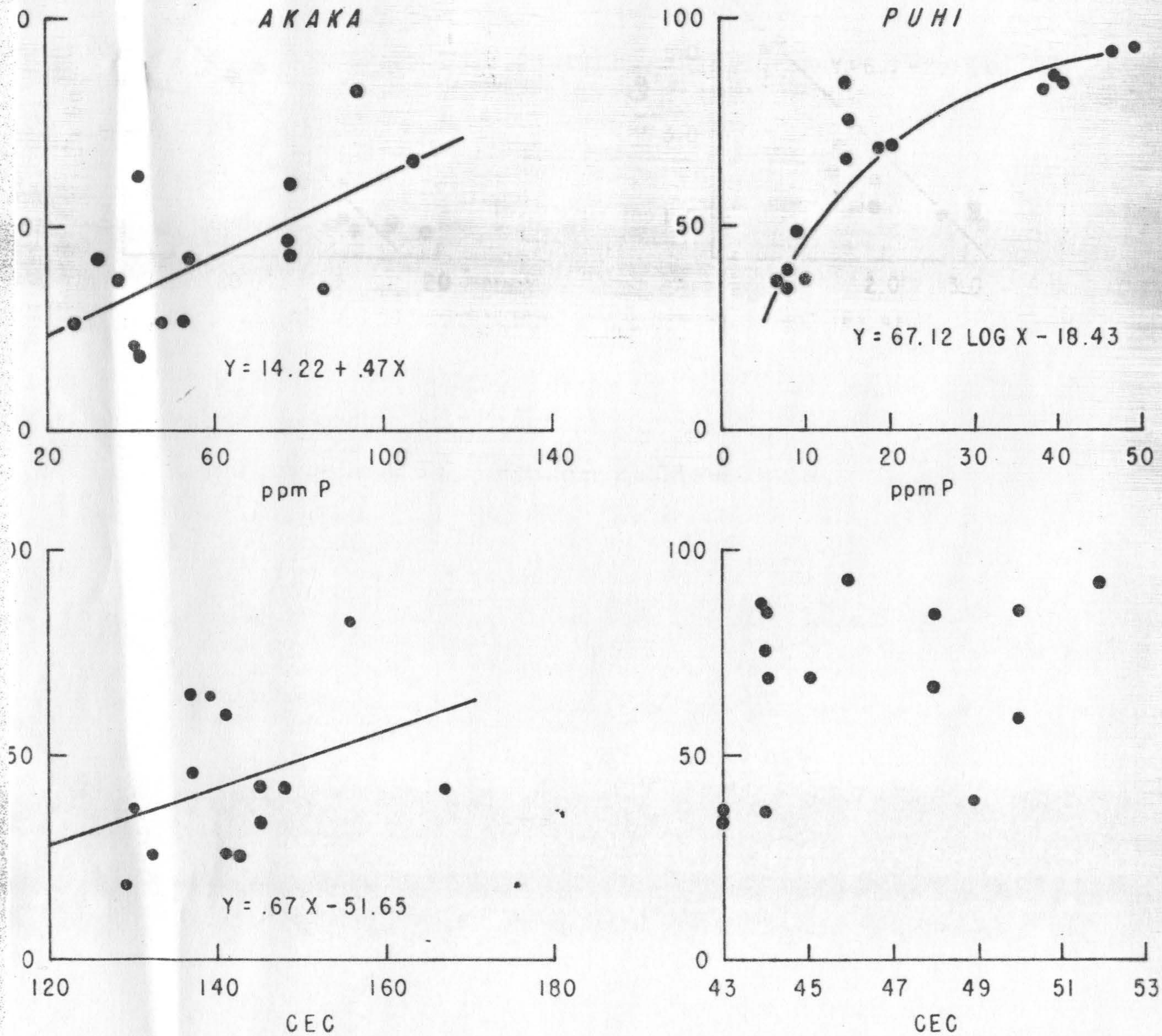
ppm Al vs % Ca



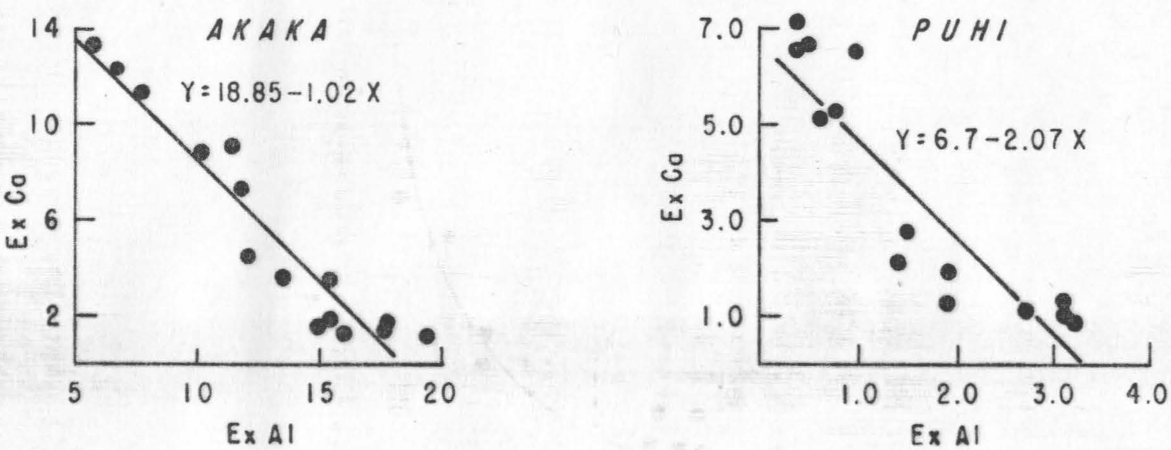
POT EXPERIMENT No. I
Yield vs Soil Analysis



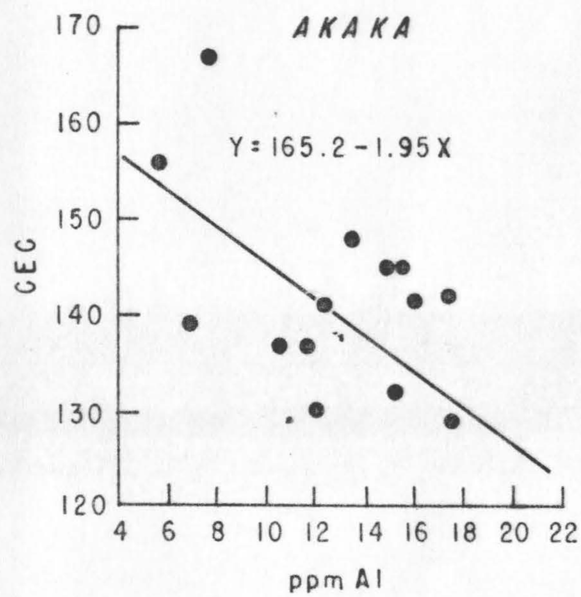
POT EXPERIMENT No. 1
Yield vs Soil Analysis



