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PHOSPHORUS-SILICON INTERACTIONS IN  
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PHOSPHORUS-SILICON INTERACTIONS  
IN SOILS AND PLANTS

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Animesh Chandra Roy

Dissertation Committee:

Dr. Robert L. Fox, Chairman  
Dr. James A. Silva  
Dr. Wallace G. Sanford  
Dr. Minoru Isobe  
Dr. Samir Al. El-Swaify

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## ABSTRACT

Interactions between phosphorus and silicon were studied in three steps: first, laboratory equilibration; second, uptake by plants from culture solutions; and third, uptake by plants from soils.

Phosphorus decreased Si sorption and Si decreased P sorption by soils but the effect of P on Si sorption was greatest. The interactions between Si and P on P and Si sorption by soils were related to their solubilities in soils. The solubility of Si in soils varied with soil pH and soil mineralogy. Phosphorus desorption from soils increased in the presence of sorbed Si, while Si desorption decreased in the presence of sorbed P.

Phosphorus requirements of surface soils decreased with increasing amounts of residual phosphate and silicate. Silicate decreased P sorption most effectively at low soil pH. Residual effects of silicate on P sorption were inversely related to the amounts of residual phosphate. Silicate applied to surface soils depressed P sorption by sub-soils. Extractable soil P increased with increasing amounts of residual silicate.

Silicon movement was measureable in all soils studied. Calcium chloride solution was more effective than water in displacing silicon in Kapaa soil. The distribution of Si in soil profiles was a function of the amounts of silicate applied and soil

pH. There was an inverse relationship between the rates of applied phosphate and Si content of soil profiles. Considerable Si had moved to 24 inches in the profiles of Kapaa soil during nine months after silicate applications.

Phosphorus and silicon absorption by plants from culture solutions was a function of plant species. In general, plants which accumulate little Si, absorbed most P in the presence of Si, while in plants which accumulate Si, P absorption was depressed by Si. Silicon absorption was depressed in the presence of P.

Pot experiments were conducted to evaluate placement effects in soils on phosphorus-silicon interactions. Placement effects varied with species. For lettuce, Mimosa, corn and sugarcane, P uptake was enhanced by placing P and Si together in the soil. For rice, the presence of Si depressed P uptake. For rice and sugarcane, Si uptake was greatest when P and Si were separated from each other, while for lettuce, Mimosa and corn, P and Si together in the soil effected greatest Si uptake. Phosphorus uptake by lettuce and Mimosa was greatest from band placements, while mixed placements were superior for corn, rice and sugarcane. Mixed placements were superior for Si uptake.

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## INTRODUCTION

Ever since the discovery of beneficial effects of silicate on crop production, attempts have been made to find an explanation in improved phosphorus nutrition of plants. More recently several investigators in the tropics have demonstrated that silicates increase the availability of soil and fertilizer P to plants.

In the humid tropics silicate rocks undergo rapid chemical weathering resulting in the release of Si, Fe, Al, etc., from the soil. The weathered Fe and Al become stabilized in the soil as free oxides, while Si is removed from the soil if there is free drainage. Under these conditions soils develop high P sorption capacities, resulting in low solubility and availability of applied P.

The highly weathered Latosols of Hawaii are capable of fixing large amounts of P. This has been attributed mostly to the hydrated oxides of Fe and Al. In the most weathered ash soils of Hawaii only a few parts per billion of added P remains in solution.

Applications of silicate slags are commercially practical for sugar production in Hawaii. Increased sugar yield has been related both to improved P nutrition and some nebulous effects resulting from silicon uptake by sugarcane. So far attempts to segregate the effects of silicate on P uptake have been rather indifferent.

It has long been known that interactions between silicate and phosphate in soils increase their solubilities, but few attempts have been made to investigate these interactions in Hawaiian soils. The solubility of Si in soils is important both for P and Si availability and Si movement, including leaching, in the soil. Modifying the Si status of sub-soils may influence the solubilities of many elements--both those that are nutrients and those which may be toxic to plants.

Several opinions exist as to the nature of phosphorus-silicon interactions in soils and plants, but no conclusion has yet been reached about the relative importance of interactions in the plant, in the soil or at the soil-root interface.

This study was initiated to:

1. Investigate effects of interactions between phosphorus and silicon in soils on the release of native and applied silicon and phosphorus from soils.
2. Evaluate some factors influencing silicon and phosphorus solubilities in soils under field conditions.
3. Investigate interactions between silicon and phosphorus in culture solutions as these influence silicon and phosphorus uptake by plants.
4. Evaluate interaction effects of silicate and phosphate placement in soils on phosphorus and silicon uptake by plants.

## REVIEW OF LITERATURE

### Fundamental Processes of Tropical Weathering

The chemical weathering of rocks and soil formation are accelerated by humid tropical conditions. Chemical weathering and leaching leads to the replacement of metallic cations, resulting in almost complete loss of bases from soil materials. Desilication proceeds apace if there is free drainage, and hydrated iron and aluminum oxides accumulate (Mohr and Van Baren, 1954).

Two fundamental weathering processes take place in the development of tropical soils (Sherman, 1949): (a) the formation of kaolinitic clay minerals from the primary minerals, and (b) the decomposition of clay minerals with the accumulation of free oxides of Fe, Al, and Ti. The distribution of rainfall determines the nature of the ultimate products of laterization in tropical soils. An alternate wet and dry condition stabilizes iron oxide in the soil, while if a constant wet condition prevails aluminum becomes stabilized as free oxides.

In a discussion of rock weathering and clay formation in Hawaii Bates (1960) pointed out that desilication was the dominant process of rock weathering in Hawaii and that the common alteration sequence is: primary silicate → clay minerals → Fe and Al oxides and hydroxides.

### Characteristics of Hawaiian Latosols

The Latosols of Hawaii have been described by Cline et al. (1955). They are derived largely from highly weathered secondary minerals. The soils are mostly red to reddish brown and are predominantly clays. Rainfall varies from 10 to over 400 inches a year, and elevation ranges from sea level to over 6,000 feet. Therefore, they occur under a wide variety of vegetation. The Latosols have been subdivided into Low Humic, Humic, Humic Ferruginous, and Hydrol Humic Latosols, mostly on the basis of increasing rainfall.

### Phosphorus Fixation in Tropical Soils

Phosphorus fixation in soils is a process by which soluble phosphorus when applied to soils reacts with inorganic soil constituents and becomes less soluble and less available to plants. Hawaiian soils of high rainfall areas are mostly Fe and Al oxides, and are noted for their P fixing capacities (Ayres, 1934).

Bear (1958), in discussing the problem of soil phosphorus transformations, stated that P fixation in soils is the result of three processes--adsorption reaction, isomorphous substitution and double decomposition. Truog (1938) considered the precipitation of P with soil minerals as the principal cause of P fixation in soils. He maintained that the readily available P in soils exists as calcium phosphate, while that which is difficultly available exists



largely as ferric phosphate. Scarseth (1935) advanced the hypothesis that P fixation is due to adsorption of P by soil colloids. He mentioned that the colloidal aluminosilicate minerals are able to hold phosphate ions on their surfaces.

Dean and Rubins (1947) considered ion exchange as a major factor in P fixation. Stout (1939) stated that phosphorus fixation is one of ionic exchange by which hydroxyl groups on clay minerals exchange with phosphate ions in soil solutions, and that this type of fixation is most likely in kaolinitic rather than montmorillonitic clays because of the nature of crystal structures. Midgley and Kelly (1943) reported that the exchange of phosphate occurs with the hydroxyl ions of the free hydrated Fe and Al oxides held on the clay surfaces rather than with the hydroxyl radical of the clay lattice.

The amount of P fixation in soils varies inversely with soil pH (Teakle, 1928; Black, 1942; Coleman, 1944). Optimum fixation of phosphate by hydrated Fe occurred in the very acid range of pH (Sieling, 1947). Alkali soils, according to Ravikovitch (1934), show progressive increase in P fixation with increasing soil pH.

Bradfield (1963) points out that the phosphorus problem is more important in the tropics than in the humid areas of the temperate zone because of the extremely high P fixing capacities of highly weathered tropical soils, which renders the use of ordinary

phosphate fertilizers uneconomical in many situations. Chu and Sherman (1952) reported on the importance of Fe and Al oxides in P fixation under acid conditions, and found that as much as 90 percent of added P was immobilized in 24 hours when P was added at 10,000 ppm P. Less than 30 percent of the applied P was fixed when the oxides were removed.

The Latosolic soil groups apparently exhibit the highest P fixing capacities. Kaolin present in the Low Humic and Humic Latosols fixes P to a considerable extent. The mechanism of fixation by kaolinitic clays has been attributed to the Al associated with the lattices (Low and Black, 1947; Russell and Low, 1954; Kittrick and Jackson, 1955; Hemwall, 1957). McGeorge (1924) suggested gibbsite as the main source of soluble Al in most Hawaiian soils.

Fox et al. (1962) studied P fixation by seven Hawaiian soils representing six great soil groups. The order of fixation for various mineralogical systems was as follows: Amorphous hydrated oxides > Goethide-Gibbsite > Kaolin > 2:1 clays. Mahilum (1965) was able to measure only 1.6 to 5.6 ppb (parts per billion) of added P<sup>r</sup> remaining in solution in an Akaka soil by labeling the phosphorus with <sup>32</sup>P. Twenty ppm P was added in solution and equilibrated for four days.

### Phosphate Sorption as an Estimate of the Phosphate Needs of Soils

The sorptive capacity of soils at a standard equilibrium P concentration was suggested as an estimate of phosphate needs of soils by Beckwith (1965). On the basis of nutrient culture studies he chose 0.2 ppm P as the standard P concentration in equilibrium solutions. Soils giving steep sorption curves have strong buffering capacity to supply P, while those giving flat curves have weak buffering capacity. Soils previously fertilized with P sorbed less applied P. Removal of exchangeable Al by preleaching soils with N NaCl decreased P sorption.

Fried and Shapiro (1956) predicted the pattern of P supply for the low P fixing soils by assuming that P released by desorption can be described by a Langmuir adsorption isotherm, and that for the high P fixing soils by assuming that in the presence of water a saturated solution of a chemical compound is formed. They believed that the level of P in initial water extracts was not a good indication of plant available P. Both intensity of soil P supply and the capacity of the soil to rapidly renew this supply must be evaluated to adequately describe plant available P in soils. Islam and Rahman (1959) suggested that in tropical earths, availability of soil P to plants is controlled by the degree of phosphate saturation of the soils and that determination of the fraction phosphate saturation will give a superior measure of soil P status.

The growth of millet was related to the degree of saturation of the P adsorption maximum (Woodruff and Kamprath, 1965). Soils with a large P adsorption maximum did not require as high P saturation as those with low P adsorption maxima. Phosphate sorption by soils at some standard equilibrium concentration was closely and linearly related to P requirement by pasture plants (Ozanne and Shaw, 1967). The simple measurement of equilibrium concentration was equally useful for determining P requirement compared to measuring phosphate potential.

Gunary and Sutton (1967) reported that short- and long-term P uptake by rye grass grown in pots were both well correlated with a combination of logarithm of P concentration in solution ( $\log P$ ), and a capacity factor (L-value). It was suggested that  $\log P$  measures an intensity/kinetic complex that takes account the intensity, rate and diffusion factors. On soils of normal P status, the capacity factor was more important, while in enriched soils the intensity/kinetic complex measured by  $\log P$  was dominant.

#### Plant Growth and Nutrient Uptake in Relation to Fertilizer Placement

The effects of placement of silicates in soil have not been studied much. Plantations usually apply silicates broadcast. There is much literature on phosphate placement which may be pertinent. Some of this literature is reviewed here.

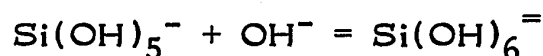
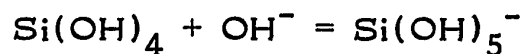
Robertson et al (1954) found that placement of nitrogen and potassium with phosphate in bands influenced P uptake. The uptake of fertilizer P from band applied phosphate rapidly diminished as the season progressed. Total P uptake during a specified growth period was little influenced by placement. Placement of nitrogen had a greater influence on fertilizer P uptake by sugar beets than did phosphate placement (Werkhoven and Miller, 1960).

Nelson et al. (1949) reported that placement of P with the cotton seed gave a higher percentage of fertilizer P uptake in the cotyledon stage. In corn, placement of P with the seed and mixed in a row resulted in highest P uptake from the fertilizer phosphate. The difference was not found later in the season. Broadcasting resulted in a relatively low P uptake. However, broadcast was equal to other placement methods with respect to yield and total P content of grain. Werkhoven and Massantini (1967) found, in general, that banding of P was more efficient than broadcasting. Banding 28 kg P/ha was as effective as broadcasting twice the amount. Placement did not affect total P uptake by plants. Nitrogen placement was less important than phosphate placement in corn. Welch et al. (1966) compared the efficiency of broadcast P with banded P. They found that at low P levels efficiency of banded P was higher than broadcast P. At high levels of P, a combination of both broadcast and banded application was most effective.

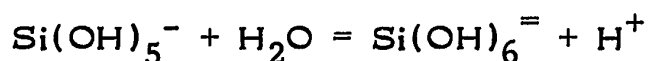
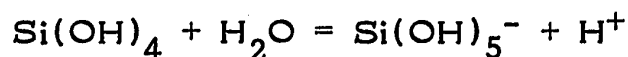
The effects of banded versus broadcast applications of P on plant uptake of P are dependent on such factors as soil moisture, temperature and chemical form of P. Olsen et al. (1961) reported that P uptake by corn seedlings was inversely related to soil moisture tension. Decreased P uptake with increased soil moisture tension may play an important role when comparing banded and broadcast applications.

### Solubility of Silica in Water

The solubility of amorphous silica in water at 25°C involves an equilibrium between the solid phase and monomeric silicic acid,  $\text{Si(OH)}_4$  (Alexander et al., 1954). For pure amorphous silica solubility obtained was between 120 and 140 ppm in the pH range 5 to 8. The concentration of  $\text{Si(OH)}_4$  in equilibrium with solid phase is independent of pH. Solubility increases sharply above pH 9 because of the formation of silicate ions in addition to  $\text{Si(OH)}_4$  in solution. At low pH the solubility may increase due to the reaction of  $\text{Si(OH)}_4$  with acids. The increase in total soluble silica at high pH was expressed as follows:



Ionization of silicic acid was written:



Using the ionization constant of silicic acid to be  $10^{-9.8}$ , these authors calculated total dissolved silica concentrations over a range of pH values from 8 to 10.6 which were in reasonable close agreement with the measured values. An interesting story about silica has been written by Alexander (1967). Eitel (1965) reviewed detailed literature on silicate chemistry in five volumes of Silicate Science.

### Silicon in Soil Solutions

Information concerning the form and concentration of soluble Si in soil solution is important for soil fertility and soil formation studies. It is commonly believed that loss of Si from soils is favored by neutral or alkaline soil reaction. However, Raupach (1957) found that the concentration of Si in saturation extracts of some Australian soils decreased with increasing soil pH throughout the pH range from 4 to 9.

Germer and Storks (1939) demonstrated that the formation of a coating of hydrated aluminum oxide around silicious particles depressed solubility of Si in soils. Adsorption of dissolved Si on alumina was a minor factor in decreasing the amount of Si in soil solutions. A successful method of removal of Si from industrial waters involved the use of freshly precipitated Fe, Al or Mg hydroxides (Behrman and Gustafson, 1940). Betz et al. (1941) demonstrated that drying or aging freshly precipitated Al

hydroxides resulted in a marked decrease in its capacity to adsorb silica.

The amounts of soil Si soluble in water and 10 percent citric acid were positively correlated with crop response to phosphate fertilizers (Birch, 1963). McKeague and Cline (1963) showed that the dissolved silica concentration in soil solutions increased with temperature and soil:solution ratio and decreased with increasing pH. Monomeric silica, probably  $\text{Si}(\text{OH})_4$ , was the form of dissolved silica in all the extracts studied. Freshly precipitated hydroxides of polyvalent metal ions were most effective, iron oxide minerals were moderately effective, and alkaline earth carbonates were ineffective in adsorbing dissolved silica. McKeague and Cline hypothesized that a pH dependent adsorption reaction is involved in controlling the concentration of silica in soil solutions. Beckwith and Reeve (1964) found that the amount of silica extracted from soils decreased with increasing soil pH. Citrate ions promoted release of native silica from soils and partially prevented sorption of added silica. They considered Fe and Al oxides responsible for most of the retention of monosilicic acid by soils.

The manner of preparation and storage of samples influences the amount of silica soluble in water and citric acid (Acquaye and Tinsley, 1964). Silica solubility in the presence of Al approaches zero at pH 5, and with Fe at pH 4. Calcium keeps silica



insoluble in alkaline media with both Fe and Al, while Na causes it to redissolve with Al but has little effect with Fe. Phosphate and molybdate both have the effect of reducing the pH for precipitation of silica and Fe from about pH 5 to pH 3.

Gifford and Frugoli (1964) calculated heats of solution of silica from silica solubilities in soil pastes which agreed with values from solid silicic acid. Concentrations of silica in soil solutions is determined by soils properties (Miller, 1967). Solubility is both temperature and pH sensitive. Changes in the concentrations of dissolved silica in soils can occur in water percolating through soil profiles. Additions of  $\text{CaCO}_3$  to soils reduced silica concentration in soil solutions. Khan (1960) demonstrated the flocculation of colloidal silica by additions of  $\text{CaCO}_3$ .

Fox et al. (1967) listed the effectiveness of anions for Si extraction from a Hydrol Humic Latosol as:  $\text{Cl} < \text{NO}_3 < \text{OAC} < \text{F} < \text{SO}_4 < \text{H}_2\text{PO}_4$ . Silicon extraction increased with increasing acidity of extractants. In a comparative study they showed that the absolute values for different extractants varied greatly but the relative values for all methods were closely related. The general order for extractable Si for soils was: Humic Ferruginous Latosol < Humic Latosol < Low Humic Latosol < Dark Magnesium clay = Gray Hydromorphic. Phosphate extractable Si ranged from 20 ppm Si for the highly weathered soil to 700 ppm Si for the less weathered ash and alluvial soils.

### Effect of Silicate on Phosphorus Availability

Several opinions exist as to the nature of phosphorus-silicon interactions in soils. However, beneficial effects of silicate applications to soils have been attributed by several workers to increased P availability. Hall and Morrison (1906) believed the seat of reaction was in the plant rather than in the soil, while Fisher (1929) indicated that the main effect of silicate was to increase the availability of soil P and had nothing to do with P metabolism in the plant. Raleigh (1953) reported increased P uptake with silicate applications only on soils deficient in P.

Tiulin (1936) suggested increased P availability due to replacement of phosphate anions by silicate ions in the soil colloidal system. Increased yields in barley associated with silicate application was due to increased availability of soil P rather than fertilizer P (Cooke, 1956). De Datta (1958) showed increased yield and greater P uptake by barseem due to high application of sodium silicate to Indian soils. Raupach and Piper (1959) reported increased soil P release by silicate application. Khan and Roy (1964) found increased P uptake by jute plant by silicate application to some East Pakistan soils.

Toth (1939) suggested that silicate anions released fixed phosphate from soils in a manner similar to the acidoid displacement by organic anions like citrate and tartrate. Many workers (Schollenberger, 1922; McGeorge and Breazeale, 1924; Gile and

Smith, 1925; Scarseth, 1935; Midgley and Kelly, 1943; Dewan and Hunter, 1949; Laws, 1950; Noda and Saito, 1952) have suggested anionic exchange of silicate for phosphate in soils for increased P availability. Mattson (1931) found that phosphate anions strongly displace silicate anions, but apparently there was not a reverse displacement of phosphate ions by silicate ions.

Gile and Smith (1925) indicated that silica-gel exerts a solvent action on phosphorus and thus renders it more available. Increased diffusion of P in the form of  $\text{SiO}_2\text{-P}_2\text{O}_5$  complex at the soil-solution-root interface was suggested by Akhromeiko (1934). Sreenivasan (1935) found that oxide gels of Fe and Al adsorbed both silicate and phosphate ions, and retention of  $\text{KH}_2\text{PO}_4$  decreased when soils were pretreated with sodium silicate. According to Taranovskaya (1941), calcium and magnesium silicates are more effective than lime for mobilizing P and reducing the soluble Al contents. Similar results were obtained by Bastisse (1950) and Noda and Saito (1952).

Brenchley et al. (1927) stated that Si can perform in the plant some functions of P, and is a means of economizing on the use of phosphate fertilizer. Okuda and Takahashi (1962) suggested that in rice plants Si inhibits luxury consumption of P. Silicate applications increased availability of soil P but not fertilizer P, was reported by Hunter (1965). He believed this effect to be anion exchange in soils and did not find any evidence of Si

substitution for P in the plant.

Investigations on the effect of silicate on yield and P uptake by plants in Hawaiian soils have been conducted by several workers. McGeorge (1924), followed by Sherman et al. (1955), observed that plants responded to silicate application in Humic Latosols but not in Low Humic Latosols, Dark Magnesium clays, and Humic Ferruginous Latosols. Increased P assimilation in the presence of silicate was associated with the mineral composition of soils. Phosphate fixing capacity of a Humic Latosol was decreased by silicate treatments (Ikawa, 1956).

Clements (1965) obtained decreased P concentration in cane by application of TVA slag to an aluminous Humic Ferruginous Latosol. This he attributed to a dilution effect associated with increased cane growth. Phosphorus concentrations of cane grown on Hydrol Humic Latosols at Paauhau and Akaka Falls were increased by slag applications. At these locations increased yields by slag applications was believed to be partly due to increases in P absorption. Phosphorus uptake by sugarcane growing on an aluminous Humic Ferruginous Latosol was increased from 18 to 29 lbs of plant P per acre by silicate applications (Ayres, 1966). He believed increased cane growth was not because of increased P uptake since P percentage of the plant was sufficient and additions of P over control did not increase yield.

Ali (1966) grew sugarcane on a Humic Latosol in pots. He obtained a two-fold increase in total P uptake by silicate application when no P was applied. He suggested that silicate increased the availability of soil P, which under conditions of P deficiency would be accompanied by increased yield. He further observed that for similar P concentrations in the plant, silicate treated plants grew best, indicating that Si probably helped to meet internal P requirements of cane by more efficient utilization of limited soil P and/or substituting for P in the plant.

#### Effect of Silicate on Growth and Yield of Plants

Silicon has not yet been shown to be essential for plant nutrition, although it has been demonstrated experimentally that this element can influence growth and development in plants, especially the members of the Gramineae family. Silicate increased the yield of barley to a considerable extent, and the effect was most marked in the absence of P (Fisher, 1929). Similar results were reported by Brenchley et al. (1927). Increased plant growth due to silicate applications were reported by several workers (Hall and Morrison, 1906; Barnette, 1924; Gile and Smith, 1925; Raleigh, 1939; Lipman, 1938; Toth, 1939; and others).

Raupach and Piper (1959) observed that silicate applications significantly increased yields at low P levels, but the effect disappeared with the second crop. Suehisa et al. (1963) reported

increased yield of Sudan grass grown on a Humic Latosol to which silicate had been applied. Monteith and Sherman (1963) reported that in a Hydrol Humic Latosol both  $\text{CaCO}_3$  and  $\text{CaSiO}_3$  increased yields of Sudan grass up to pH 6.8. Above this pH yield was depressed. In a Humic Ferruginous Latosol lime depressed yields at high pH values, but silicate at high rates still slightly increased yields.

Mitsui and Takatoh (1963) found that 100 ppm silicate added to a culture solution increased the production of new roots and tillers in rice plants and advanced the time of head sprouting. When Si content was less than 0.5 percent of total dry matter plants showed retarded growth during both vegetative and reproductive stages. Sterility was greatest in Si deficient barley and rice.

Khan and Roy (1964) found increased P uptake and yields of jute plant by silicate applications to lateritic and alluvial soils. Silicate treatments increased fineness of fibre cells. Sudan grass grown in amorphous and differentially crystallized sub-soils of Akaka soil responded best to  $\text{CaSiO}_3$ , intermediate to coral stones, and not at all to olivine sand (Dias, 1965).

Clements (1965) reported yield increases in sugarcane when TVA slag was applied to Hydrol Humic Latosols at Paauhau and Akaka Falls. Ayres (1966) reported that silicate did not benefit cane growth in pots where water containing 50 ppm  $\text{SiO}_2$  was

used, but pronounced increases in growth was obtained using the same soil and distilled water. Pure  $\text{CaSiO}_3$  greatly increased cane yields over control treatment which received equivalent amounts of Ca as nitrate. He concluded that Si per se was the main factor in increasing cane yields over control.

Ali (1966) grew sugarcane on a Humic Latosol in pots. Cane yields were increased about two-fold by silicate application when no P was applied. When plant P was brought to sufficiency the effect of silicate mostly disappeared. The yields of corn and kikuyu grass grown in pots on a Kapaa soil were increased significantly by silicate applications (Manuelpillai, 1967). In corn and sedge grass, increases in yields by silicate applications were accompanied by a decrease in P requirements. Ibrahim (1968) reported that though silicate did not increase grain yields in rice, it was effective in increasing straw weight by greater production of tillers. Teranishi (1968) reported increased cane yields by both silicate and phosphate applications to a Kapaa soil. Increased yields as a result of silicate applications was attributed only partly to increased P uptake, since P uptake decreased at the highest Si rate yet this treatment produced best. TVA slag applied to Kapaa soil increased sugar yields by 12 tons per hectare. In this experiment phosphate extractable soil Si and trichloro acetic acid (TCA) extractable Si of sugarcane leaf sheaths were about 20 ppm Si (Fox et al., 1967). Phosphate or lime application to this

soil did not alleviate leaf freckle, while slag did so to a considerable extent.

### Silicate and Trace Elements in Plants

Rhoads et al. (1956) demonstrated decreased Mn uptake by avocado seedlings by silicate application. The decrease was attributed to increased soil pH and not Si uptake. Silicon decreased Mn necrosis in barley by preventing localization of Mn in small spots on the leaves (Williams and Vlamis, 1957). Vlamis and Williams (1967) showed that Si application increased yields in barley, oats, wheat and rye in the presence of Mn and decreased Mn concentrations in these plants. Clements (1965) believed that part of the response of sugarcane to TVA slag was due to decreased Mn concentration and lower Mn/Si ratio in the cane which reduced the incidence of "freckling", a physiological disease of sugarcane.

Ayres (1966) showed decreased Mn uptake by cane due to slag application. This was explained by higher soil pH and decreased solubility of Mn in soils. Leaf freckle of sugarcane was alleviated to a considerable extent by slag applications to Kapaa soil (Fox et al., 1967). Rice plants grown in Fe + Mn solution without Si produced brown spots on the leaf blades (Okuda and Takahashi, 1962). Slightly decreased Zn uptake by cane due to silicate application was reported by Ali (1966).