Ex Al vs Ex Ca in Soil

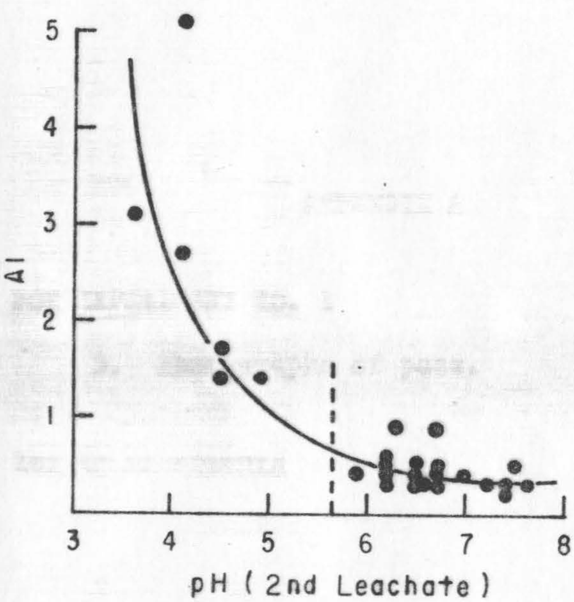


CEC vs ppm Al



2nd LEACHATE - BOTH PUHI & AKAKA

ppm Al vs pH



APPENDIX A

POT EXPERIMENT NO. 1

3. Photographs of pots.

Key to treatments

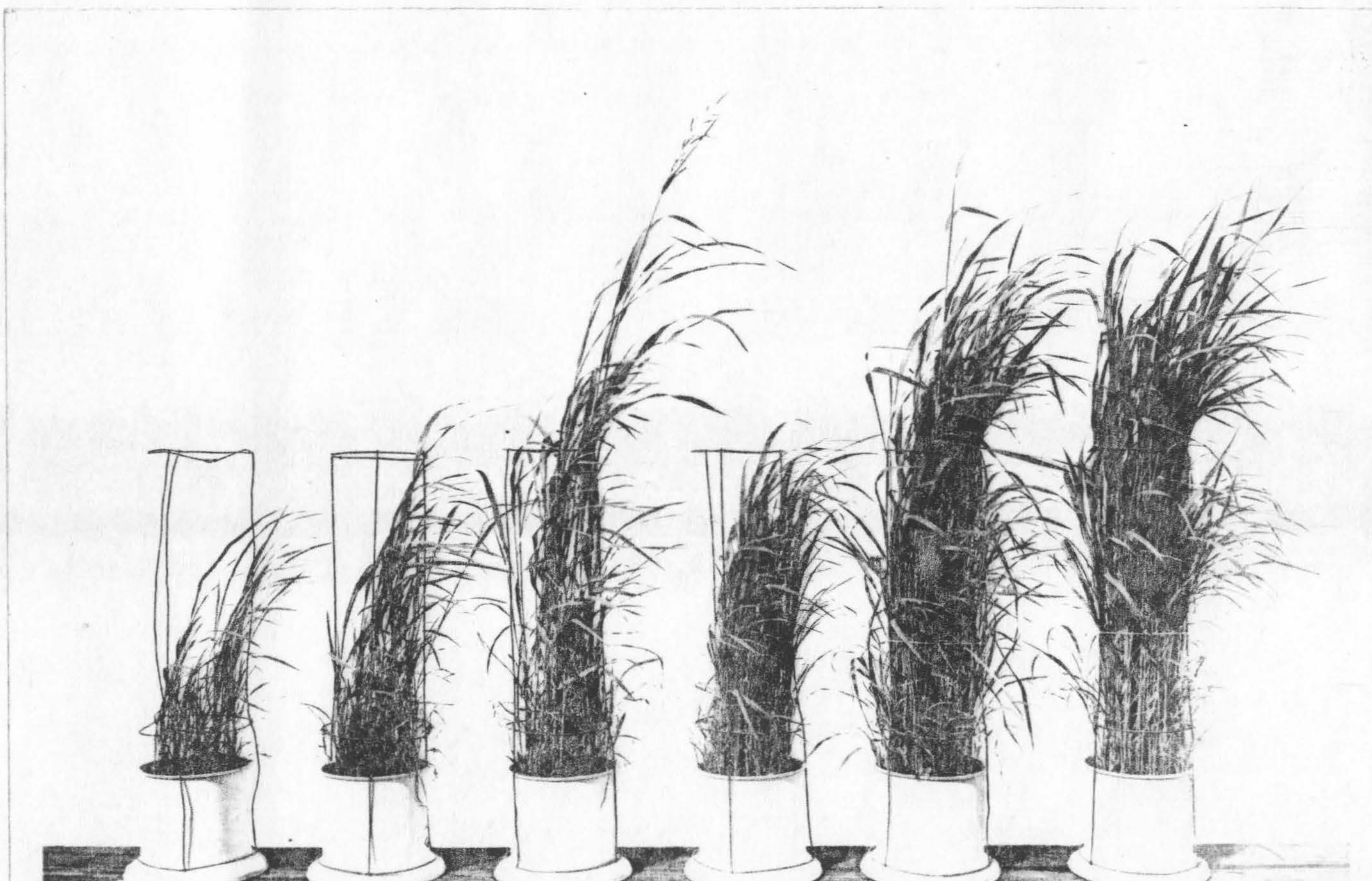
A - Akaka soil

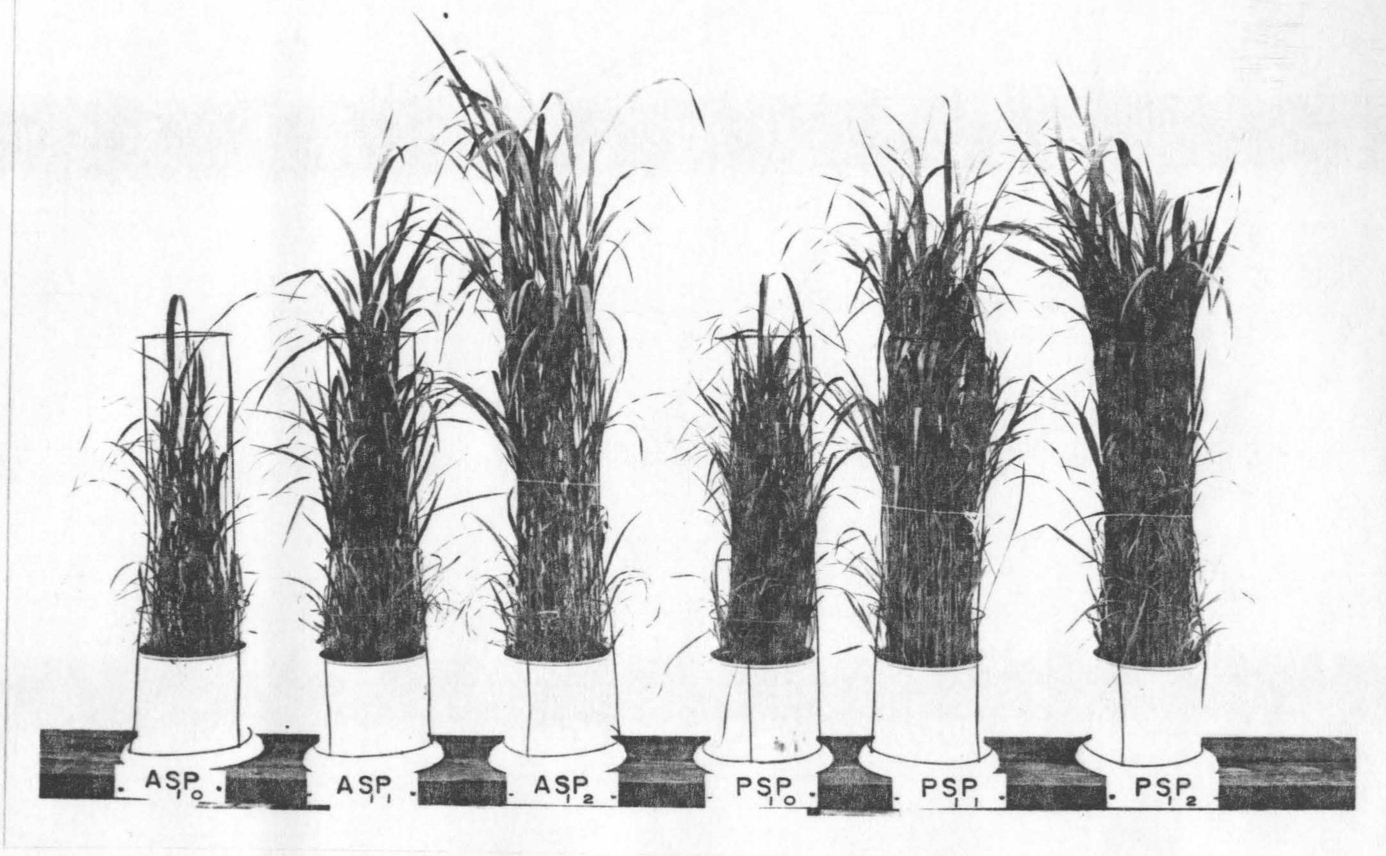
P - Puhi soil

$0, S_1, S_2$ - Levels of calcium silicate

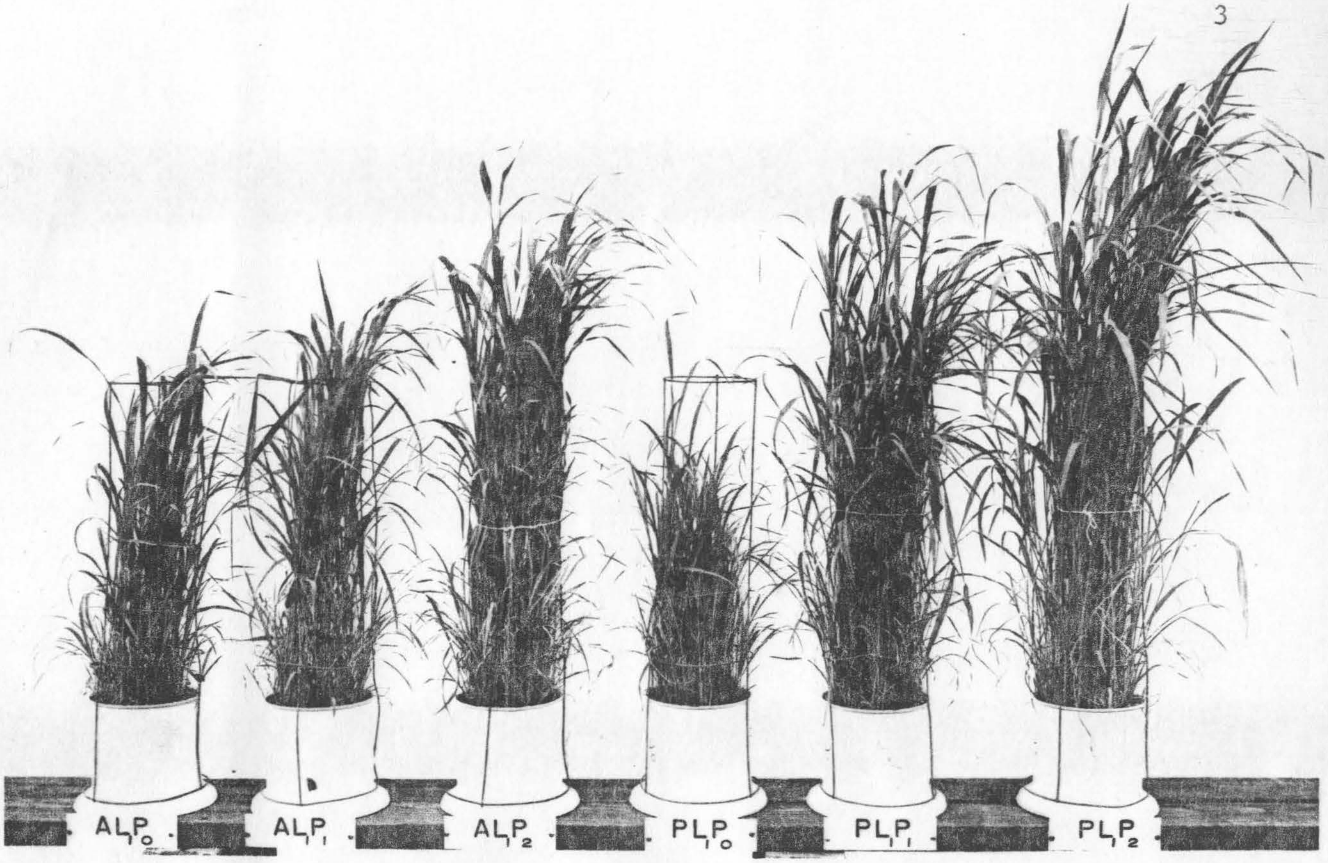
$0, L_1, L_2$ - Levels of calcium carbonate