Teranishi (1968) did not find significant effects of silicate on Al and Mn content of sugarcane. However, the Mn/Si ratio was decreased with silicate application. The lowest Mn/Si ratio was associated with the highest cane yields.

### Silicon Uptake and Distribution in Plant

Schollenberger (1922) reported that deposition of silica causes hardening of outer walls of plant stems, sharpening of edges of leaf blades, and stiffening of hairs. Absorption of Si was increased by excess nitrogen and was limited by potassium deficiency in plants (Germer, 1934). Germer also reported that Si deposition varies directly with transpiration. Raleigh (1939) found that barley plants deficient in Si were severely attacked by mildew, and that Si application corrected damping off in beet seedlings. Whittenberger (1945) indicated that under natural conditions Si is probably absorbed by plants as soluble silicic acid.

Engel (1953) indicated the presence of organic complexes of Si in rye straw. Silicon initially accumulated in the roots and later transported to the stalks of wheat seedlings and remained there when the supply was stopped. Most plant Si exists in inorganic form, although a part of the Si in higher plants was reported to be present in combination with protein (Ozaki and Higashiro, 1957).

Rothbuhr and Scott (1957) using radioactive Si showed that

added P slightly decreased Si uptake by wheat, while Si enhanced P absorption. Fletcher and Kurtz (1964), in agreement with the above authors, stated that P and Si have an inverse relationship, and that plant P + Si in milliequimoles tended to remain constant. Silicon levels in cane leaf sheaths increased with increasing levels of TVA slag applications (Clements, 1965). In many cases, slag induced ten-fold increases in Si yields in millable cane. Increased Si uptake by slag applications were demonstrated by several workers (Ali, 1966; Manuelpillai, 1967; Ibrahim, 1968; Teranishi, 1968; and others).

Jones and Handreck (1965) indicated that Si absorption both in graminaceous and leguminous species decreased with increasing soil pH. Oats grown in different soils of the same pH contained different amounts of Si at maturity. Silicon uptake was lowered by the presence of sesquioxides in soils. Mitsui and Takatoh (1963) used radioactive Si to demonstrate that 75 percent of Si in rice plants was transported to the shoots. They concluded that Si absorption by roots was performed by utilizing the energy released during the respiration by roots. Yoshida et al. (1962a) reported on the distribution of Si in leaf blades, leaf sheaths, stems and husks of rice. In leaf blades the density of silicified cells was maximum within one centimeter from the tip and decreased towards the base. They further demonstrated that the mobility of Si in plants is very low, and once deposited, its

redistribution is unlikely. Using infrared absorption and solubility tests in hot water, they found that about 90 percent of plant Si was in the form of silica-gel and poly-silicic acid, with only 10 percent in the form of dispersed state Si and colloidal silicic acid.

Fox et al. (1969) suggested that soluble Si in plant tissues can give useful information about the Si status of plants. Total and soluble Si was higher in sugarcane leaf sheaths than in leaf blades. Total Si was much greater in leaf sheaths and leaf blades than in the internodal tissue. Soluble Si was highest in the least mature tissues, whereas total Si was highest in the recently mature tissues. They concluded that Si deposition in sugarcane is associated with growth.

Resistance to blasts in rice corresponds to an increase in the Si content of the leaves (Volk et al., 1957). Sasamoto (1957) indicated that Si accumulation is an important factor in the resistance to rice böhler.

## MATERIALS AND METHODS

### PHASE I. LABORATORY EXPERIMENTS

#### Description of Experimental Soils

The soils used for laboratory experiments represent four great soil groups of Hawaii. They came from three different islands of the Hawaiian chain and developed under a wide range of environmental and climatic conditions. These soil groups have been described by Cline et al. (1955). The soils and some of their important characteristics are as follows:

The Wahiawa soil belongs to the Low Humic Latosol group (Tropheptic Entrorthox). It developed from basalt under low to medium rainfall. Physically the soil acts like a silty clay or a silty clay loam. The clays are mostly kaolinitic with considerable amounts of hydrated Fe and Al oxides. The soil contains considerable amounts of manganese oxide concretions. Exchangeable bases and Si content is relatively high compared to highly leached Latosols. The pH of the soil is around 6.5. Phosphate fixation by this soil is moderately high.

The Kawaihoa soil belongs to the Humic Latosol group (Humoxic Tropohumult). It was formed under heavier rainfall than the Wahiawa soil. This soil developed under a rather heavy cover of vegetation, which with greater rainfall, has allowed them to accumulate more organic matter. The profiles of Humic

Latosol contain less silica and alumina than the Low Humic Latosols, but much more Fe and Ti oxides. Clays are mostly kaolin, gibbsite and some illite. Clay crystals are coated with Fe and aluminosilicate gels. Soil pH is about 5.0. Phosphate fixation by this soil is less than by the Wahiawa soil. These soils respond to silicate applications.

The Akaka soil belongs to the Hydrol Humic Latosol group (Typic Hydrandept). It developed from volcanic ash under heavy rainfall (over 200 inches a year). The soil is continually wet in its natural conditions and hold about 250 to 350 percent water. On drying it becomes irreversibly dehydrated. The organic matter content on an oven dry basis is high. The inorganic fraction of the soil is weathered and highly leached, and bases have been reduced to very low levels. Silica has also been depleted. The clays are apparently highly hydrated oxides. Soil pH is around 5.0. The soil has an extremely high phosphate fixing capacity. The soil may respond to silicate application, but due to its amorphous nature Si in soil solution tend to be higher than for the more highly weathered basaltic soils.

The Kapaa soil belongs to the aluminous Humic Ferruginous Latosol group (Typic Gibbsihumux). This is a highly weathered soil and according to Sherman (1958) approached the end product of soil formation in the Latosol suborder. Outstanding characteristics of this soil group is the presence of crystalline alumina as

gibbsite and concentration of resistant heavy minerals (concretions of Fe and Ti oxides) in the upper part of the soil profiles. This soil is almost completely depleted of bases and silica. It has a comparatively low (about 1.5) bulk density and a low soil pH (around 5.0). Oxides are the dominant minerals. The soil has a high phosphate fixing capacity. It responds to phosphate and silicate applications.

#### Soil Collection and Preparation

The Wahiawa and the Kawaihoa soils were collected from Waialua Plantation on the Island of Oahu. The Akaka soil was collected from an idle field in the Pepeekeo Sugar Plantation near Akaka Falls. The Kapaa soil was collected from the Kauai Branch Station of the University of Hawaii.

Bulk samples of soils (0-9 inches depth) were collected. All soils except Akaka were air dried and screened through a 16 mesh sieve for laboratory work. Coarse organic residue was removed from the Akaka soil before it was screened through a 1/4 inch mesh sieve. This soil was stored in double polyethylene bags. Care was taken to avoid drying the Akaka soil. Samples were drawn to determine moisture content. However, all experiments with the Akaka soil were performed on a field moist basis (on the basis of 40 percent dry matter). This was considered desirable because the amount of water held by the soil under field

conditions is considered to be an integral part of the soil mass.

#### Determination of Time of Equilibration for Phosphorus and Silicon Sorption by Soils

Phosphorus Sorption: Phosphorus sorption as a function of time was investigated for Wahiawa, Kawaihoa, Kapaa and Akaka soils. The time of equilibration for succeeding experiments was based on this investigation. The soils were equilibrated with specific concentrations of P added as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  in 0.01 M  $\text{CaCl}_2$  for different periods of time and P remaining in solution was determined. The results (Fig. 1, Appendix Table 26) indicate that sorption was more than 95 percent completed in 24 hours. After 96 hours the curves leveled out. Four to six days equilibration was adequate for near equilibrium. However, a few experiments were conducted with 24 hours equilibration time.

Silicon Sorption: Silicon sorption as a function of time was determined for the soils. The soils were equilibrated with specific concentrations of Si solutions added as  $\text{CaSiO}_3$  in water for different equilibration periods and Si remaining in solution was determined. The results (Fig. 2, Appendix Table 27) indicate that Si sorption by the soils was very rapid. Although concentration of Si in soil solution continued to decrease with time, the rate of decrease was very slow. One to twelve hours equilibration was found to be adequate for near equilibrium. Based on

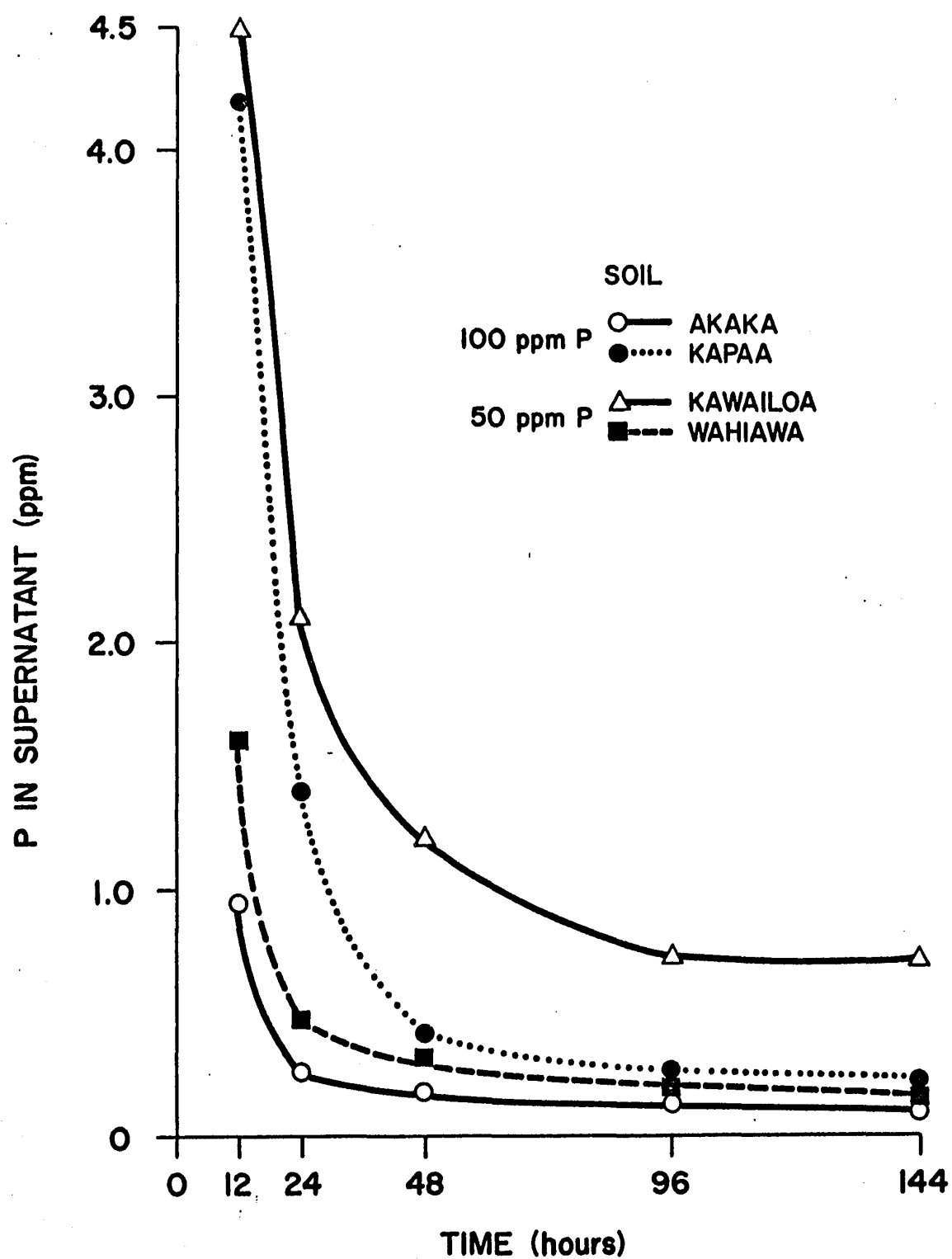


Fig. 1. Phosphorus Remaining in Solution in Four Hawaiian Soils in Relation to Time of Equilibration.