P_0, P_1, P_2 - Levels of monocalcium phosphate

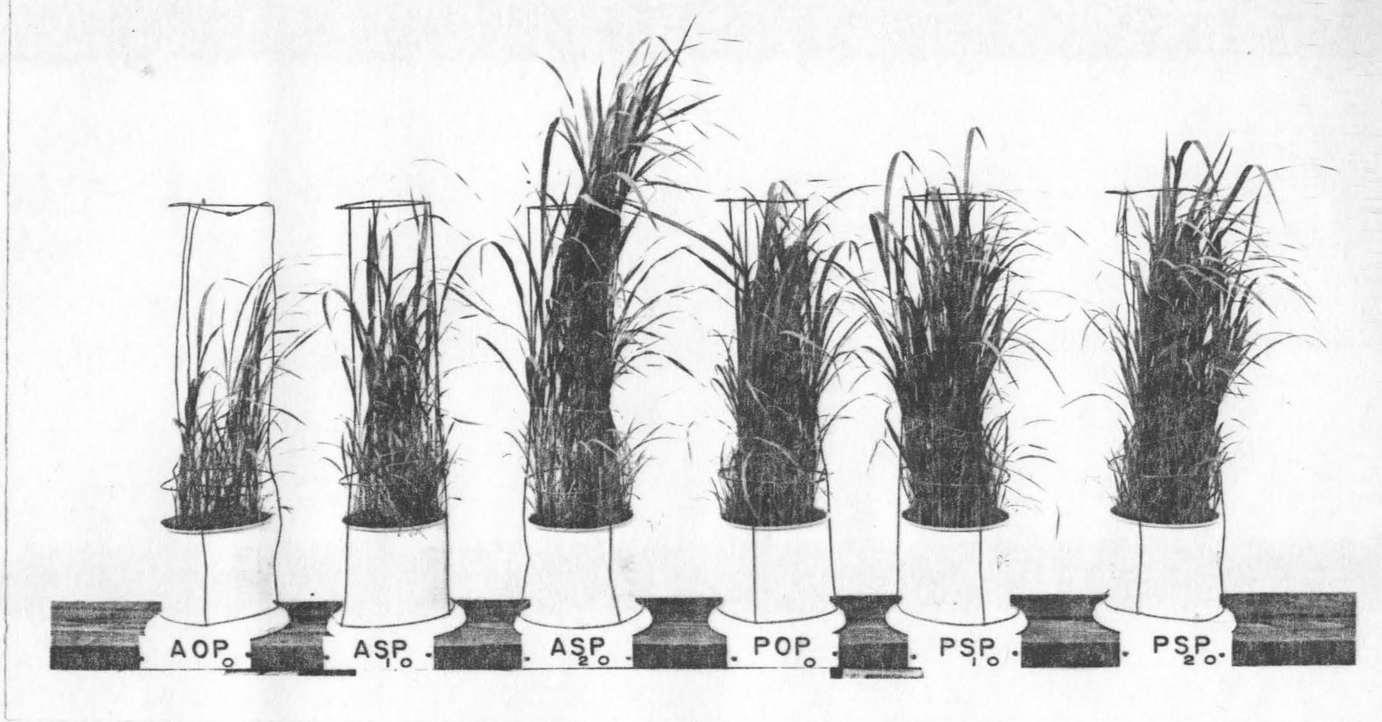

AOP0
AOP1
AOP2
POP0
POP1
POP2

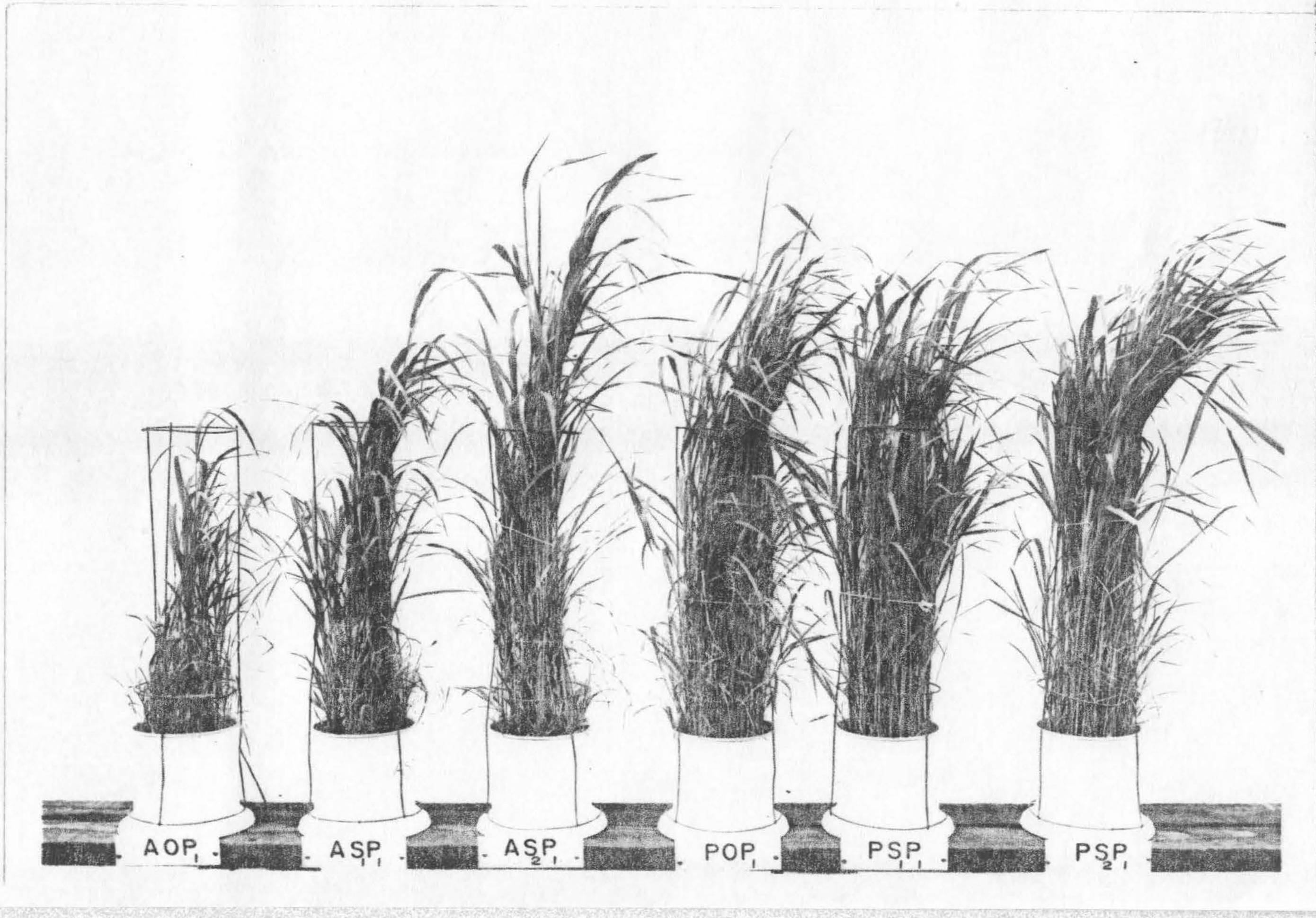

ASP10
ASP11
ASP12
PSP10
PSP11
PSP12

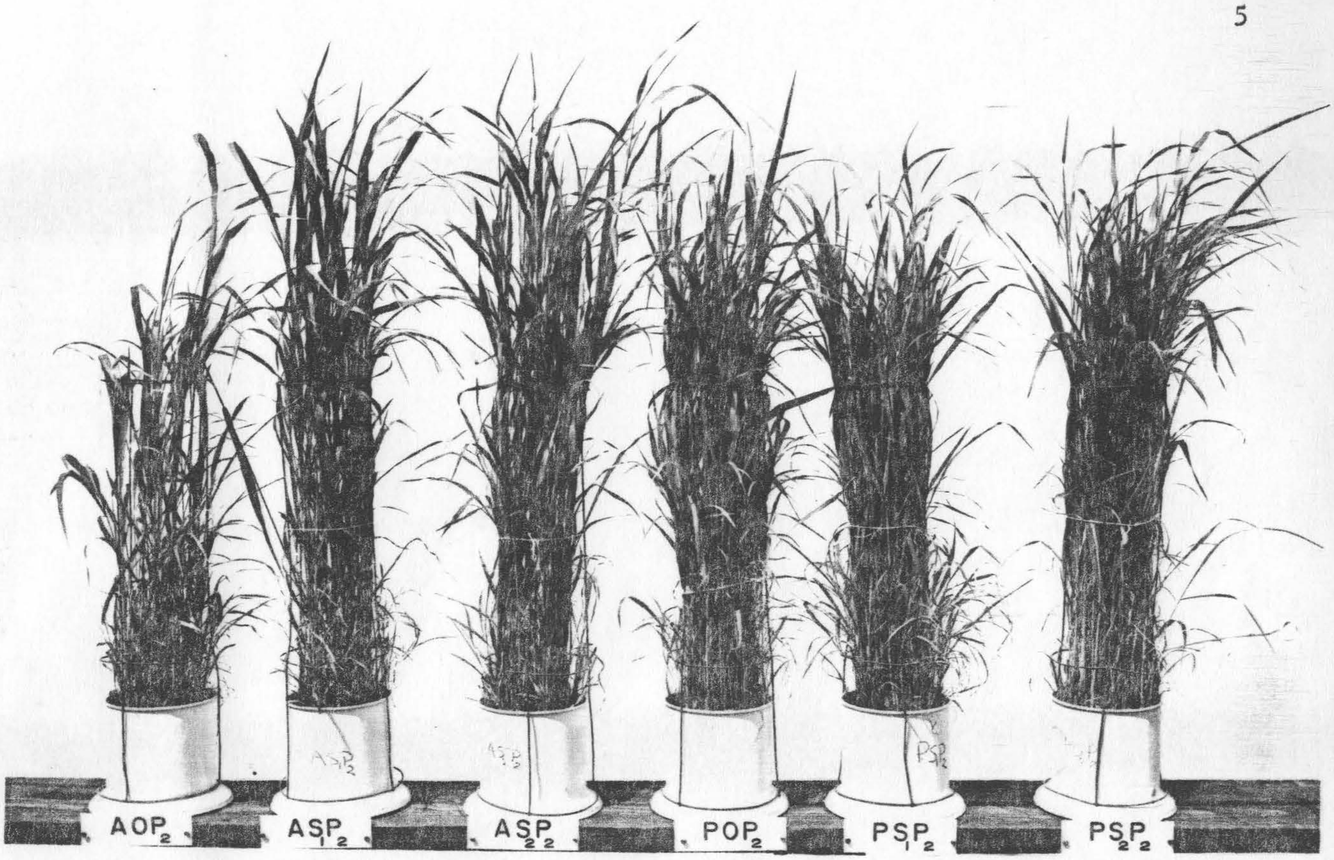

ASP20
ASP21
ASP22
PSP20
PSP21
PSP22


AL_1P_0
AL_1P_1
AL_1P_2
PL_1P_0
PL_1P_1
PL_1P_2

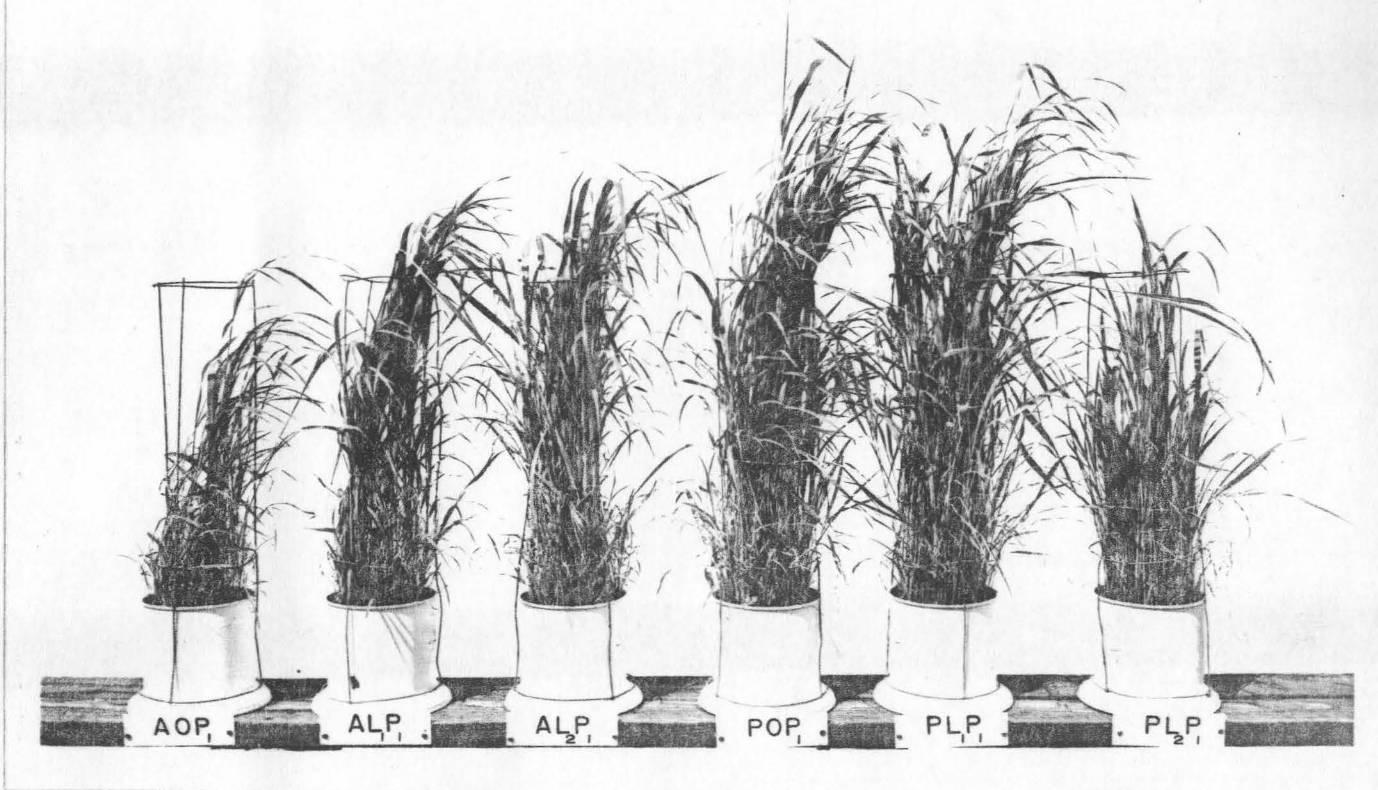

AL_2P_0
AL_2P_1
AL_2P_2
PL_2P_0
PL_2P_1
PL_2P_2

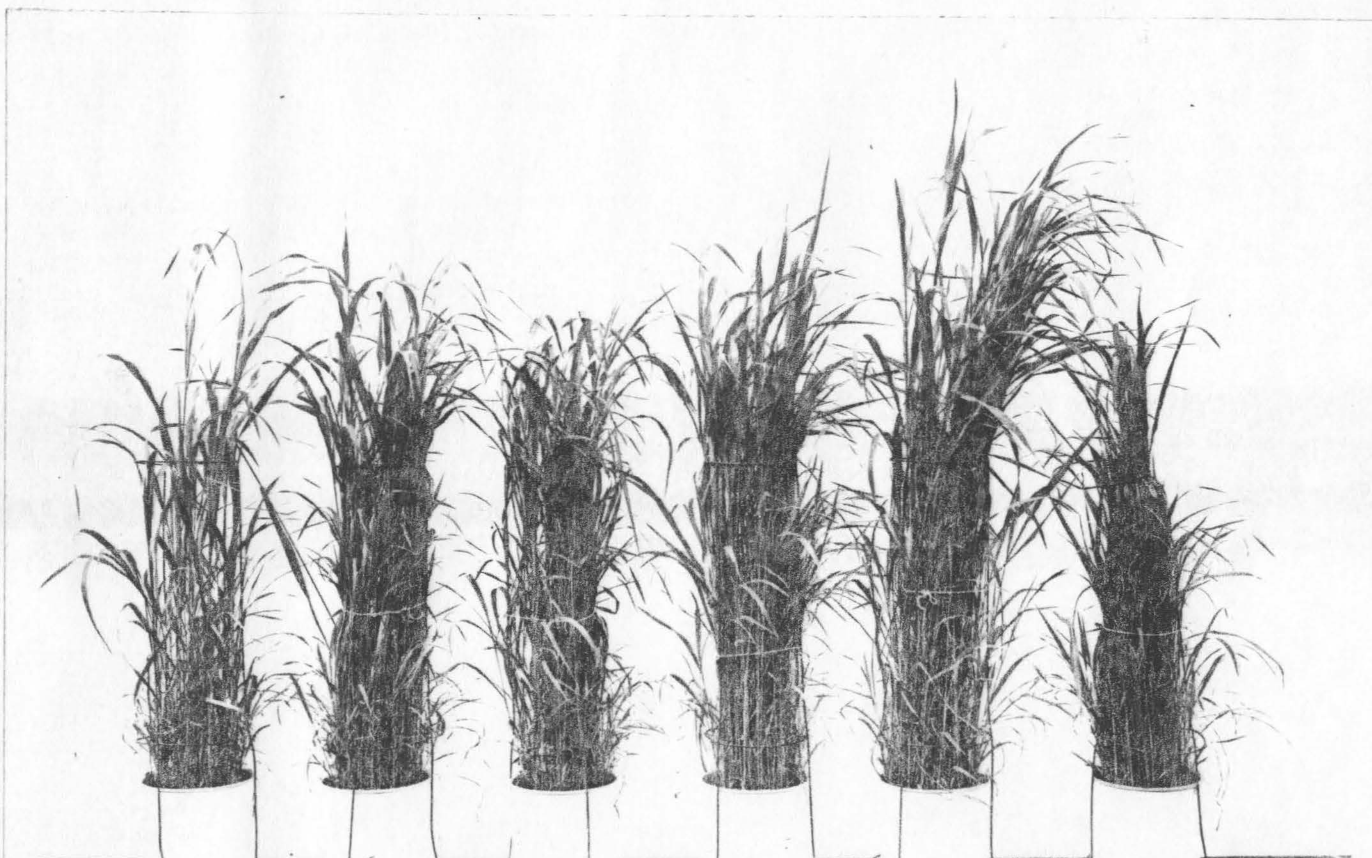

AOP_{0}
ASP_{10}
ASP_{20}
POP_{0}
PSP_{10}
PSP_{20}


AOP_{1}
ASP_{11}
ASP_{21}
POP_{1}
PSP_{11}
PSP_{21}


AOP_2
ASP_{12}
ASP_{22}
POP_2
PSP_{12}
PSP_{22}


AOP_0
ALP_{10}
ALP_{20}
POP_0
PLP_{10}
PLP_{20}


AOP1
AL1P1
AL2P1
POP1
PL1P1
PL2P1


AOP2
AL1P2
AL2P2
POP2
PL1P2
PL2P2

APPENDIX B

POT EXPERIMENT NO. 2

Yield and soil analysis results.

POT EXPERIMENT No. I

Analysis Of Plant Material — Tops

YIELD OF PLANT MATERIAL — grams dry weight

KAKA
OIL

	L_0	L_1	L_2
P_2	38.3	64.7	58.0
P_1	26.2	46.3	42.7
P_0	19.8	33.7	28.3

	S_0	S_1	S_2
P_2	38.3	59.7	83.3
P_1	26.2	41.7	63.7
P_0	19.8	25.7	41.7

HI
IL

	L_0	L_1	L_2
P_2	85.8	93.3	53.6
P_1	72.8	69.0	35.6
P_0	35.8	28.6	24.0

	S_0	S_1	S_2
P_2	85.8	84.3	92.0
P_1	72.8	66.3	85.3
P_0	35.8	35.6	49.0

P_0 — Nil Phosphorus

P_1 — 1.81 gram $Ca(HPO_4)_2\ 2H_2O$ / Pot

P_2 — 7.24 " " " " "

L_0 — Nil $CaCO_3$

L_1 — 18.12 gram $CaCO_3$ / Pot

L_2 — 72.48 " " "

S_0 — Nil $CaSiO_3$

S_1 — 18.12 gram $CaSiO_3$ / Pot

S_2 — 72.48 " " "

PHOSPHORUS PER CENT DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	.120	.127	.124
P_1	.123	.114	.157
P_0	.103	.101	.124

	S_0	S_1	S_2
P_2	.120	.115	.105
P_1	.123	.117	.110
P_0	.103	.105	.104

PUHI SOIL

	L_0	L_1	L_2
P_2	.073	.184	.129
P_1	.081	.096	.082
P_0	.068	.075	.110

	S_0	S_1	S_2
P_2	.073	.167	.195
P_1	.081	.085	.085
P_0	.068	.069	.069

PHOSPHORUS mg/Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	45.8	82.1	71.5
P_1	32.3	53.2	66.9
P_0	20.7	33.9	35.0

	S_0	S_1	S_2
P_2	45.8	66.0	87.6
P_1	32.3	48.6	70.6
P_0	20.7	27.1	42.5

PUHI SOIL

	L_0	L_1	L_2
P_2	149.2	171.8	68.5
P_1	59.3	66.1	29.3
P_0	24.5	21.7	26.3

	S_0	S_1	S_2
P_2	149.2	140.9	179.4
P_1	59.3	56.0	72.6
P_0	24.5	24.7	34.1

CALCIUM PERCENT DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	.81	1.01	1.30
P_1	.79	.94	1.15
P_0	.75	.92	1.25

	S_0	S_1	S_2
P_2	.81	.96	.96
P_1	.79	.87	1.00
P_0	.75	1.00	.92

PUHI SOIL

	L_0	L_1	L_2
P_2	.87	.94	1.36
P_1	.75	1.00	1.38
P_0	.75	.96	1.16

	S_0	S_1	S_2
P_2	.87	.86	.86
P_1	.75	.88	.95
P_0	.75	.64	.91

CALCIUM mg / Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	312.8	652.0	757.0
P_1	204.5	437.7	488.2
P_0	149.3	307.0	352.4

	S_0	S_1	S_2
P_2	312.8	575.1	807.3
P_1	204.5	362.8	634.0
P_0	149.3	256.5	378.9

PUHI SOIL

	L_0	L_1	L_2
P_2	749.7	881.8	725.0
P_1	547.0	684.7	492.5
P_0	269.6	275.3	278.7

	S_0	S_1	S_2
P_2	749.7	724.3	791.0
P_1	547.0	578.5	817.1
P_0	269.6	227.4	451.0

ALUMINUM ppm DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	148	129	167
P_1	138	121	137
P_0	136	118	132

	S_0	S_1	S_2
P_2	148	111	102
P_1	138	101	119
P_0	136	125	113

PUHI SOIL

	L_0	L_1	L_2
P_2	143	151	181
P_1	130	149	176
P_0	115	121	199

	S_0	S_1	S_2
P_2	143	137	99
P_1	130	104	105
P_0	115	96	90

ALUMINUM mg / Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	5.8	8.1	9.6
P_1	2.6	5.7	5.8
P_0	2.7	4.3	3.7

	S_0	S_1	S_2
P_2	5.8	6.7	8.4
P_1	2.6	4.1	10.2
P_0	2.7	3.1	4.5

PUHI SOIL

	L_0	L_1	L_2
P_2	12.3	14.1	9.5
P_1	9.3	10.9	6.3
P_0	4.1	3.5	4.8

	S_0	S_1	S_2
P_2	12.3	11.5	9.1
P_1	9.3	6.9	8.7
P_0	4.1	3.4	4.5

POT EXPERIMENT No. 1

Analysis Of Plant Material – Roots

YIELD OF ROOTS – grams dry weight

AKAKA SOIL

	L_0	L_1	L_2
P_2	4.6	12.6	10.1
P_1	2.6	6.1	7.5
P_0	3.0	3.9	4.4

	S_0	S_1	S_2
P_2	4.6	9.2	13.9
P_1	2.6	3.8	8.1
P_0	3.0	3.4	5.1

PUHI SOIL

	L_0	L_1	L_2
P_2	13.9	14.5	7.0
P_1	12.1	10.9	4.8
P_0	5.6	4.3	2.9

	S_0	S_1	S_2
P_2	13.9	13.6	17.2
P_1	12.1	10.9	12.9
P_0	5.6	4.5	8.7

ROOTS

PHOSPHORUS PER CENT DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	.119	.104	.089
P_1	.135	.109	.124
P_0	.125	.092	.106

	S_0	S_1	S_2
P_2	.119	.113	.089
P_1	.135	.098	.097
P_0	.125	.111	.101

PUHI SOIL

	L_0	L_1	L_2
P_2	.105	.124	.138
P_1	.074	.080	.102
P_0	.091	.079	.111

	S_0	S_1	S_2
P_2	.105	.114	.148
P_1	.074	.079	.086
P_0	.091	.085	.069

PHOSPHORUS mg/Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	5.5	13.1	9.1
P_1	3.5	6.6	9.4
P_0	3.7	3.6	4.7

	S_0	S_1	S_2
P_2	3.5	9.9	12.7
P_1	3.5	3.6	7.9
P_0	3.7	3.8	5.0

PUHI SOIL

	L_0	L_1	L_2
P_2	13.2	17.7	9.7
P_1	9.1	8.7	4.8
P_0	5.2	3.3	3.2

	S_0	S_1	S_2
P_2	13.2	14.6	25.8
P_1	9.1	8.4	11.2
P_0	5.2	3.7	6.0

ROOTS

CALCIUM PERCENT DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	.22	.33	.62
P_1	.22	.28	.61
P_0	.21	.29	.56

	S_0	S_1	S_2
P_2	.22	.24	.26
P_1	.22	.29	.35
P_0	.21	.24	.33

PUHI SOIL

	L_0	L_1	L_2
P_2	.09	.18	.48
P_1	.12	.20	.77
P_0	.17	40	.54

	S_0	S_1	S_2
P_2	.09	.13	.13
P_1	.12	.18	.15
P_0	.17	.43	.28

CALCIUM mg / Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	10.1	40.7	62.4
P_1	5.8	17.3	46.3
P_0	7.1	11.4	25.1

	S_0	S_1	S_2
P_2	10.1	22.3	38.1
P_1	5.8	12.1	29.1
P_0	7.1	8.2	16.9

PUHI SOIL

	L_0	L_1	L_2
P_2	12.6	25.1	34.1
P_1	14.4	21.8	34.4
P_0	9.1	17.2	15.3

	S_0	S_1	S_2
P_2	12.6	16.4	21.9
P_1	14.4	18.6	20.1
P_0	9.1	20.5	22.0

ROOTS

ALUMINUM ppm DRY MATTER

AKAKA SOIL

	L_0	L_1	L_2
P_2	2110	2080	1330
P_1	2940	1780	1370
P_0	3470	1670	1400

	S_0	S_1	S_2
P_2	2110	2130	1540
P_1	2940	1070	980
P_0	3470	2030	1780

PUHI SOIL

	L_0	L_1	L_2
P_2	4080	4370	1000
P_1	2950	2870	2560
P_0	1610	950	2600

	S_0	S_1	S_2
P_2	4080	4540	5960
P_1	2950	2760	2200
P_0	1610	1260	3000

ALUMINUM mg / Pot

AKAKA SOIL

	L_0	L_1	L_2
P_2	9.7	16.7	13.6
P_1	7.3	11.8	11.0
P_0	9.5	7.0	6.5

	S_0	S_1	S_2
P_2	9.7	18.1	21.3
P_1	7.3	3.9	8.4
P_0	9.5	6.9	9.6

PUHI SOIL

	L_0	L_1	L_2
P_2	56.0	66.7	6.8
P_1	39.3	31.9	11.3
P_0	9.1	4.2	7.5

	S_0	S_1	S_2
P_2	56.0	43.4	104.7
P_1	39.3	34.1	30.3
P_0	9.1	5.5	9.1

POT EXPERIMENT No. I

Analysis Of Soil

pH AT HARVEST

…KAKA SOIL

	L_0	L_1	L_2
P_2	4.6	5.6	7.0
P_1	4.6	5.6	6.8
P_0	4.5	5.5	7.0

	S_0	S_1	S_2
P_2	4.6	5.0	5.4
P_1	4.6	5.0	5.5
P_0	4.5	4.9	5.4

…IHI …OIL

	L_0	L_1	L_2
P_2	4.5	5.7	7.4
P_1	4.5	5.5	7.4
P_0	4.5	5.9	7.4

	S_0	S_1	S_2
P_2	4.5	4.9	5.8
P_1	4.5	4.9	5.9
P_0	4.5	4.9	5.9

EXCHANGEABLE CALCIUM - me / 100 gm

…KAKA SOIL

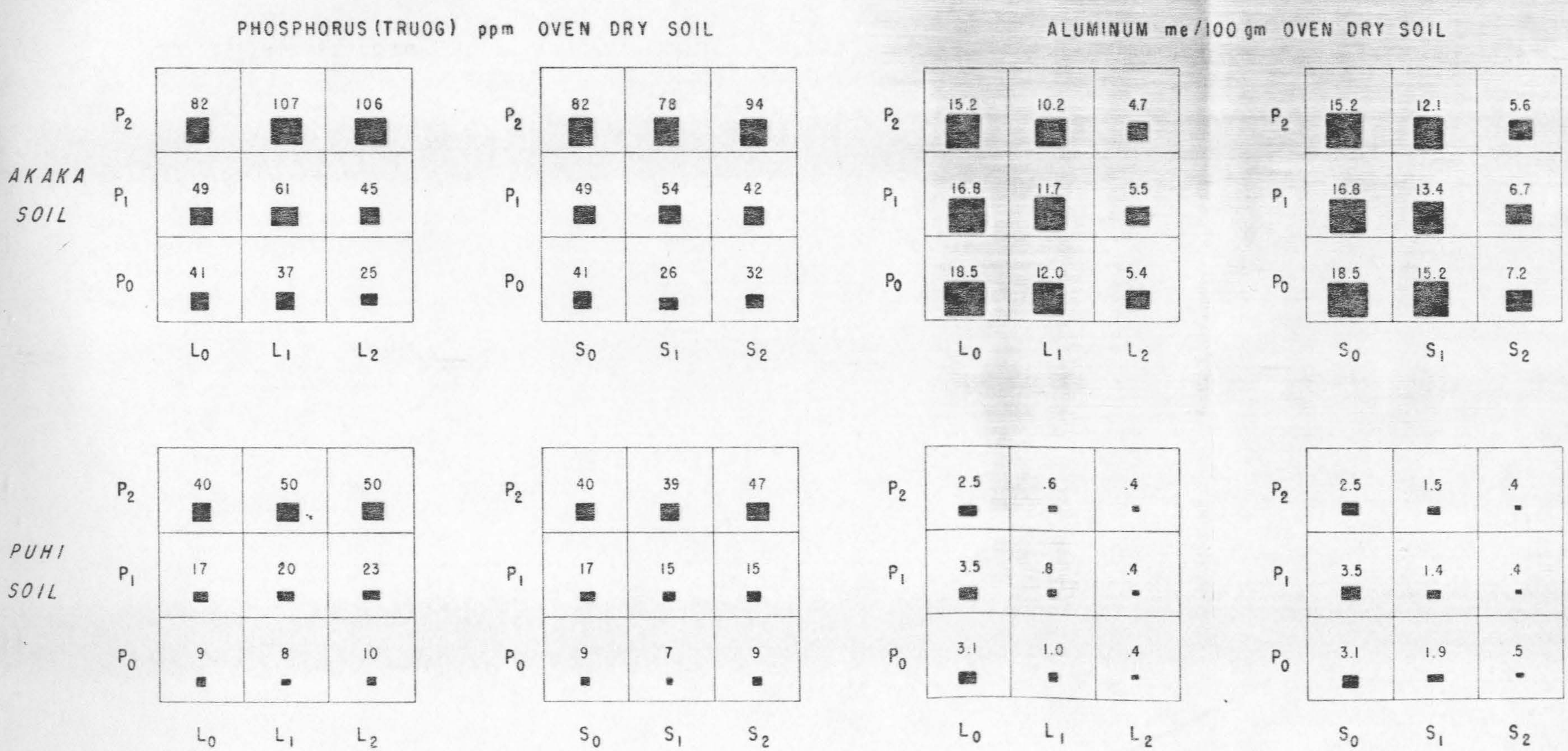
	L_0	L_1	L_2
P_2	1.8	8.8	24.0
P_1	1.4	9.4	24.2
P_0	1.2	7.7	23.4