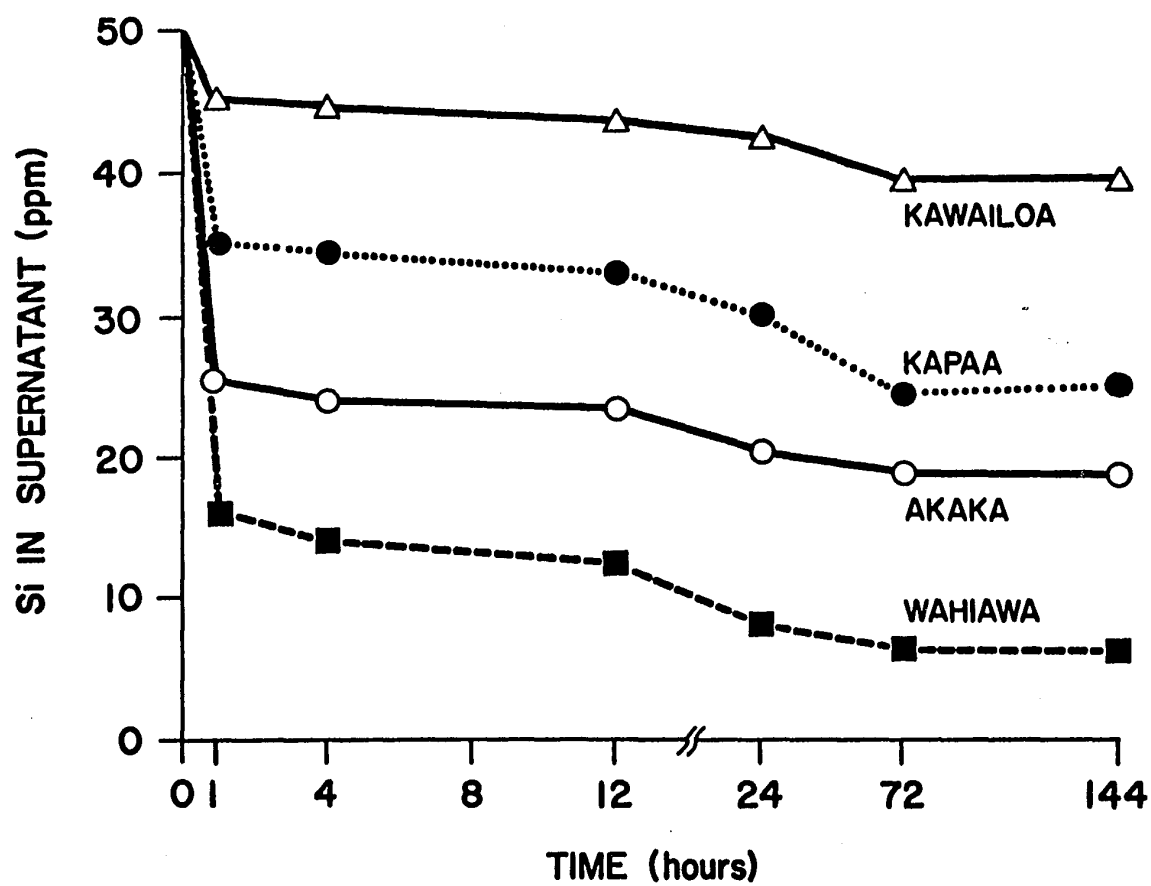


Fig. 2. Added Silicon Remaining in Solution in Four Hawaiian Soils in Relation to Time of Equilibration.

this investigation, four-hour equilibration was used.

#### Native Silicon Release from Soils

Three grams soil was weighed into a 50 ml centrifuge tube and 30 ml of distilled water was added. The soil-solution mixture was then equilibrated for one hour to six days with one-half shaking twice a day for the samples that were shaken beyond 24 hours. The samples were then centrifuged at 16,000 RPM for 20 minutes and Si in the supernatant solution was determined. Values reported are means of two replications.

#### Sorption of Added Phosphorus and Silicon by Soils

Three grams samples of soils were weighed into 50 ml centrifuge tubes and a 30 ml aliquot of phosphate solution varying in concentration [as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  in 0.01 M  $\text{CaCl}_2$ ] was added to each sample. One set of samples was equilibrated by shaking for 24 hours. In a second set, the samples were shaken one-half hour twice a day for six days. Samples were centrifuged and P in the supernatant solution was determined.

The silicon sorption study was carried out in a similar manner by equilibrating soils with  $\text{CaSiO}_3$  solutions which varied in concentrations from 0 to 100 ppm Si. The equilibration period was four hours.

## Some Factors Influencing the Solubility of Native and Applied Silicon in Soils

Effect of Acid Leaching: One hundred grams soil samples were leached with two liters of 0.1 N HCl followed by several liters of distilled water over a period of eight hours. All soils except Akaka were air dried after leaching and crushed to pass a 16 mesh sieve. The Akaka soil was stored moist in double polyethylene bags. Except for the Akaka soil experiments were carried out on an oven dry soil basis. The Akaka soil was used on the basis of 40 percent dry matter.

Five grams of leached soils were weighed into 250 ml Erlenmeyer flasks and 50 ml of  $\text{CaSiO}_3$  solutions in serial concentrations were added. The samples were equilibrated for four hours and then centrifuged. Silicon was determined in the supernatant solution. Solution pH values were also recorded.

Effect of pH: Five grams samples of soil were weighed into 250 ml Erlenmeyer flasks and 50 ml of distilled water or a 50 ppm Si solution was added. Varying pH values of the samples were obtained by adding 0.1 N HCl or  $\text{Ca}(\text{OH})_2$  to the samples. The samples were equilibrated by shaking for four hours and then centrifuged. Silicon was determined in the supernatant solution. Solution pH values were determined.

Effect of Neutral Salt Concentrations: Five grams soil samples were weighed into 250 ml Erlenmeyer flasks containing

graded amounts of  $\text{CaCl}_2$ , and 50 ml of distilled water or a 50 ppm Si solution was added. The samples were equilibrated by shaking for four hours and then centrifuged. Silicon was determined in the supernatant solution. The pH values of the solutions were also recorded.

#### Phosphorus-Silicon Interaction in Soils

Three grams soil samples were weighed into 50 ml centrifuge tubes and three levels of P (0, 500 and 1000  $\mu\text{g P/g}$ ) and three levels of Si (0, 250 and 500  $\mu\text{g Si/g}$ ) were added. The final volume was 30 ml. Samples were equilibrated by shaking for 24 hours and then centrifuged. Phosphorus and Si were determined in the supernatant solution.

After decanting the supernatant liquid, samples were brought to the original soil:solution ratio by adding water. The samples were resuspended and equilibrated by shaking and then centrifuged. Desorbed P and Si were determined in the supernatant solution.

#### Effect of Silicon on Phosphorus Status of Soil Solutions During Continued Depletion of Phosphorus from Soil Solution

The experiment was carried out to see the effect of Si on P levels in soil solutions. Depletion of P from soil solutions was effected by repeated extraction of the same sample and decanting supernatant solution each time.

One gram soil samples in 50 ml centrifuge tubes were equilibrated with three levels of P and two levels of Si at a soil:solution ratio of 1:30 by shaking for one-half hour periods twice daily for six days. The P solutions added to Kapaa soil were 500, 750, 1000 and 2000  $\mu\text{g}$  P/g soil, while 500, 1000, 2000 and 3000  $\mu\text{g}$  P/g soil were added to Akaka soil. Silicon levels were 0 and 500  $\mu\text{g}$  Si/g soil. The samples were centrifuged and the supernatant solution was decanted. They were brought back to the original soil:solution ratio by adding distilled water, resuspended and equilibrated by shaking for four hours. This process was continued for four times. Phosphorus and Si were determined in the supernatant solution following each extraction.

## PHASE II. FIELD EXPERIMENTS

The study on P-Si interactions in soils was extended by means of field experiments. The effect of phosphate and silicate fertilization on P and Si status of soils was evaluated by laboratory studies.

Profile samples were collected from the following existing field experiments: (i) An experiment laid out on an aluminous Humic Ferruginous Latosol (Kapaa soil) on the Kauai Branch Station of the University of Hawaii in August, 1966. A factorial experiment of three levels of silicate, three levels of phosphate, and three pH levels were replicated three times. Sugarcane was

grown on the plots and the first crop was harvested nine months after planting. Profile samples were taken after the first harvest.

(ii) A comparison of TVA slag, kau cinders, and a mixture of kau cinders and ground coral stone as sources of calcium or magnesium silicate were replicated four times. This experiment was laid out on a Hydrol Humic Latosol (Akaka soil) near Akaka Falls on the Pepeekeo Sugar Plantation, Island of Hawaii in 1961. Sugarcane had grown on these plots for five years. In March, 1966, profile samples were taken from plots receiving TVA slag.

#### Sampling Procedure

Auger borings with five depth increments to four feet were taken from the center of each plot. The Kapaa soil samples were air dried for several days, ground and screened through a 2 mm sieve. The samples were composited and moisture samples were drawn from each composite sample. All experiments were performed on the composite samples.

The sampling procedure for the Akaka soil profiles was similar to that of the Kapaa soil profiles, except that six depth increments with two auger borings per plot were taken. Composite samples of two borings were taken as representative profile samples. The samples were stored in double polyethylene bags and care was taken to avoid drying of the samples. The samples

were screened through a 1/4 inch mesh screen before laboratory use.

#### Effect of Silicate, Phosphate and Soil pH on Phosphorus Sorption by Kapaa Soil

Eight treatment combinations from the Kapaa location, 100 and 1000 lbs P/A, zero and 4 tons slag/A, and pH 5.5 and 6.2, were equilibrated with serial concentrations of P by shaking for six days, and P was determined in the supernatant solution. Two depth increments were used: surface (0-6 inches) and sub-surface (12-24 inches).

#### Residual Effects of Silicate Application on Phosphorus Sorption by Akaka Soil

Effects of silicate on P sorption by Akaka soil was evaluated by equilibrating the surface soil (0-6 inches) and the sub-soil (12-18 inches) samples of the control plot and the 8 tons of slag/A plot with serial concentrations of P solutions in the manner described above.

#### Extractable Soil Phosphorus

Extractable P was determined in the surface soil and the sub-soil samples of the Kapaa soil profiles. Two grams soil samples were weighed into 500 ml Erlenmeyer flasks and 200 ml of modified Truog extractant ( $0.02 \text{ N H}_2\text{SO}_4 + 3 \text{ g (NH}_4)_2\text{SO}_4$

per liter) was added. The samples were extracted by shaking for one-half hour. The soil-solution mixture was immediately filtered through a Whatman No. 42 filter paper. Phosphorus was determined in the clear filtrate.

#### Silicon Movement in Soils by Unsaturated Flow

Air dried soils which had passed a 2 mm screen were packed in 10 cm leaching columns to a bulk density of 1.2. The leaching columns were made by joining aluminum rings 2.5 cm long and 6 cm in diameter. Calcium silicate powder was added on top of the soil columns at the rate of 1000 ppm Si. Forty ml of distilled water was added three times a day. Silicon in the effluents was determined every 24 hours. Control columns were leached with distilled water in a similar manner. Differences between Si concentrations in leachates of treated and the control columns were reported as added Si in the effluents.

After passing 70 cm of water through each column, the columns were fractionated into four sections. Soils in each section were mixed thoroughly and extracted for water soluble and phosphate extractable Si.

#### Silicon Movement in Kapaa Soil by Saturated Flow

Air dried soils which had passed a 2 mm sieve were packed in leaching columns made of 5 polyethylene rings (4.4 cm in diameter and 10 cm long) held together with screw clamps.



The column ends were sealed with porous polyethylene plates lined with double-filter papers. The soil columns were presaturated with  $\text{CO}_2$  gas before saturating with water to expel entrapped air in the pores. These water saturated columns were then pre-leached with 100 ml of 0.01 M  $\text{CaCl}_2$  or water before introducing Si solution into the soil columns. This step was necessary to determine the effect of  $\text{CaCl}_2$  solution and water on native Si release from the soil. Silicate solution was then introduced into the columns, followed by 0.01 M  $\text{CaCl}_2$  or water.

The columns were leached with one liter (67 cm) of displacing liquids. Twenty ml leachate fractions were used for pH and Si determination. The flow rate was approximately one ml per minute. The leached columns were fractionated into five sections and analyzed for water soluble Si.

#### Silicon Movement in the Field

Water soluble and phosphate extractable Si was determined in the profile samples of Kapaa and Akaka soils. Five grams soil was weighed into a 250 ml Erlenmeyer flask and 50 ml of water or a 50 ppm P solution (buffered with  $\text{NH}_4\text{OAC}$  and adjusted to pH 3.5) was added. The samples were equilibrated for four hours by shaking and then centrifuged. Silicon was determined in the supernatant solution. Water soluble Si was reported as ppm Si in a 1:10 water extract, while phosphate extractable

Si was expressed as ppm Si on an oven dry soil basis.

### Extractable Soil Aluminum in Soil Profiles

The effect of silicate and silicate plus lime applications on distribution of extractable soil Al in soil profiles was evaluated by extracting profile samples with 1 N KCl. Treatments sampled were as follows:

<u>Kapaa Profile</u>	<u>Treatment</u>
1	Check
2	100 lbs P + 4 tons slag/A
3	100 lbs P + 4 tons slag/A + lime
4	1000 lbs P + 4 tons slag/A
5	1000 lbs P + 4 tons slag/A + lime

### Akaka Profile

1	Check
2	8 tons of slag/A

Ten grams soil was weighed into a 500 ml Erlenmeyer flask and 100 ml of 1 N KCl was added. The samples were equilibrated by shaking for two hours and then filtered, using 5 aliquots of KCl solution to wash the soil during filtration. Aluminum was determined colorimetrically in the filtrate using the Aluminon method as outlined by Chapman and Pratt (1961).

### PHASE III. SOLUTION CULTURE EXPERIMENTS

#### Interaction Effects of Phosphorus and Silicon on Silicon and Phosphorus Uptake by Plants from Culture Solutions (Split-Root Technique)

This experiment was designed to investigate interactions between silicon and phosphorus in the plant itself; eliminating the effects of soil. Both Si and P were supplied in solution separately from adjacent containers or together in one container. Sugarcane (Saccharum officinarum), corn (Zea mays), rice (Oriza sativa), lettuce (Lactuca sativa), and sensitive plant (Mimosa pudica) were used as the test plants.

Seedlings of all plants except sugarcane were raised in culture solutions by germinating the seeds on moist cheese cloth over a 1/4 strength Hoagland solution. Sugarcane sets (Variety H 50-7209) were first germinated and raised for three weeks in trays of acid washed quartz sands and then transferred to 1/4 strength Hoagland solution. Corn and sugarcane were supplied with 0.2 ppm P, while lettuce, Mimosa and rice received 1 ppm P in solution during the pre-experimental growth period. The seedlings were grown in the nursery until they developed appreciable root systems. Plastic containers and freshly prepared distilled water were used to minimize contamination from silicon. The culture solutions were aerated continuously. The solutions

were renewed twice a week and pH values were adjusted to 5.5 every day by adding 0.1 N  $\text{H}_2\text{SO}_4$  or NaOH as required.