	S_0	S_1	S_2
P_2	1.8	4.3	13.2
P_1	1.4	3.8	12.2
P_0	1.2	3.5	11.5

…IHI …OIL

	L_0	L_1	L_2
P_2	1.3	5.2	10.1
P_1	1.1	5.3	11.3
P_0	.9	6.6	13.9

	S_0	S_1	S_2
P_2	1.3	2.8	7.1
P_1	1.1	2.1	6.6
P_0	.9	1.9	6.7



PHOSPHORUS (TRUOG) ppm OVEN DRY SOIL
ALUMINUM me/100 gm OVEN DRY SOIL
AKAKA SOIL
P2 82 107 106
P1 49 61 45
P0 41 37 25
L0 L1 L2
P2 82 78 94
P1 49 54 42
P0 41 26 32
S0 S1 S2
P2 15.2 10.2 4.7
P1 16.8 11.7 5.5
P0 18.5 12.0 5.4
L0 L1 L2
P2 15.2 12.1 5.6
P1 16.8 13.4 6.7
P0 18.5 15.2 7.2
S0 S1 S2
PUHI SOIL
P2 40 50 50
P1 17 20 23
P0 9 8 10
L0 L1 L2
P2 40 39 47
P1 17 15 15
P0 9 7 9
S0 S1 S2
P2 2.5 .6 .4
P1 3.5 .8 .4
P0 3.1 1.0 .4
L0 L1 L2
P2 2.5 1.5 .4
P1 3.5 1.4 .4
P0 3.1 1.9 .5
S0 S1 S2

AKA
IL

CATION EXCHANGE CAPACITY – me / 100 gm

	L_0	L_1	L_2
P_2	145	137	131
P_1	142	137	133
P_0	118	130	132

	S_0	S_1	S_2
P_2	145	141	156
P_1	142	148	139
P_0	118	132	167

EXCHANGEABLE POTASSIUM – me / 100 gm

	L_0	L_1	L_2
P_2	.4	.3	.3
P_1	.5	.4	.4
P_0	.5	.6	.6

	S_0	S_1	S_2
P_2	.4	4	.2
P_1	.5	.6	.4
P_0	.5	.8	.7

HI
L

	L_0	L_1	L_2
P_2	44	46	47
P_1	45	44	45
P_0	43	49	50

	S_0	S_1	S_2
P_2	44	48	52
P_1	45	48	50
P_0	43	44	50

	L_0	L_1	L_2
P_2	.1	.1	.2
P_1	.2	.1	.3
P_0	.3	.1	.1

	S_0	S_1	S_2
P_2	.1	.1	.1
P_1	.2	.1	.1
P_0	.3	.3	.2

LEACHATES

pH

1st Leachate

AKAKA SOIL

	L_0	L_1	L_2
P_2	6.5	6.6	7.7
P_1	6.4	6.3	7.7
P_0	6.4	6.2	7.8

	S_0	S_1	S_2
P_2	6.5	5.6	6.7
P_1	6.4	4.0	6.5
P_0	6.4	6.3	6.1

UHI SOIL

	L_0	L_1	L_2
P_2	6.1	6.5	7.7
P_1	6.4	6.6	7.6
P_0	6.4	6.3	7.5

	S_0	S_1	S_2
P_2	6.1	6.0	6.6
P_1	6.4	5.8	6.2
P_0	6.4	5.6	6.1

2nd Leachate

AKAKA SOIL

	L_0	L_1	L_2
P_2	4.5	6.7	7.5
P_1	4.9	6.7	7.5
P_0	4.2	6.6	7.6

	S_0	S_1	S_2
P_2	4.5	6.2	6.2
P_1	4.9	6.5	6.5
P_0	4.2	6.2	6.7

UHI SOIL

	L_0	L_1	L_2
P_2	4.1	6.5	7.4
P_1	3.6	6.7	7.4
P_0	6.2	7.2	7.4

	S_0	S_1	S_2
P_2	4.1	5.9	7.0
P_1	3.6	4.5	6.8
P_0	6.2	6.3	7.2

LEACHATES

Phosphorus

ppm SOLUTION

1st Leachate

AKAKA SOIL

	L_0	L_1	L_2
P_2	.03	.26	.16
P_1	.07	.05	.10
P_0	.09	.07	.09

	S_0	S_1	S_2
P_2	.03	.05	.13
P_1	.07	.05	.16
P_0	.09	.03	.02

PUHI SOIL

	L_0	L_1	L_2
P_2	.08	1.42	.41
P_1	.08	.27	.26
P_0	.08	.13	.33

	S_0	S_1	S_2
P_2	.08	.06	.63
P_1	.08	.05	.10
P_0	.08	.05	.10

2nd Leachate

AKAKA SOIL

	L_0	L_1	L_2
P_2	.06	.14	.09
P_1	.06	.11	.09
P_0	.05	.08	.05

	S_0	S_1	S_2
P_2	.06	.11	.21
P_1	.06	.05	.17
P_0	.05	.05	.07

PUHI SOIL

	L_0	L_1	L_2
P_2	.08	.65	.11
P_1	.06	.22	.08
P_0	.06	.05	.08

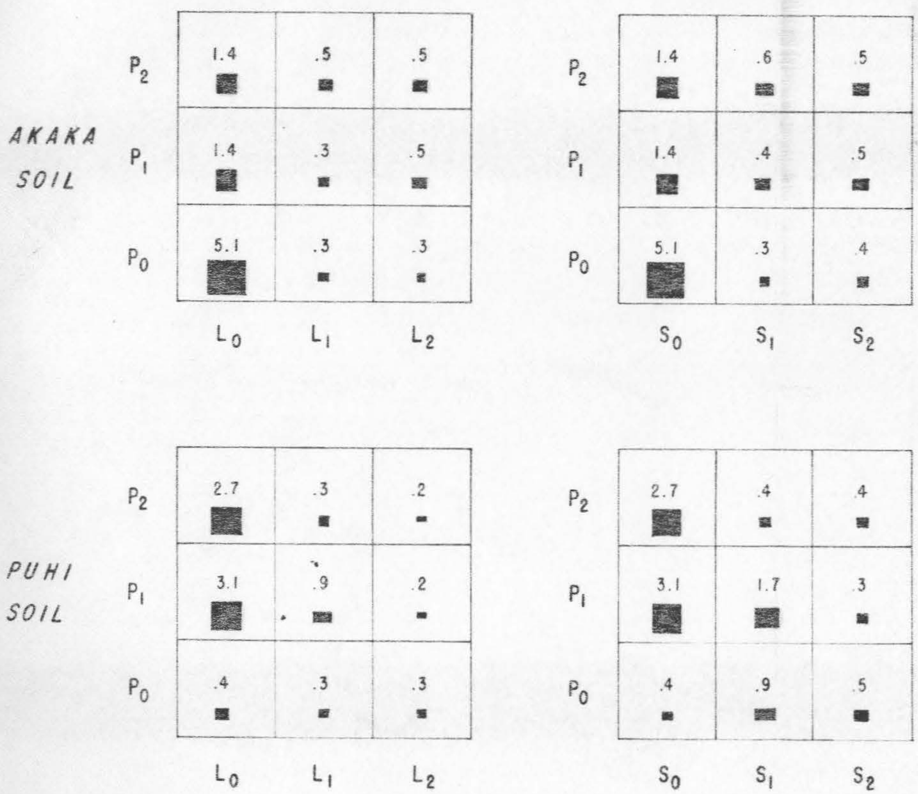
	S_0	S_1	S_2
P_2	.08	.08	.09
P_1	.06	.05	.14
P_0	.06	.14	.18

LEACHATES

Aluminum

ppm SOLUTION

2nd Leachate



POT EXPERIMENT No. 2

PUHI SOIL

	YIELD Grams		SOIL pH		EXTRACTABLE Al	
	+P	−P	+P	−P	+P	−P
NIL	112	8	4.5	4.5	3.6	3.6
CHELATE	118	12	4.9	NOT ANALYSED	3.2	3.5
GYPSUM	119	(1 REP) 35	4.4	5.1	2.6	1.9
$CaSiO_3$	132	12	5.1	5.0	1.0	2.2
SLAG	118	95	6.2	6.3	NOT ANALYSED	NOT ANALYSED
$CaCO_3$	124	10	6.4	6.2	.6	1.7
CORAL LIME	116	7	6.2	6.3	NOT ANALYSED	NOT ANALYSED

LSD = 14 grams

AKAKA SOIL

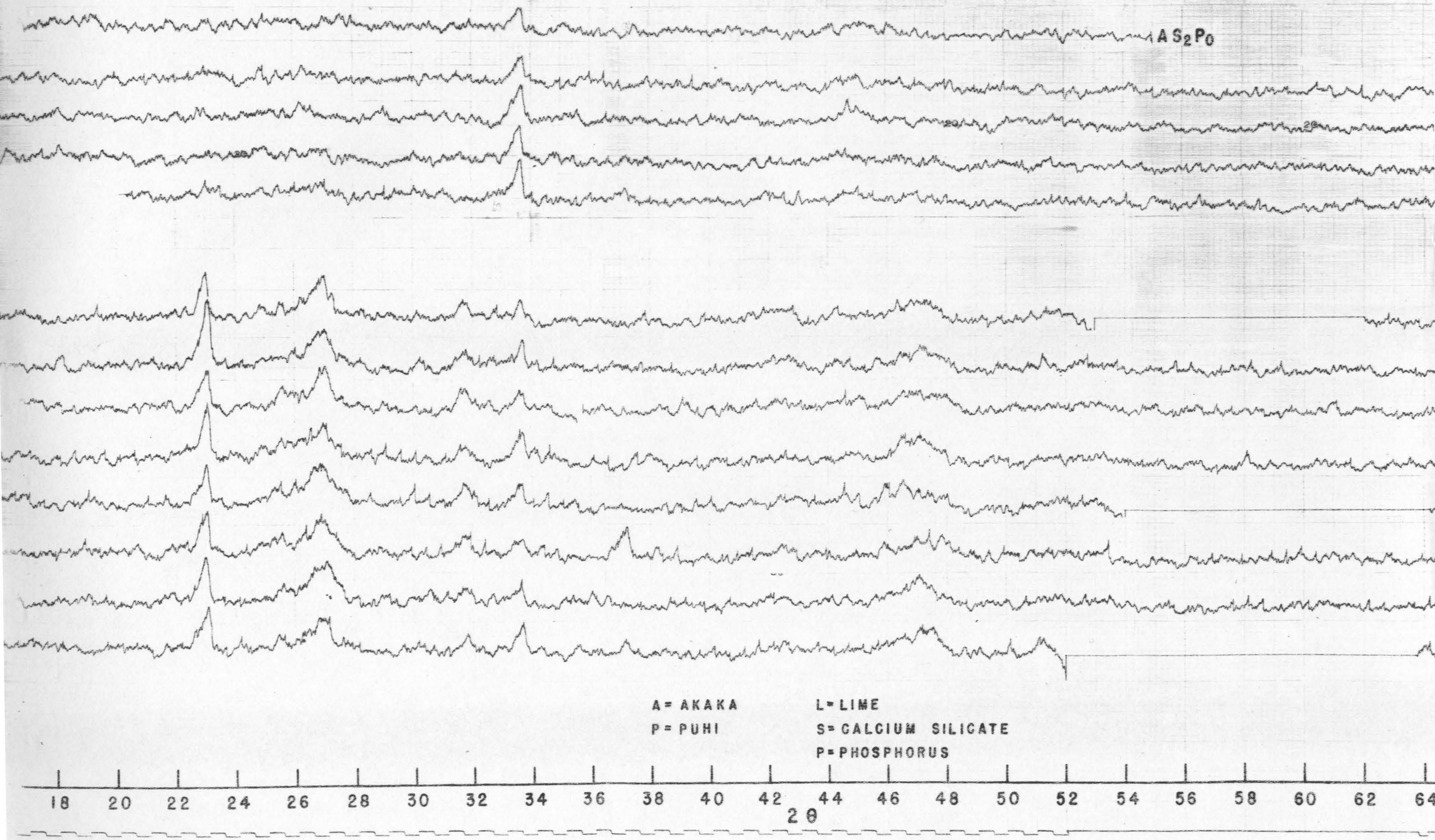
	YIELD Grams		SOIL pH		EXTRACTABLE Al	
	+P	−P	+P	−P	+P	−P
NIL	97	17	4.5	4.3	24.0	19.
CHELATE	99	12	4.2	NOT ANALYSED	18.9	17.
GYPSUM	124	40	4.8	5.0	14.2	16.
$CaSiO_3$	118	30	5.2	4.9	11.0	14.
SLAG	127	107	6.1	6.2	NOT ANALYSED	NOT ANALY
$CaCO_3$	112	17	6.0	5.9	9.8	8.
CORAL LIME	123	23	6.0	6.1	NOT ANALYSED	NOT ANALY

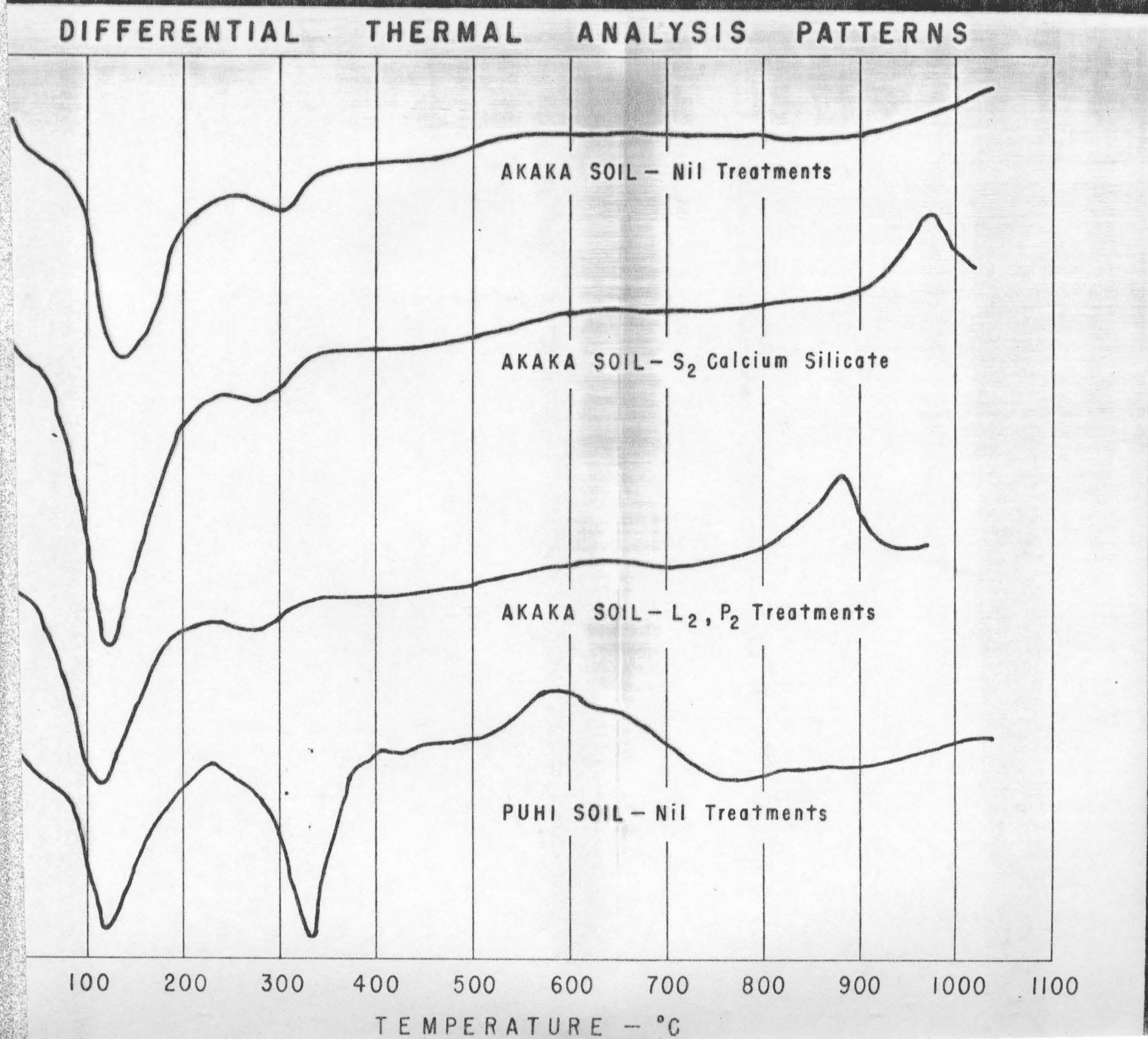
LSD = 14 grams

APPENDIX C

X-ray and DTA patterns.

X-RAY DIFFRACTION PATTERNS





DIFFERENTIAL THERMAL ANALYSIS PATTERNS
AKAKA SOIL – Nil Treatments
AKAKA SOIL – S_2 Calcium Silicate
AKAKA SOIL – L_2, P_2 Treatments
PUHI SOIL – Nil Treatments
100 200 300 400 500 600 700 800 900 1000 1100
TEMPERATURE – °C

APPENDIX D

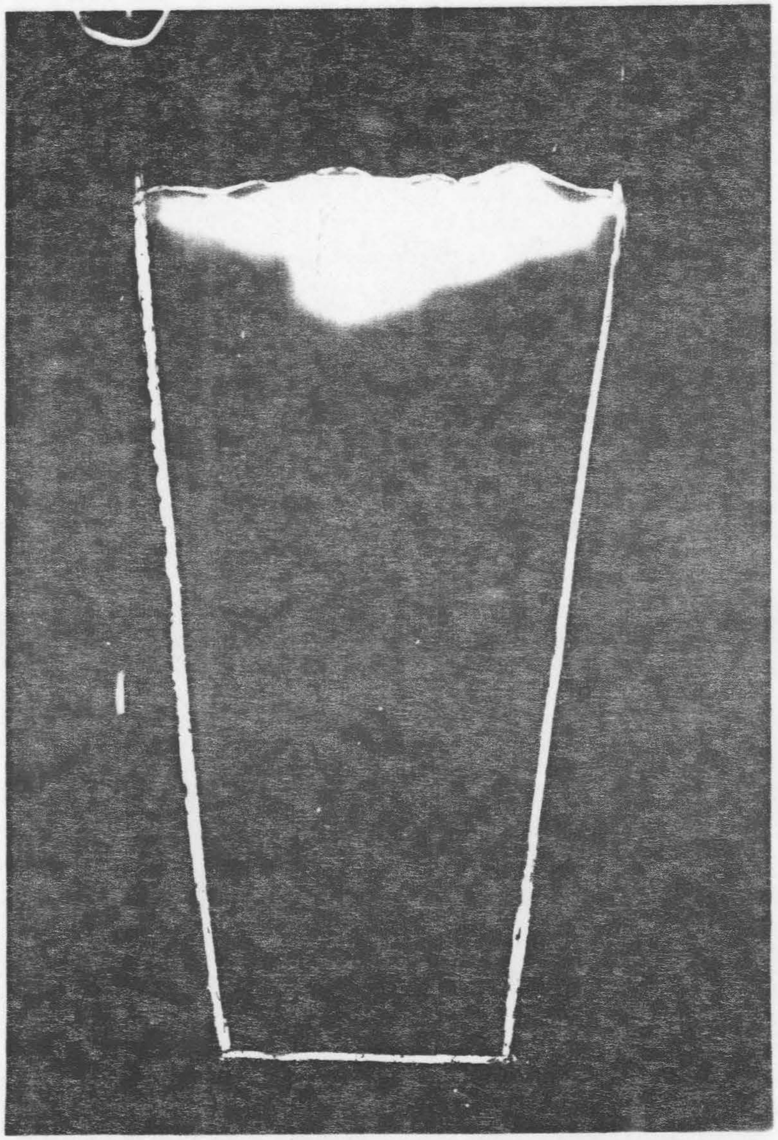
Radioautographs of P^{32} leaching experiment.

Key

1. Puhi soil - Nil $CaCO_3$
2. " " - " "
3. " " - Medium $CaCO_3$
4. " " - " "
5. " " - High $CaCO_3$
6. " " - " "
7. Akaka " - Nil $CaCO_3$

7a. " " - " "