### Experimental Procedure

A randomized complete block design with 5 treatments and three replications was used for each species except that corn had 5 treatments replicated twice. All species except sugarcane were grown in growth chambers. Sugarcane was grown outdoors. The roots of each plant were divided approximately equally and placed into two adjacent chambers. Each chamber contained 900 ml of nutrient solution except those for sugarcane which contained six liters. The combinations of Si and/or P in 1/4 strength Hoagland solution provided were as follows:

<u>Treatment</u>	<u>Chamber 1</u>	<u>Chamber 2</u>
1	0	0
2	Si	0
3	$^{32}\text{P}$	0
4	$^{32}\text{P}$	Si
5	$^{32}\text{P} + \text{Si}$	0

Phosphorus was supplied as  $\text{H}_3\text{PO}_4$  solution at the rate of 1 ppm P tagged with  $^{32}\text{P}$ . Silicon was supplied as  $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$  solution at the rate of 5 ppm Si. Phosphorus concentrations in the chambers were adjusted to 1 ppm P twice daily by determining relative specific activities (cpm/ml solution) of the

solutions compared to a standard. Additional sodium silicate solution was added to the pots as needed to maintain 5 ppm Si in solution. Silicon depletion was determined colorimetrically. The pH values of the solutions were adjusted to 5.5 every day by adding 0.1 N  $\text{H}_2\text{SO}_4$  or NaOH as needed. The solutions were constantly aerated. Two plants per pot were used for sugarcane, corn and lettuce, and four plants per pot for rice and Mimosa. Except for corn all experiments were conducted for seven days.

Corn seedlings were raised directly on culture solutions in a growth chamber at a low light intensity. As a result the seedlings were weak. During the experimental period these plants received 0.2 ppm P and 2 ppm Si instead of 1 ppm P and 5 ppm Si as received by the other plants. Instead of adjusting P and Si in the culture solutions to their original concentrations, the culture solutions were completely renewed every two days during the first week and every four days during the second week. The experiment was continued for twelve days.

#### Plant Sampling and Analyses

When sampled, plants, except sugarcane, were divided into tops and roots. Sugarcane plants were divided into seven parts: leaf 1, leaves 2 and 3, lower leaves, immature cane, mature cane, secondary shoots, and roots. The roots were sampled

separately according to placements. Immediately after harvest the samples were washed with 0.01 percent soap solution, followed by distilled water rinsing and oven dried at 70°C for 48 hours. The root samples were washed with 0.5 N HCl, followed by distilled water rinsing and oven dried at 70°C. Ground oven dried samples were analyzed for total P,  $^{32}\text{P}$  activity and total Si.

Effects of Varying Ratios of Silicon and Phosphorus in Culture Solutions on the Yield, and Phosphorus and Silicon Content of Sugarcane

This experiment was conducted to evaluate interactions between P and Si in culture solutions on the performance of sugarcane. Two seedlings of sugarcane variety H 50-7209 were transplanted into plastic containers holding six liters of 1/4 strength Hoagland solution. A 4 x 4 complete factorial experiment with two replications, in a randomized complete block design, was used. Phosphorus levels were 0, 0.2, 0.5, and 1 ppm P. Levels of Si were 0, 0.2, 2, and 5 ppm Si. Other experimental procedures were similar to those described for the split-root experiment.

One plant per pot was harvested after two months, and the second plant was harvested four months after transplanting. At two months the plants were divided into tops and roots, while at four months they were divided into tops, sheaths and roots.

Leaf sheaths 3, 4, 5 and 6 were sampled from each plant as an indicator tissue, and the rest of the plant except roots were put together and called "tops". The roots were processed as described for the split-root experiment. The samples were dried at 70°C in an oven. Ground, oven-dry samples were analyzed for total P and Si.

#### PHASE IV. GREENHOUSE EXPERIMENT

The mutual effects of silicon and phosphorus placements in pots on the yield, and Si and P uptake by plants were investigated in the greenhouse. Three soils, Akaka, Kapaa and Kawaihoa, and five plant species, lettuce, Mimosa, rice, corn and sugarcane were used. A randomized complete block design with two replications were used for each species.

Sugarcane was grown in 5 gallon cans lined with polyethylene bags. Each pot contained 30 pounds soil on an oven dry basis except for the Akaka soil. Each pot of this soil contained 35 pounds of moist soil. The volume of each soil was about equal. Corn, Mimosa, lettuce and rice were grown in one gallon cans with polyethylene bags. Each pot contained 2 kg of the Kawaihoa or the Wahiawa soil on an oven dry basis, and 2 kg of field moist Akaka soil. Initial pH of the Akaka and the Kawaihoa soils were adjusted to 5.6 by adding appropriate amounts of  $\text{CaCO}_3$ , while 0.1 N  $\text{H}_2\text{SO}_4$  was added to the Wahiawa soil to

depress the soil pH to 5.6. Each pot received a blanket application of 200 ppm N as urea, 200 ppm K as KCl, 50 ppm Mg as  $\text{MgSO}_4$ , 50 ppm Zn as  $\text{ZnSO}_4$ , and 2 ppm B as  $\text{H}_3\text{BO}_3$ . Phosphorus was applied at the rate of 250 ppm P as  $\text{H}_3\text{PO}_3$  solution tagged with  $^{32}\text{P}$ , except in sugarcane. Silicon was added at the rate of 1,000 ppm Si as C.P. grade  $\text{CaSiO}_3$ .

The placement treatments were:

- 1 P banded
- 2 P + Si banded together
- 3 P and Si banded separately
- 4 P mixed with one-half of the soil
- 5 P + Si mixed together in one-half of the soil
- 6 P and Si mixed with separate one-half portions of the soil.

In the case of sugarcane two additional placements were included. They were as follows: Si banded and Si mixed with one-half of the soil.

#### Potting Procedure

In band placement treatments P and/or Si were mixed with 2 cm depth portions of soils, while in mixed placement treatments P and/or Si were mixed with one-half of the soil volume. The P bands always were placed above the Si bands and covered with 2 cm portions of soils. Equivalent amounts of  $\text{CaCO}_3$  were



added to neutralize excess acidity due to  $\text{H}_3\text{PO}_4$  additions. Individual placements were made by weighing out appropriate amounts of soils to be banded or to be mixed with P and/or Si and mixing them thoroughly with P solution and/or  $\text{CaSiO}_3$  powder. The treated soils were then put back into their respective positions in the pots according to placement designations. Each placement was demarcated from soil above and below by a circular piece of nylon netting.

#### Planting and Subsequent Operations

All species except sugarcane were seeded directly 2 cm below the surface. Lettuce, rice and corn seeds were pretreated with 10 percent clorox to help avoid fungus attack. Mimosa seeds were scarified with concentrated  $\text{H}_2\text{SO}_4$  to facilitate early germination. Sugarcane seed pieces, variety H 50-7209, were germinated and raised in acid washed quartz sand trays for three weeks and then transplanted into the 5 gallon cans. Two seedlings of equal size and root development were transplanted per pot. The pots were watered twice daily with distilled water and maintained at field capacity by weighing individual pots at least once each day.

One week after germination the pots were thinned to the following number of plants per pot: 3 corn, 8 Mimosa, 10 lettuce, and 20 rice. Plants were sprayed with insecticide weekly.

### Plant Sampling and Analyses

Rice, corn and Mimosa were harvested six weeks after germination. Lettuce was harvested twice, at 4 weeks and at 6 weeks. Sugarcane was also harvested twice, at 2 months and at 4 months. Immediately after harvests the plants were washed with 0.01 percent soap solution, followed by distilled water rinsing, and were then oven dried at 70°C. Sugarcane was divided into tops and sheath samples as described in an earlier section. Ground oven dry plant samples were analyzed for total P,  $^{32}\text{P}$  activity and total Si.

## ANALYTICAL METHODS

### Plant Analyses

Ashing of Plant Samples: One gram plant sample was weighed into a porcelain crucible and ashed overnight at 550°C in an electric muffle furnace. The sample was cooled to room temperature, moistened with a few drops of distilled water, treated with one ml of 1 N  $\text{HNO}_3$ , evaporated to dryness on a hot plate, re-ashed at 550°C for an additional four hours and cooled, dissolved in 10 ml of 4 N  $\text{HCl}$ , evaporated to about 3 ml and finally transferred with distilled water to a 50 ml volumetric flask and made to volume. The digest was stored in plastic vials and was used for all chemical analyses except for Si.

A modification of the lithium metaborate fusion method

developed by Suhr and Ingamells (1966) was used for determining Si in plant samples. One-half gram samples were weighed into platinum crucibles and ashed overnight at 550°C. After cooling the ash, 0.5 gram lithium tetraborate was added and mixed thoroughly. The mixture was transferred to a graphite crucible and fused at 950°C for 15 minutes in a muffle furnace. The melt was poured into a 250 ml beaker containing 100 ml of dilute HNO<sub>3</sub> (30 ml HNO<sub>3</sub> per liter), and stirred with a magnetic stirrer until the melt was completely dissolved. The solution was stored in plastic vials. This digestion procedure was utilized for all chemical analyses of the root samples due to very small quantities of samples in many cases.

Total P was determined colorimetrically by the Vanado-Molybdi-Yellow complex method using Barton's reagent (Kitson and Mellon, 1944). Silicon was determined colorimetrically using the silico-Molybdate Blue complex method of Kilmer (1965).

Activity of <sup>32</sup>P in the plant samples was determined by pipetting a one ml aliquot of dissolved ash on a stainless steel planchet and counting under a thin-window G-M counter. Relative specific activities (cpm/g plant material) of the samples were determined by comparing with a standard <sup>32</sup>P tagged phosphorus solution.

### Soil Analyses

Soil Phosphorus: Phosphorus in soil solutions was determined using the Molybdenum Blue method of Dickman and Bray as outlined by Chapman and Pratt (1961).

Soil Silicon: Silicon in soil solutions was determined colorimetrically using the Silico-Molybdate Blue complex method of Kilmer (1965). Silicon determinations in soil extracts were performed immediately after extraction, since silicon in soil solutions polymerized rapidly.

## RESULTS AND DISCUSSION

### PHASE I

#### Native Silicon Release from Soils

The silicon status of Akaka, Kapaa, Kawaihoa and Wahiawa soils, representing a wide range of physical, chemical and mineralogical properties, were investigated. The soils were equilibrated for different periods of time by shaking in distilled water and Si in the supernatant solution was determined. Silicon in all the equilibrating solutions increased with time of shaking (Fig. 3, Appendix Table 27). The rate of increase in concentration of Si in solutions varied among the soils. The concentrations of Si for the soils after four hours of shaking ranged from 0.75 to 1.05 ppm, and after six days the values were between 1.18 and 2.25. The order of Si release by the soils during four hours was: Wahiawa > Kapaa > Akaka = Kawaihoa. Consistently high values for soluble Si were obtained for the Wahiawa soil, a Low Humic Latosol with a kaolin type clay minerals developed under low rainfall regime.

McKeague and Cline (1963) demonstrated that concentration of Si in soil solutions continued to increase even after 15 days of equilibration by shaking. Equilibrium was attained at lower concentrations more rapidly by perfusion or standing. They did not consider shaking techniques suitable for obtaining equilibrium water

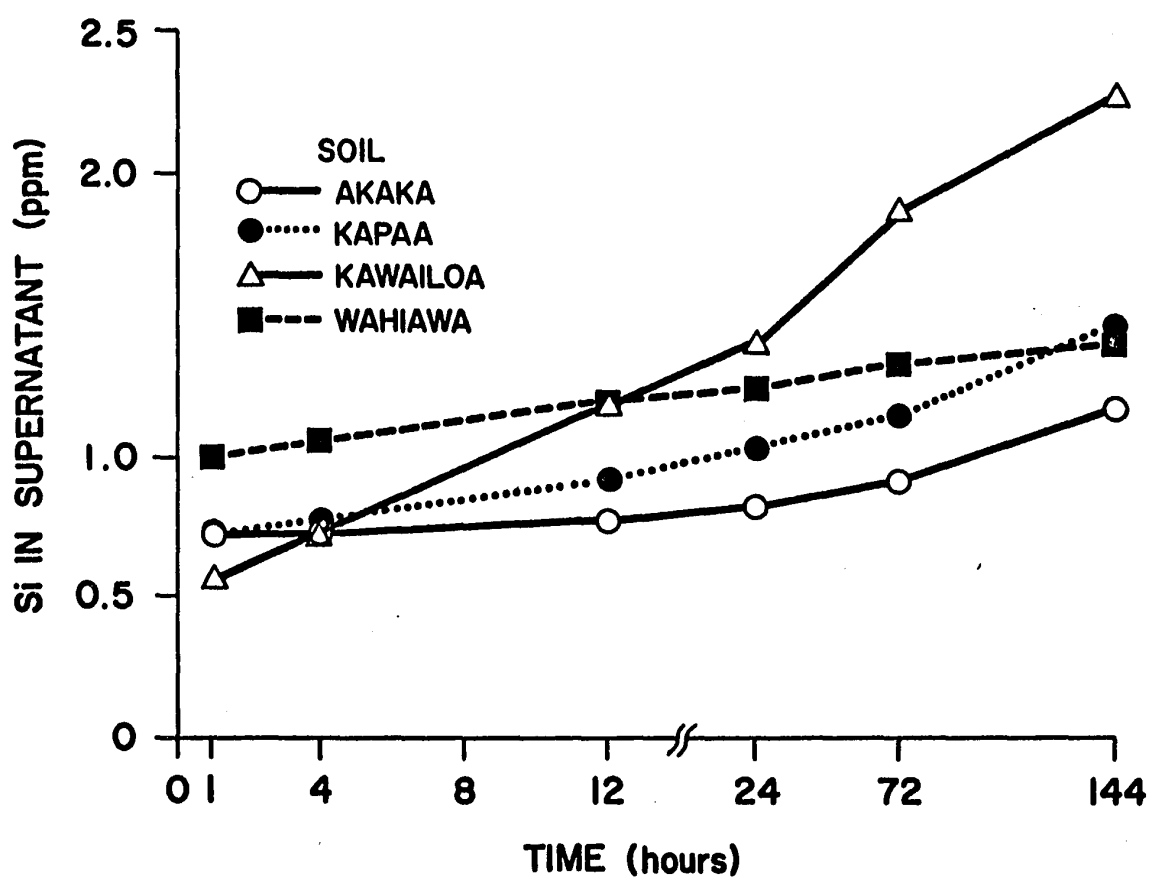


Fig. 3. Effect of Time of Equilibration on the Solubility of Native Silicon in Four Hawaiian Soils.

extracts of some soils. As a result of their experience soils in this study were not shaken continuously but for one-half hour periods twice a day.