8. " " -Medium $CaCO_3$
9. " " - " "
10. " " - High $CaCO_3$
11. " " - " "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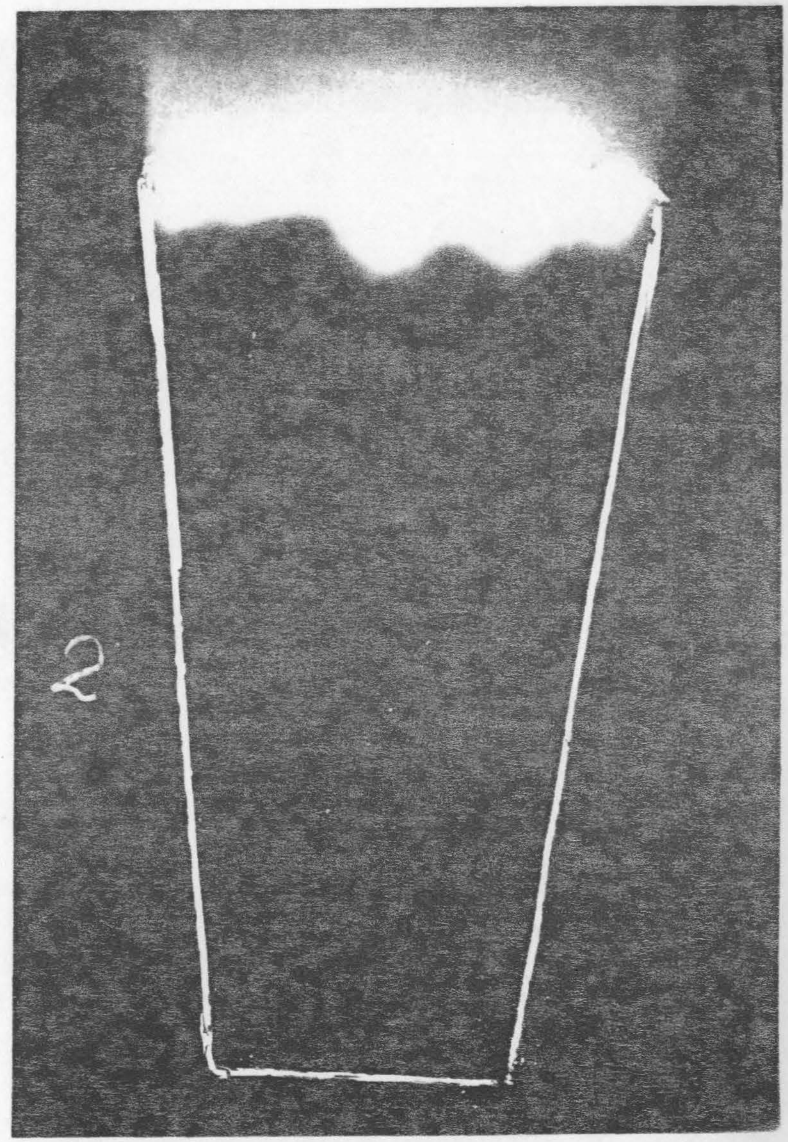
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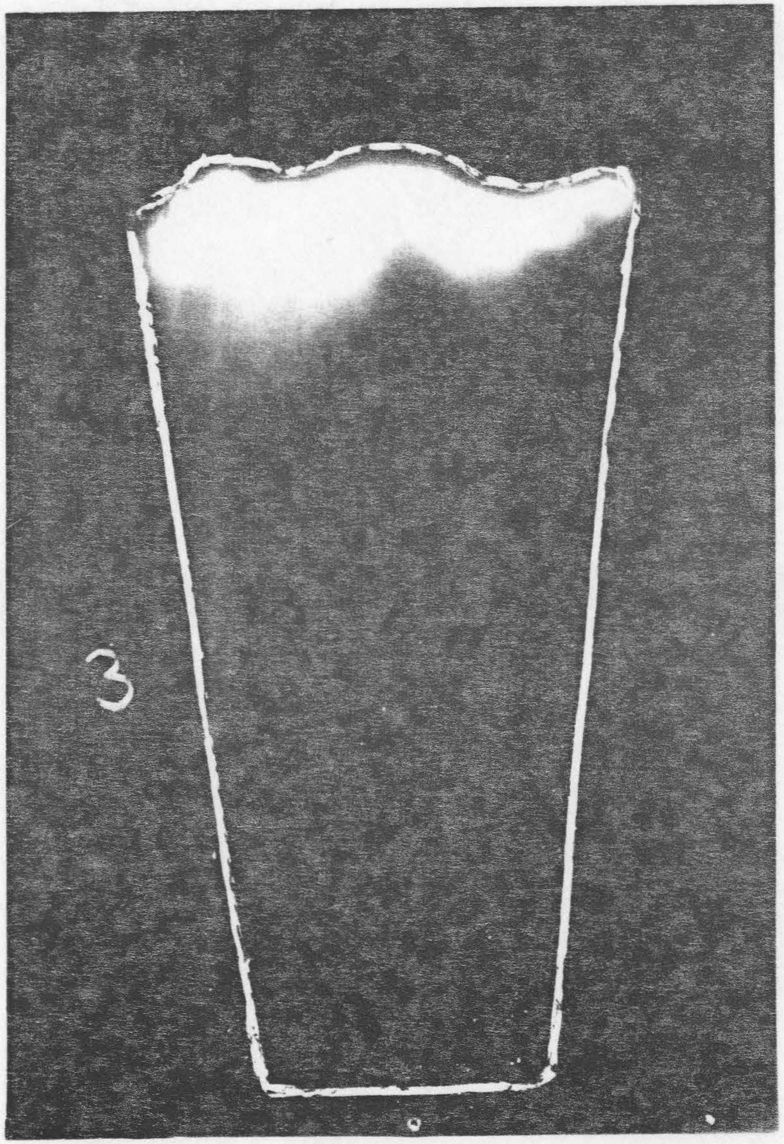
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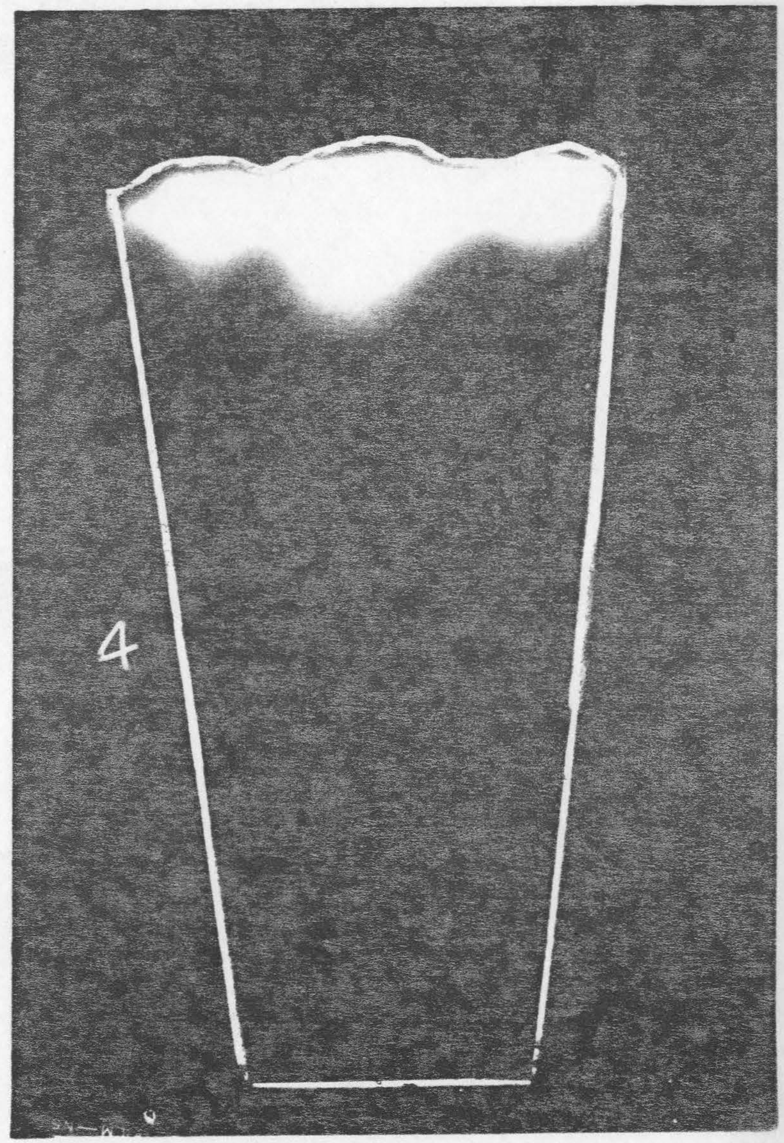
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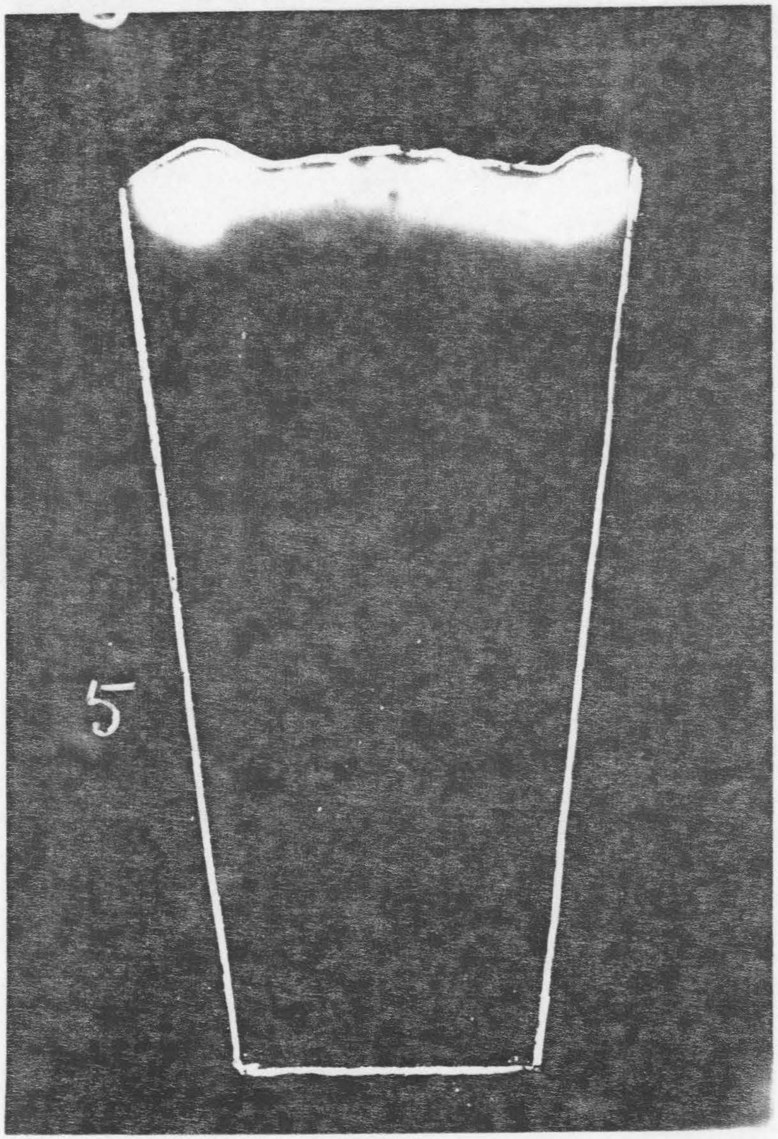
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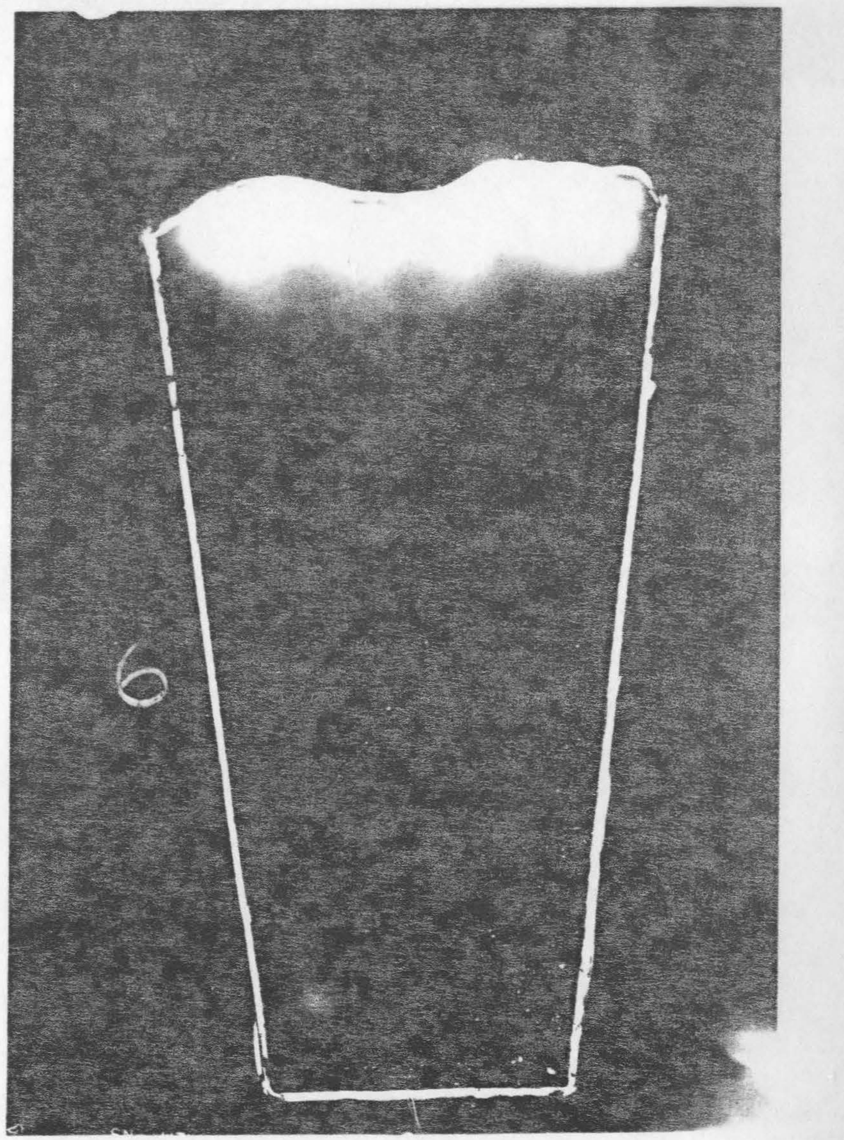
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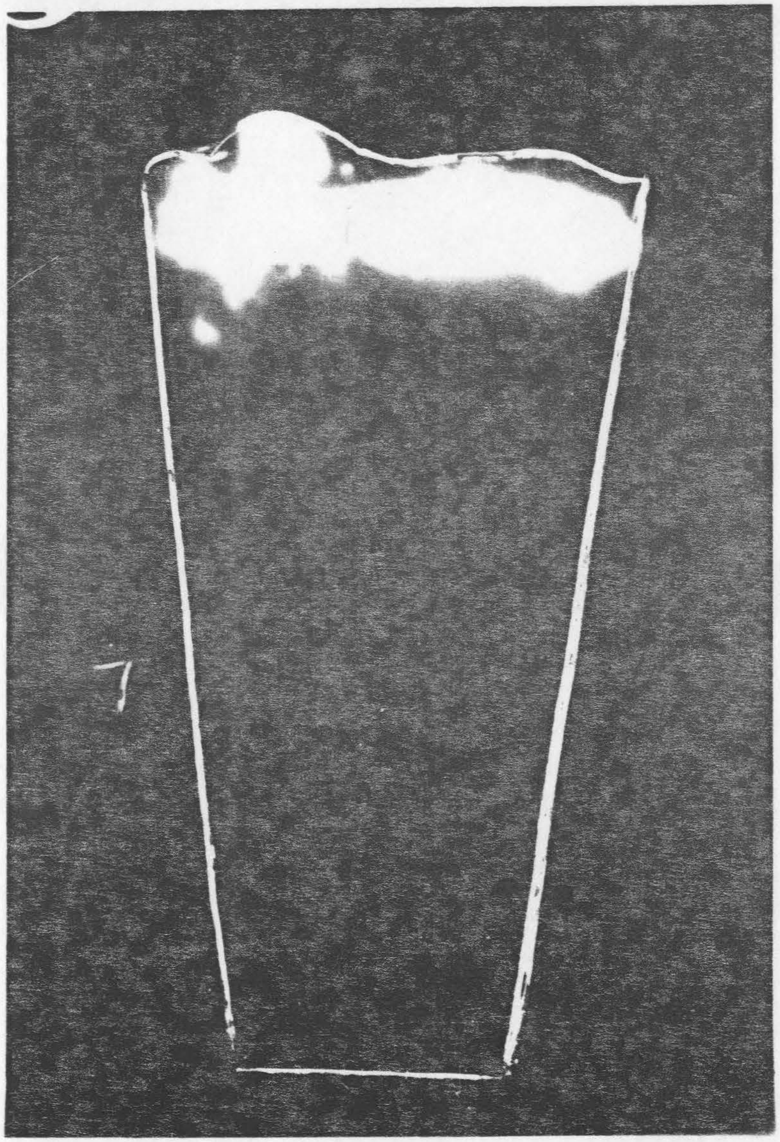
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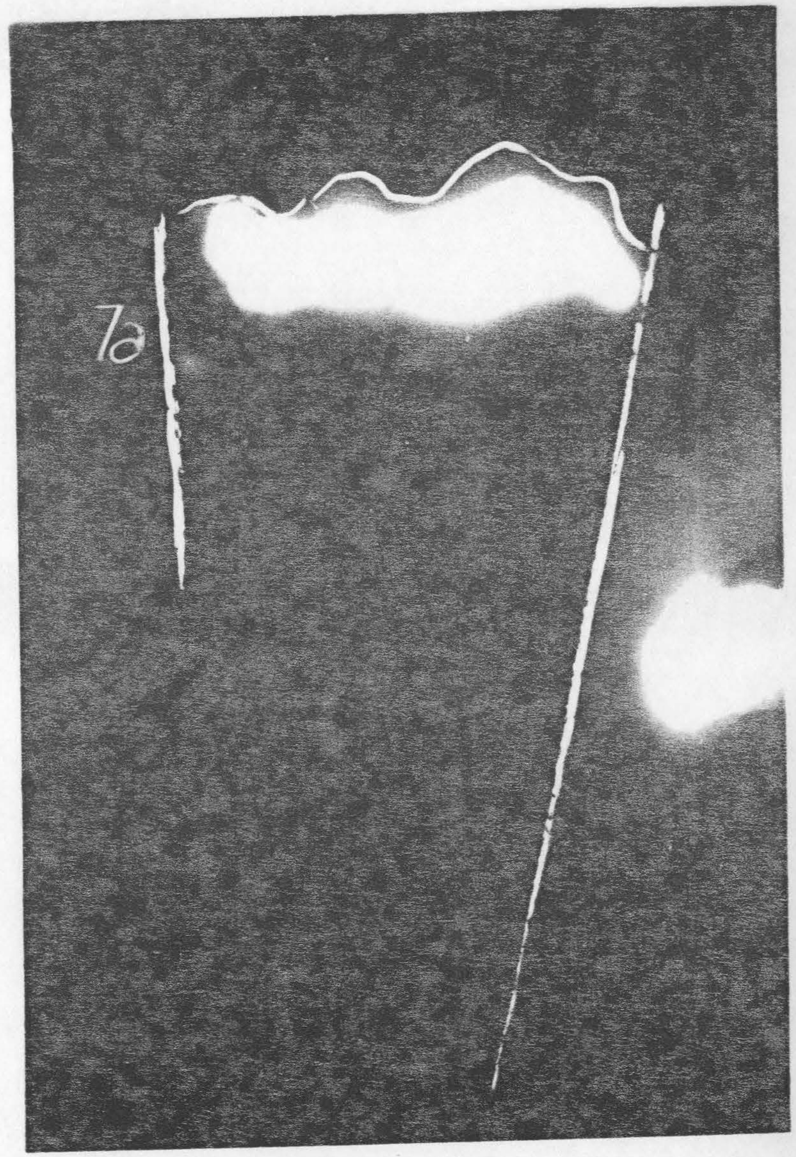
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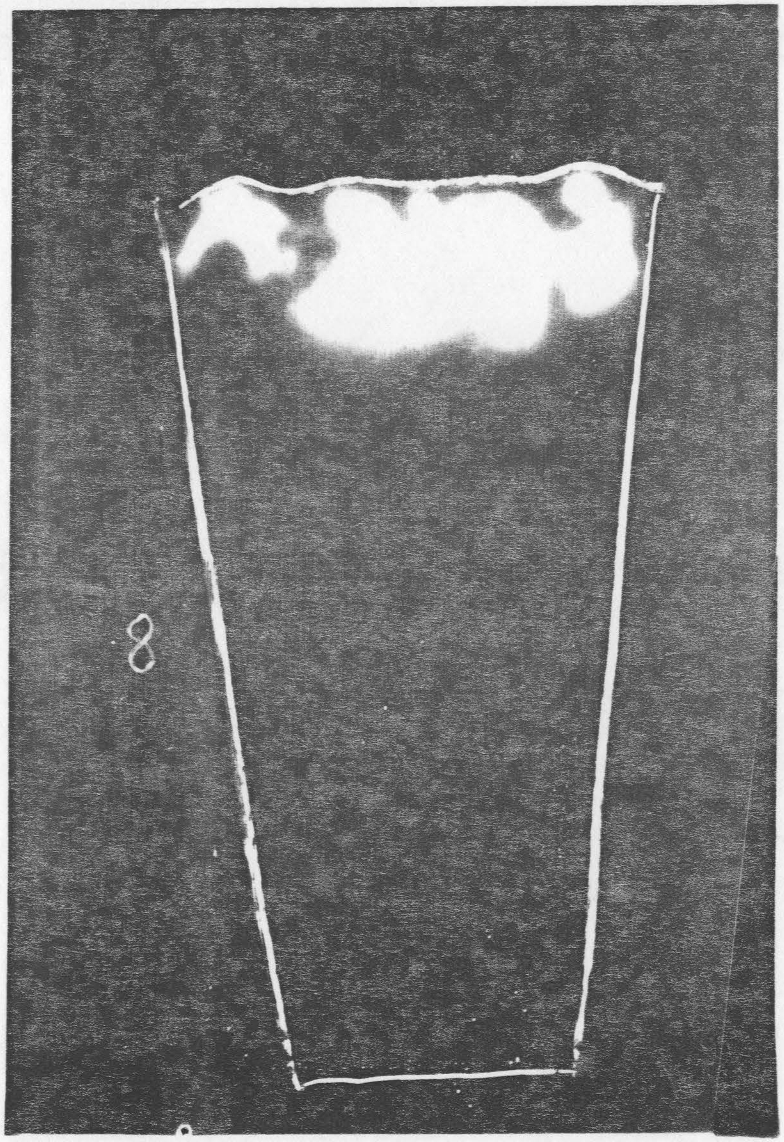
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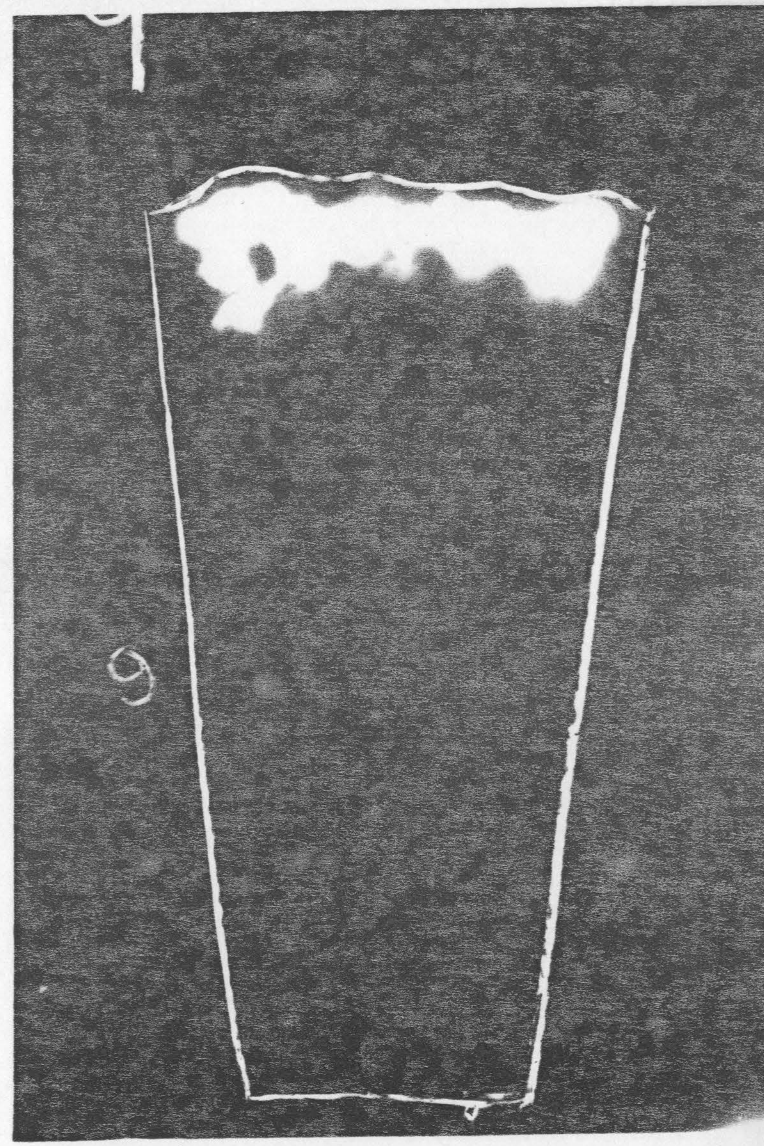
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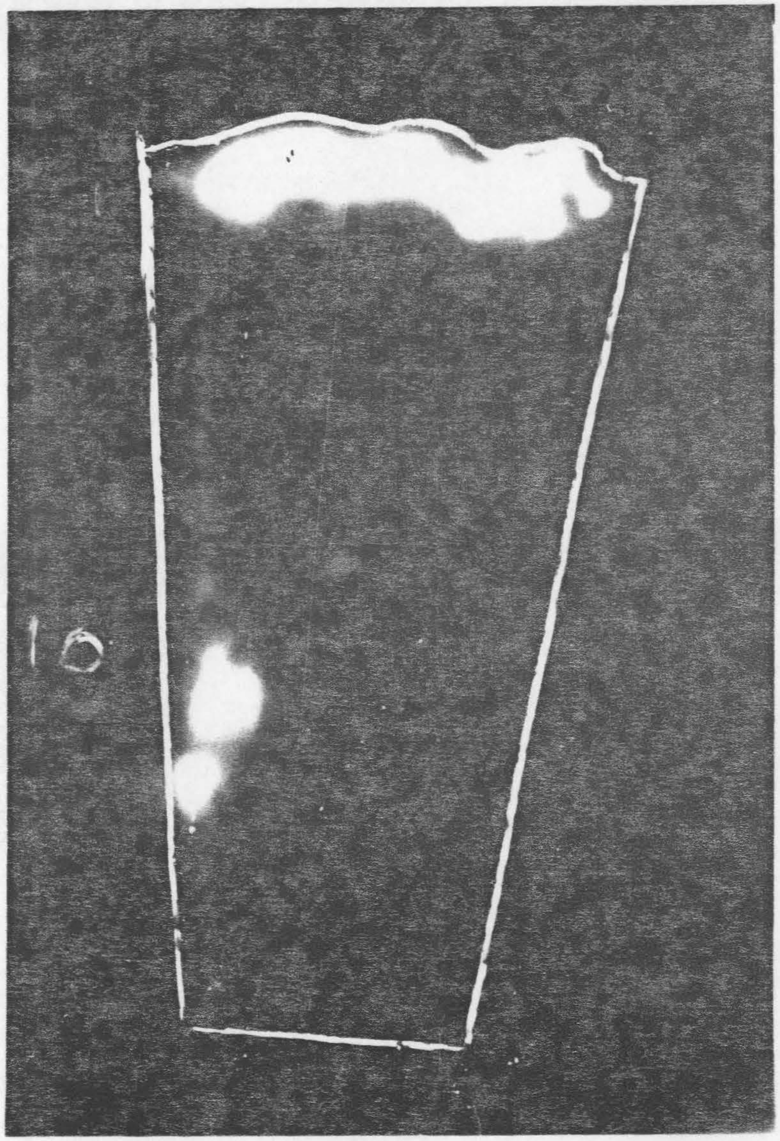
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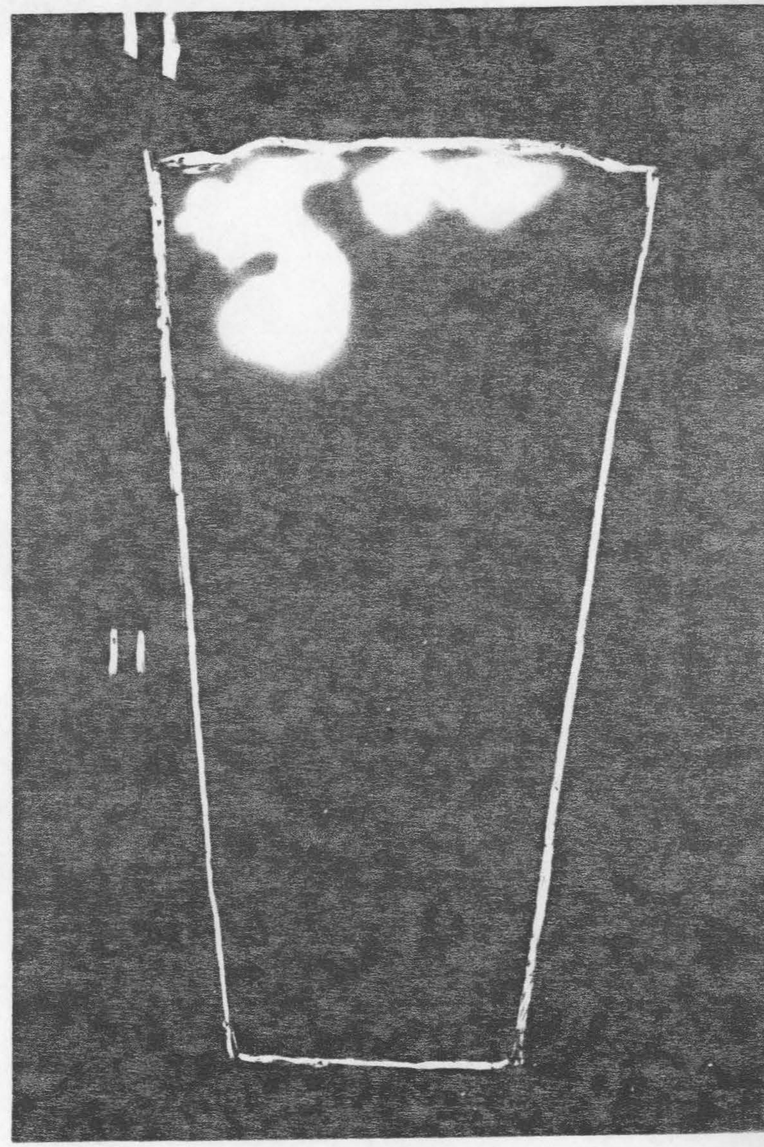
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