The Kawaihoa soil has developed under high rainfall. This soil contains crystalline kaolin-gibbsite clays with hydrated oxides of Fe and Al. The clay crystals in this soil are thought to be coated with Fe and aluminosilicate gels (R. C. Jones, personal communication). The gel coatings and crystallinity of Kawaihoa soil may have accounted for low Si solubility at the beginning. The gels may have been removed from the surface of the kaolin crystals by continued shaking. Germer and Storks (1939) demonstrated that the formation of a coating of hydrated Fe and Al oxides around silicious particles depressed the solubility of Si in soils. McKeague and Cline (1963) demonstrated increasing concentration of dissolved Si in solution with time of shaking from medium and coarse textured soils.

Wahiawa, although a kaolinitic soil, had a high pH and was less leached than the Kawaihoa soil. Consistently high Si release by this soil seems to be related to soil mineralogy. Lowest Si release was from the Akaka soil and intermediate Si release was from the Kapaa soil. The Akaka soil developed from volcanic ash with high rainfall. Extremely high leaching has depleted the soil of bases and Si. The system remaining is mostly highly hydrated oxides. Extremely high leaching and the highly hydrated

oxide of this soil may have accounted for its very low Si release. A slightly higher Si release was obtained for the Kapaa soil than for the Akaka soil. The Kapaa soil developed under lower rainfall than the Akaka soil. Comparatively high soluble Si in the Kapaa soil may have been due to less leaching.

These results support the statements of Beckwith and Reeve (1964) who suggested that the primary source of soluble Si in soils is adsorbed Si on the surface of soil particles. This fraction comes into solution quickly. Secondary sources were assumed to be the disorganized silicate surfaces which release Si in solution with time and shaking. The contribution from secondary sources depends largely on the silicate minerals.

#### Sorption of Added Silicon by Soils

Silicon immobilization by soils may influence available Si. Silicon in soil solution is mostly monosilicic acid. The concentration of monosilicic acid in the liquid phase of soil suspensions is governed by adsorption equilibria (McKeague and Cline, 1963). Beckwith and Reeve (1964) state that the amount of monosilicic acid remaining in solution depends on the following: amount of Si added, soil:solution ratio, nature of soil minerals, and pH of soil suspensions. Sesquioxides are the most active constituents of soils contributing to the soil's sorption capacity.

Silicon sorption capacities of soils were determined by



equilibrating the soils with serial amounts of Si in solution added as  $\text{CaSiO}_3$ , and determining Si remaining in the supernatant solution. Silicon sorbed by the soils ranged from 10 to over 2200  $\mu\text{g Si/g soil}$  at 20 ppm Si in solution (Fig. 4, Appendix Table 28). The order of sorption by the soils was: Akaka > Wahiawa > Kapaa > Kawaihoa. Sorption seems to be associated with the noncrystalline nature and sesquioxides content of soils. Akaka soil being the most amorphous sorbed the greatest amount of Si. The next highest sorption by the Wahiawa soil may be due to its high pH. Both Kawaihoa and Kapaa soils were mostly crystalline which may partially explain low sorption by these soils. The limited sorption by these two soils is believed to be due largely to the hydrated Fe and Al oxides of the soils.

Jones and Handreck (1965) demonstrated that Al oxides were more active than Fe oxides in Si sorption. The sorptive capacities of the oxides increased with their more amorphous nature. The present data agree with their idea.

Solubility of Si in soils are known to be affected by soil pH. However, a comparison of the results presented here demonstrates that soils with almost identical pH values differ widely in Si sorption. The Wahiawa soil (pH 6.4) and Akaka soil (pH 4.7) sorbed about 5 and 15 times more Si, respectively, than the Kawaihoa soil (pH 5.5).

There is an inverse relationship between Si release and Si

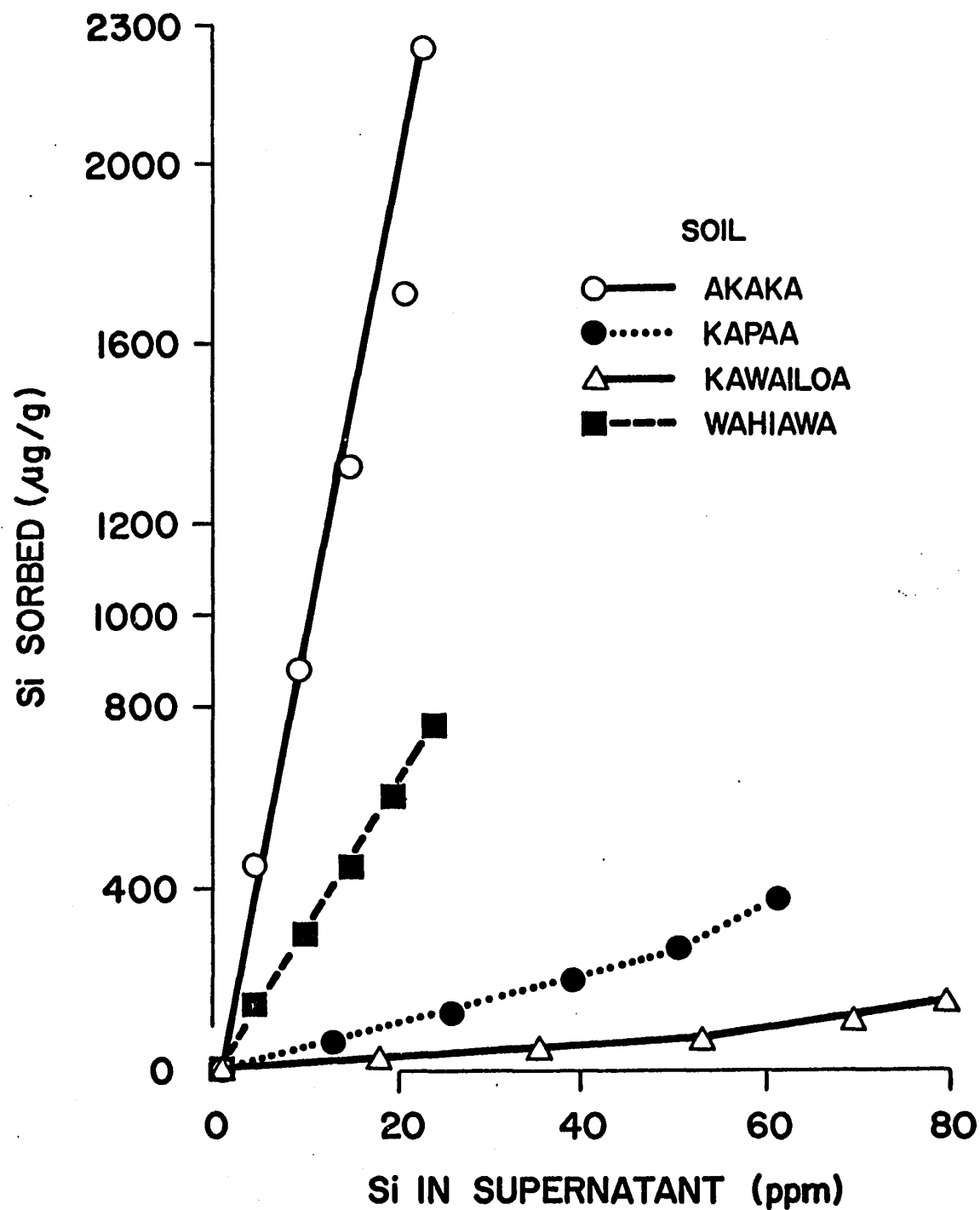


Fig. 4. Silicon Sorption by Four Hawaiian Soils.

sorption by the Akaka soil. This may be attributed to the reactivity and tremendous extent of surfaces associated with non-crystalline nature. The low sorption and high Si release by the Kawaihoa soil may be due to low specific surface available for sorption and high Si content of the soil minerals, respectively. The high pH of the Wahiawa soil may partially explain its high "sorption." This soil does not fit the pattern. The results support the idea that this soil had some ash influence (G. D. Sherman, personal communication). Crystalline gibbsite has low sorption capacity (Jones and Handreck, 1965); therefore, low sorption by the gibbsitic Kapaa soil was not surprising.

#### Effect of Acid Leaching on Silicon Sorption by Soils

The removal of Si from soil solution by the Al and Fe oxide fractions of soils has been suggested in the previous section. Evidently, the sorptive capacities of soils increase with increasing oxide content, especially if the oxides are amorphous. If sorption is due to amorphous oxides, their removal or dissolution should result in decreased Si sorption by soils. To investigate this hypothesis the soils were leached with dilute acid followed by distilled water, and adsorption isotherms were run on these treated soil samples.

Silicon sorption by the Akaka soil was reduced almost three-fold by acid treatment (Fig. 5, Appendix Table 28). The

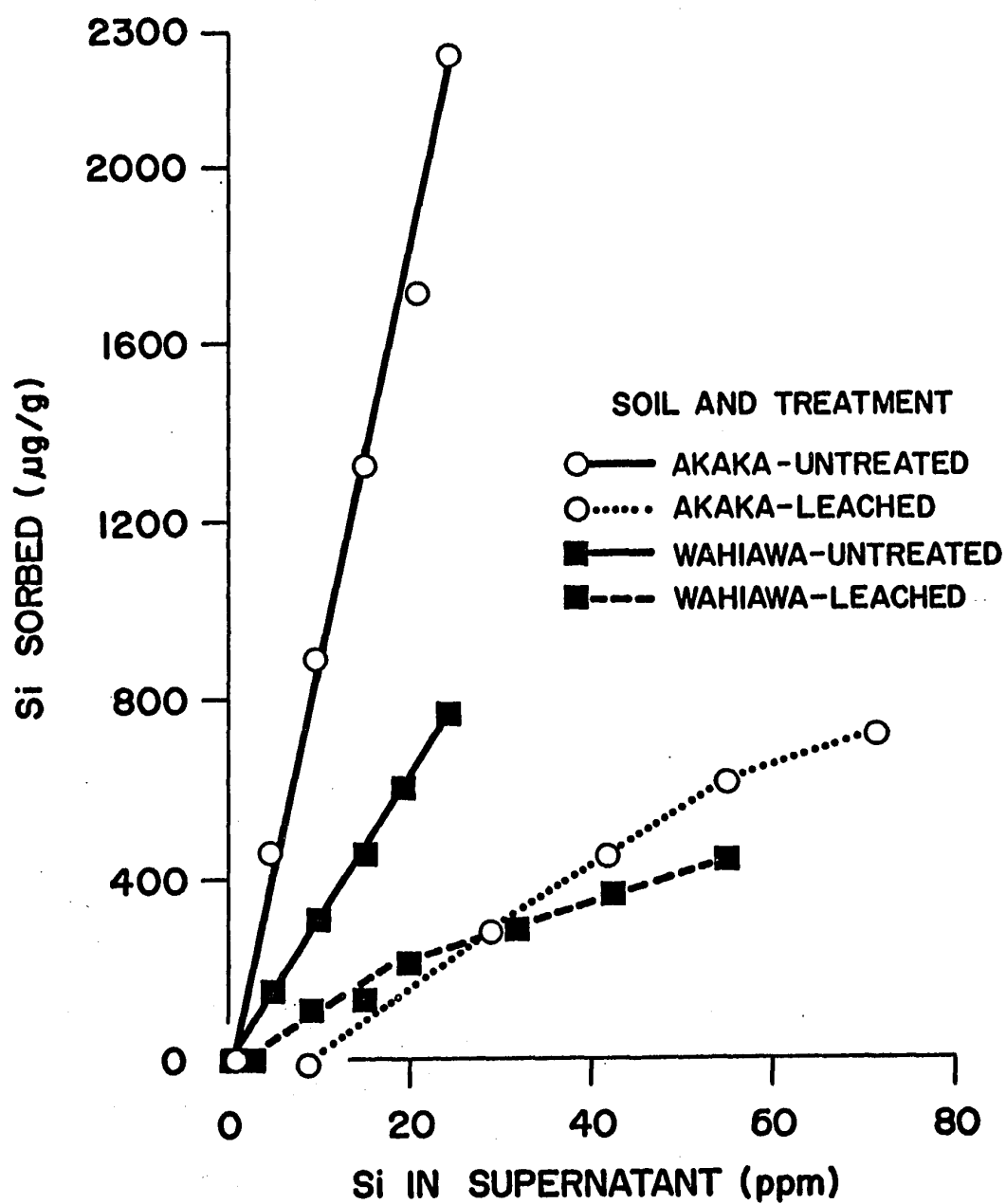


Fig. 5. Effect of Acid Leaching on the Sorption of Added Silicon by Akaka and Wahiawa Soils.

effect of acid leaching on Si sorption by the soils was: Akaka > Wahiawa > Kapaa > Kawaihoa. The sequence was identical to the sequence of Si sorption by untreated soils.

These results suggest that the extent of decrease of sorptive capacities of the soils, due to acid leaching, was related to the oxide content of the soils. The effect was more pronounced as the soil became more amorphous. Decreased sorption after acid leaching was attributed to partial dissolution and removal of amorphous Fe and Al oxides from the soils and a lowering of soil pH effected by acid leaching. Deshpande et al. (1968) effected removal of Fe and Al oxides from soils by acid treatments. The greater release of native Si by treated soils than by the untreated soils may have been due to partial dissolution and removal of oxide materials from soils. At pH values below 4 it was thought possible that a considerable amount of Si came into solution by disintegration of soil minerals. It is believed that the hydrogen-saturated kaolinite disintegrates releasing Al from the crystal lattice. During such disintegration Si may also be released. The lower the pH of the leached soil, greater was native Si in solution.

McKeague and Cline (1963) reported that  $\text{Si}(\text{OH})_4$  removal from soil solutions increased with increasing surface area of the adsorbent. Grinding goethite to finer particles increased its sorptive capacity considerably. Similar results were obtained with

bauxite, which was composed of gibbsite mainly. The results of the present investigation support the above idea.

In agreement with Jones and Handreck (1965), the results of the present investigation suggest that the most amorphous Al oxides contributed most to the sorptive capacity of soils. Even after acid leaching, the soils retained their characteristic sorption properties according to their oxide content. Only the relative values changed, the original order was retained. That the crystalline soils are less affected by acid leaching was well demonstrated with the Kawaihoa and Kapaa soils (Fig. 6, Appendix Table 28). It is certain that complete removal and dissolution of oxides was not effected by leaching. The data also are in keeping with the idea that removal of Si from soil solutions is a pH dependent adsorption process and that most of the adsorptive power is being contributed by the Al oxides in the soil.

#### Effect of pH on the Release of Native Silicon from Soils

Silicon in soil solution is a function of pH. This aspect of Si solubility was studied by equilibrating soils in the presence of HCl or  $\text{Ca}(\text{OH})_2$ , to give different pH values.

Silicon concentrations in soil solutions increased as the pH of the soil suspensions decreased (Fig. 7, Appendix Table 29). Silicon solubility increased rapidly with decreasing pH below pH 4. Solubility was always low near pH 7. The pH variable was

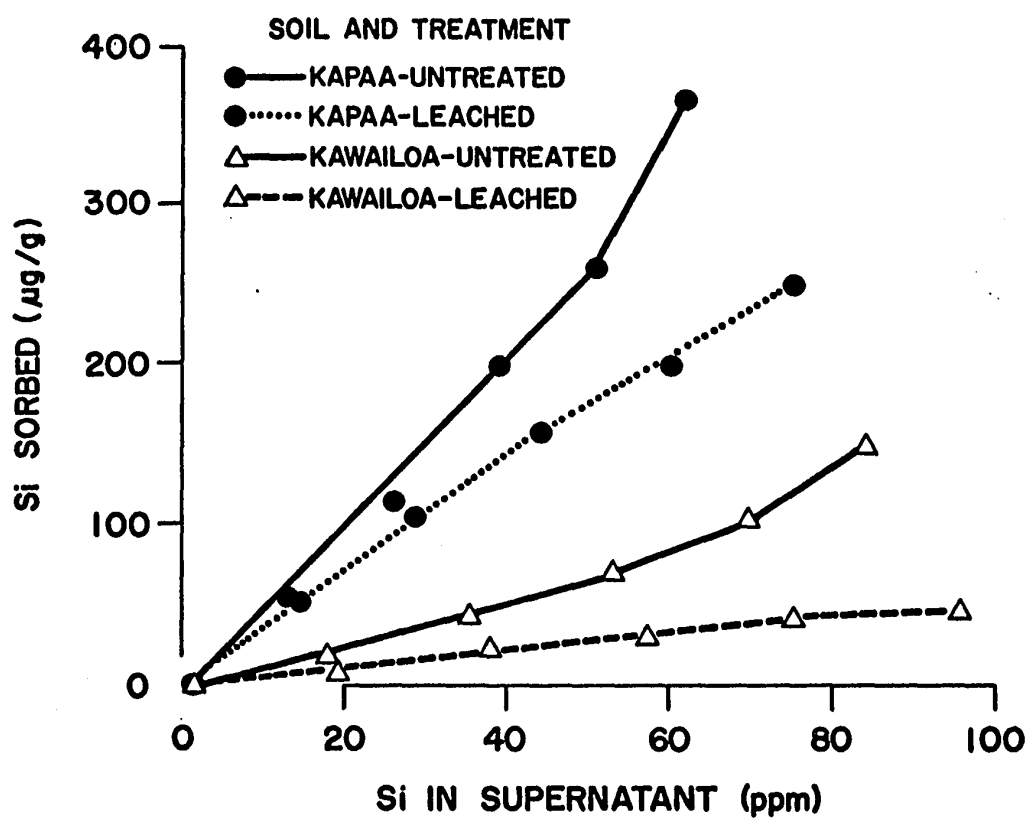


Fig. 6. Effect of Acid Leaching on the Sorption of Added Silicon by Kapaa and Kawaihoa Soils.

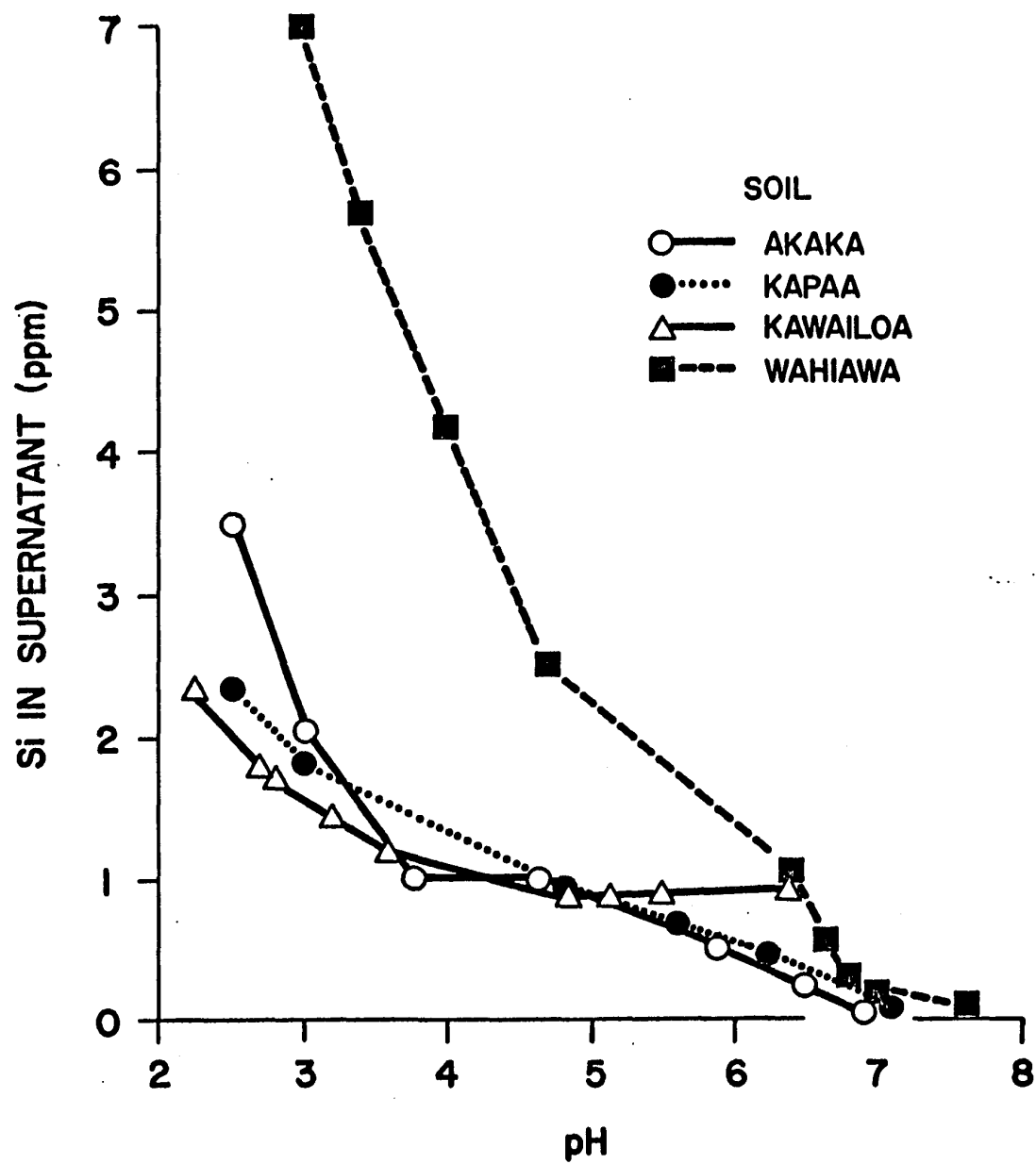


Fig. 7. Effect of pH on the Solubility of Native Silicon in Four Hawaiian Soils.



observed most in the Wahiawa soil. Drastically increased Si solubility with decreasing pH in this soil was probably caused by unstability of the crystal lattice. Beckwith and Reeve (1964) stated that, under acid conditions, particularly below pH 4, a considerable amount of native Si may dissolve. The low concentrations of native Si at high pH values are consistent with results of Woodruff (1954) and Raupach (1957).

Low pH was associated with smaller release of Si by the Kawaihoa soil than by the Wahiawa soil. The aluminosilicate gel coatings presumed on the surfaces of the clay crystals in this soil may explain its low Si release. It was shown earlier that solubility of native Si in this soil increased gradually with time of shaking. Perhaps the pH effect on the solubility of Si in this soil would be increased by increasing the shaking time. Relatively high Si release at low pH values by the Akaka soil may be explained in terms of high solubility of amorphous oxides and release of sorbed Si in solution.

#### Effect of pH on Silicon Sorption by Soils

"Sorptions" of added Si as a function of pH was studied by equilibrating soils with a 50 ppm Si solution in the presence of graded amounts of HCl or  $\text{Ca}(\text{OH})_2$ . Immobilization of added Si increased with increasing pH (Figs. 8 and 9, Appendix Table 30) in these soils. The pH had its greatest effect on the Akaka

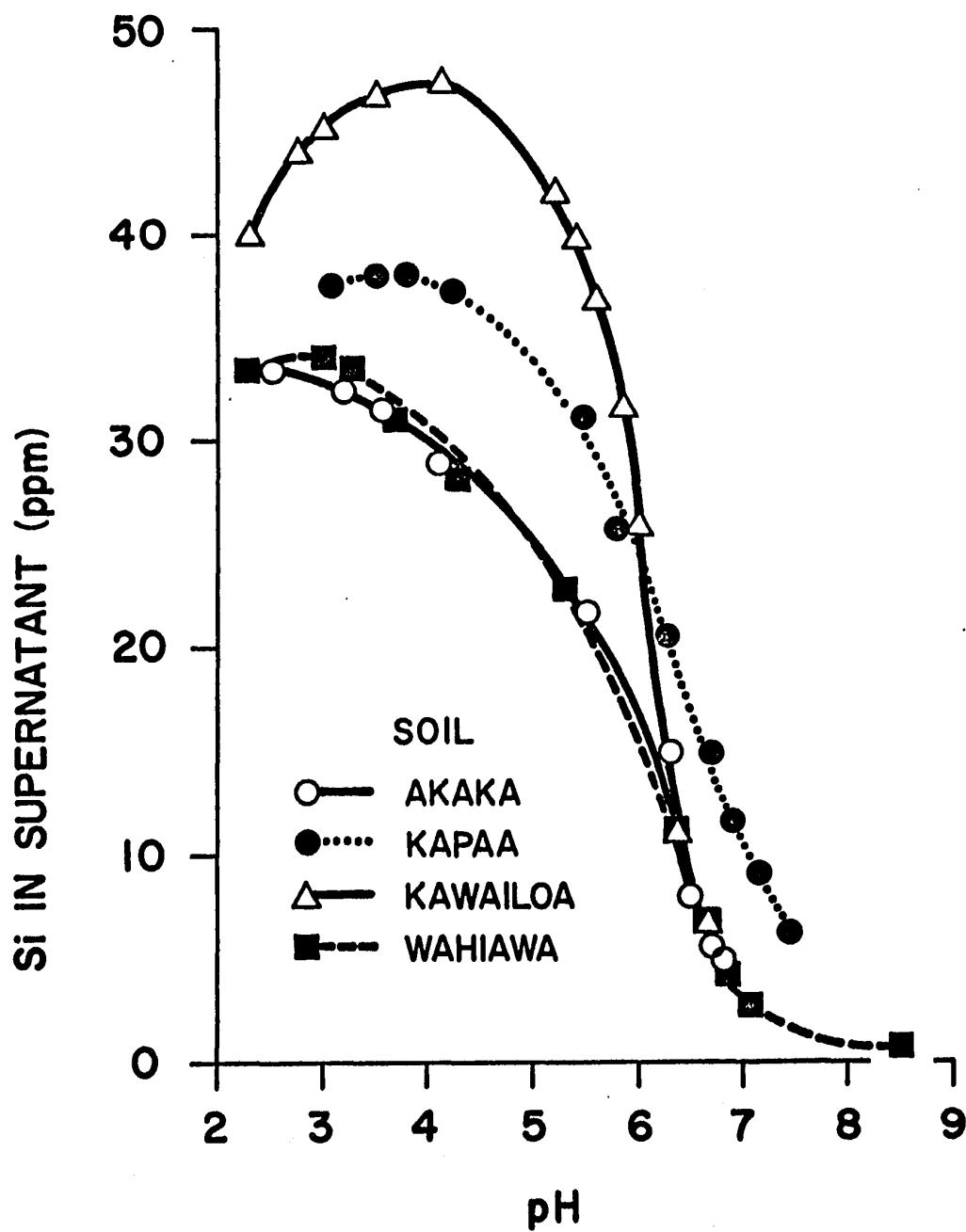


Fig. 8. Effect of pH on the Solubility of Added Silicon in Four Hawaiian Soils.

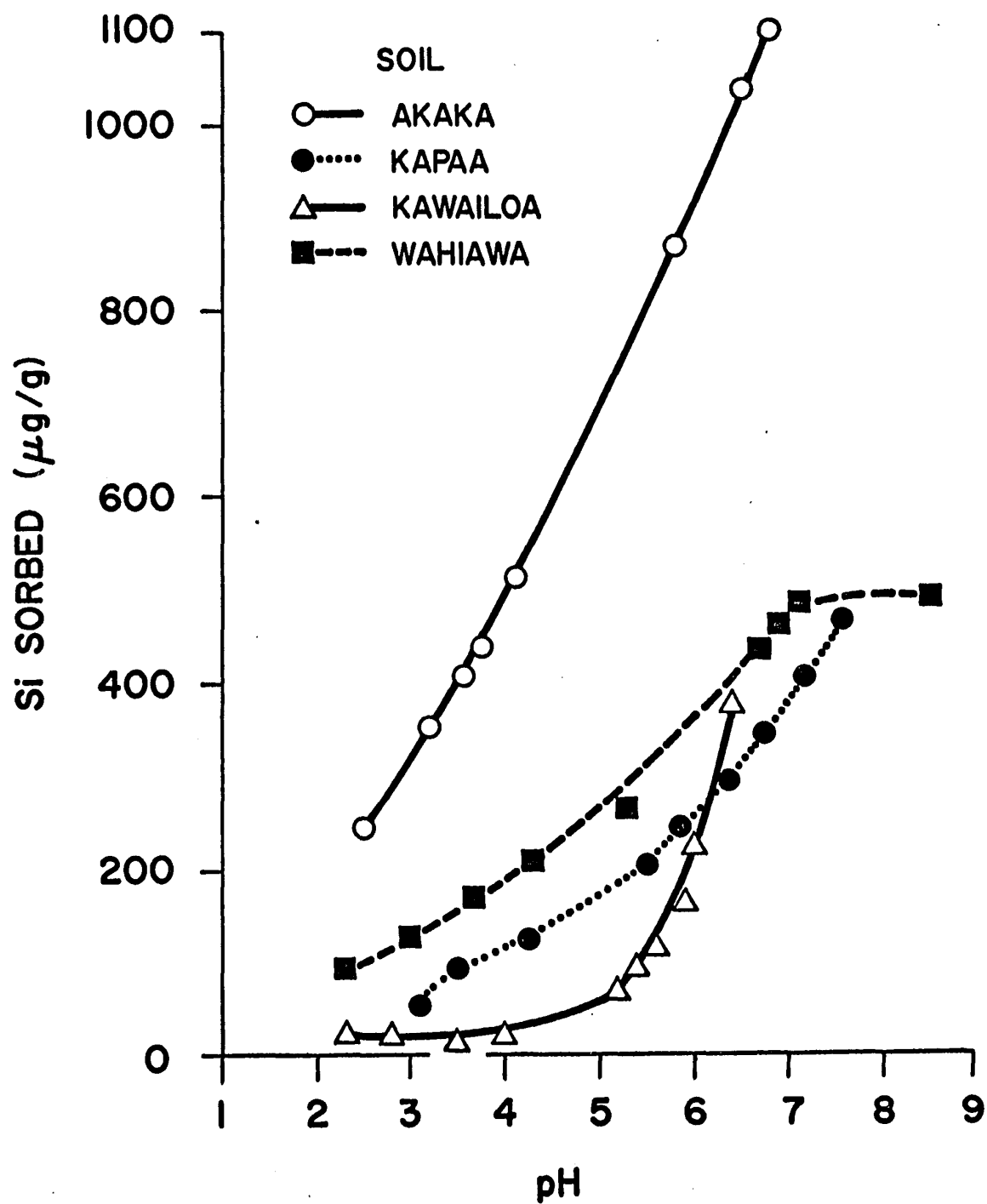


Fig. 9. Effect of pH on the "Sorption" of Added Silicon by Four Hawaiian Soils.

soil and least on the Kawaihoa soil. As soil pH changed the soils retained their order of sorption; only the magnitude of sorption varied. At a pH value of 8.5, the Si sorption curve for the Wahiawa soil leveled off. The pH of the other soils did not exceed 7.5. In that range the soils continued to sorb increasing amounts of Si with increasing pH. No explanation was found for the decreased solubility of added Si in the Kawaihoa soil below pH 4. In agreement with McKeague and Cline (1963), solubility of Si in soils was taken to be the function of pH-dependent "adsorption". However, an important part was played by soil mineralogy and texture.

#### Effect of Neutral Salt Concentrations on Silicon Solubility in Soils

Effects of a neutral salt concentration on solubility of Si in soils were studied by equilibrating soil-water mixtures in the presence of serial concentrations of  $\text{CaCl}_2$  and determining Si in the supernatant solution. Concentrations of  $\text{CaCl}_2$  had little effect on the solubility of native and applied Si in soils (Table 1). McKeague and Cline (1963) also found little effect of salts on Si solubility in soils, except where salts changed pH.

#### Phosphorus Sorption and Native Silicon Release by Soils

Phosphorus Sorption: Phosphorus sorption by soils was determined by equilibrating soils with serial rates of P added as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  in 0.01 M  $\text{CaCl}_2$  and determining P remaining

Table 1. Effect of Calcium Chloride Concentrations on the Solubility of Silicon in Soils<sup>1/</sup>

CaCl <sub>2</sub> Concentration (mM)	Soil							
	Akaka		Kapaa		Kawailoa		Wahiawa	
	Solution pH	Si in Solution (ppm)	Solution pH	Si in Solution (ppm)	Solution pH	Si in Solution (ppm)	Solution pH	Si in Solution (ppm)
<u>No Si Added</u>								
0	5.0	0.75	5.2	0.87	5.5	0.91	6.3	1.15
1	4.8	0.77	4.5	0.92	4.0	0.93	6.0	1.22
2	4.7	0.75	4.5	0.90	3.9	0.91	5.8	1.17
3	4.6	0.77	4.4	0.90	3.8	0.90	5.8	1.18
4	4.6	0.76	4.4	0.89	3.8	0.83	5.8	1.18
5	4.6	0.76	4.4	0.89	3.8	0.84	5.8	1.19
10	4.6	0.74	4.3	0.86	3.7	0.83	5.7	1.18
<u>500 µg/g Si added</u>								
0	5.5	23.2	5.5	29.5	5.7	43.6	6.5	13.5
1	5.2	23.1	5.1	29.2	4.4	44.8	6.2	13.3
2	5.1	23.7	5.0	30.6	4.2	44.4	6.1	13.3
3	5.1	23.0	5.0	30.1	4.1	43.8	6.0	13.2
4	5.1	23.1	5.0	31.5	4.1	42.8	6.0	13.3
5	5.0	23.0	5.0	31.3	4.0	42.3	6.0	13.1
10	5.0	22.0	4.6	32.0	3.9	42.0	6.0	12.8

<sup>1/</sup> Values are ppm Si in a 1:10 soil extract.

in solution. The experiment was done in two sets--one equilibrated for 24 hours and the other for 6 days.

The soils varied widely in their sorption capacities (Figs. 10 and 11, Appendix Table 31). The order of sorption was: Akaka > Kapaa > Wahiawa > Kawaihoa. Fox et al. (1968) reported similar results. He used 0.2 ppm P in the supernatant solution as standard value for estimating phosphate requirements of Hawaiian Latosols. Concentrations of this magnitude are adequate for normal P nutrition for several plant species growing in nutrient solutions (Andrew, 1962).

Phosphorus requirements of the soils were between 120 and 1000 ppm P, at 0.2 ppm P in the supernatant solution, when 24 hours equilibration was used. The values for 6 days equilibration were from 240 to 1400 ppm P. Although equilibrium was not attained in 24 hours, these data are useful for comparative studies. The order of sorption was not changed by increasing equilibration time; only the absolute values decreased. Least sorption was by the most crystalline Kawaihoa soil with a kaolin type of clay minerals. Almost six times more P was sorbed by the Akaka soil than by the Kawaihoa soil. High sorption by the Akaka soil may be attributed to high specific surface area and very reactive hydrated Fe and Al oxides. The Kawaihoa and Wahiawa soils were mostly kaolinitic with considerable amounts of Fe and Al oxides. Comparatively greater sorption by the

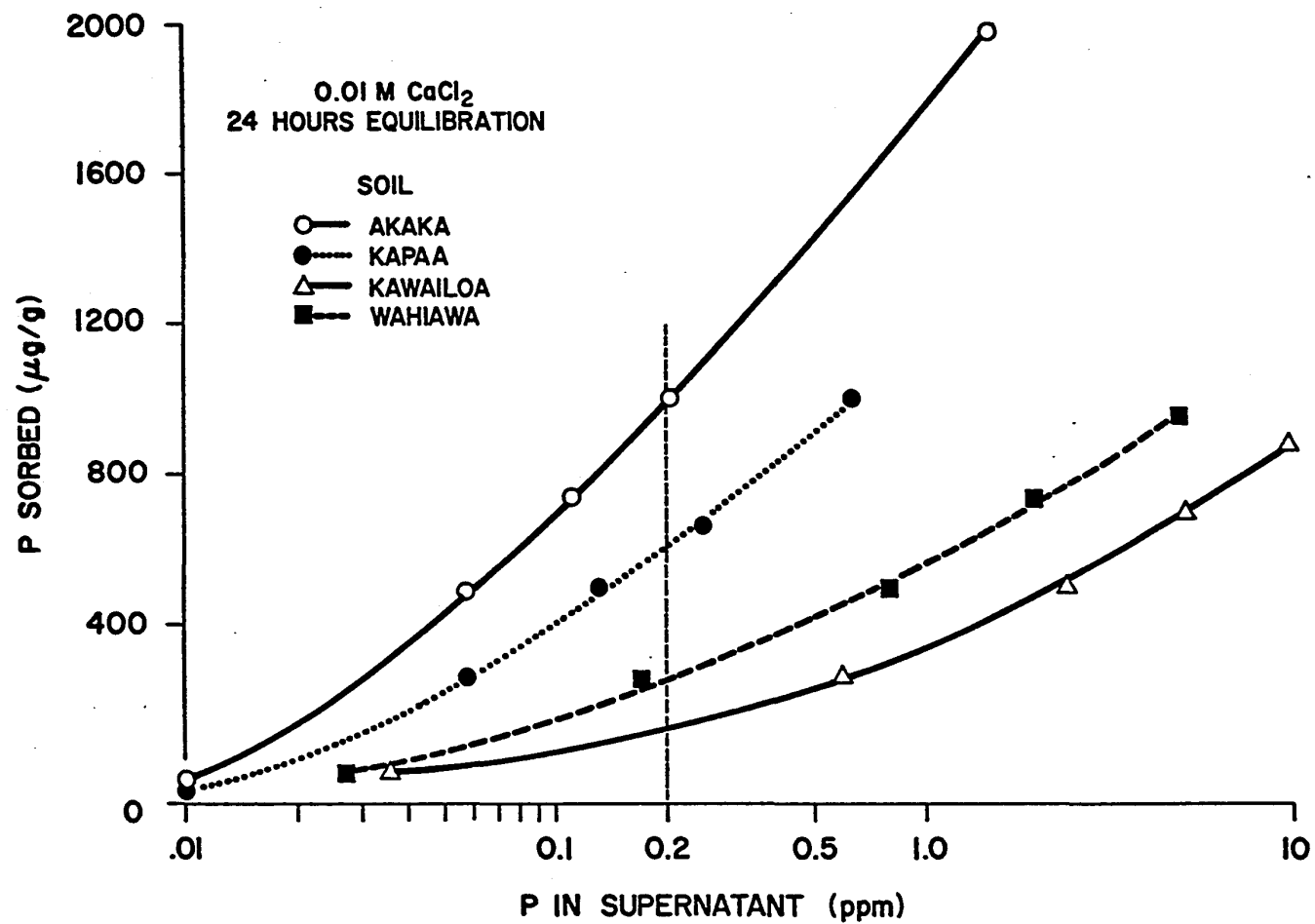


Fig. 10. Phosphorus Sorption by Four Hawaiian Soils  
(24 Hours Equilibration).

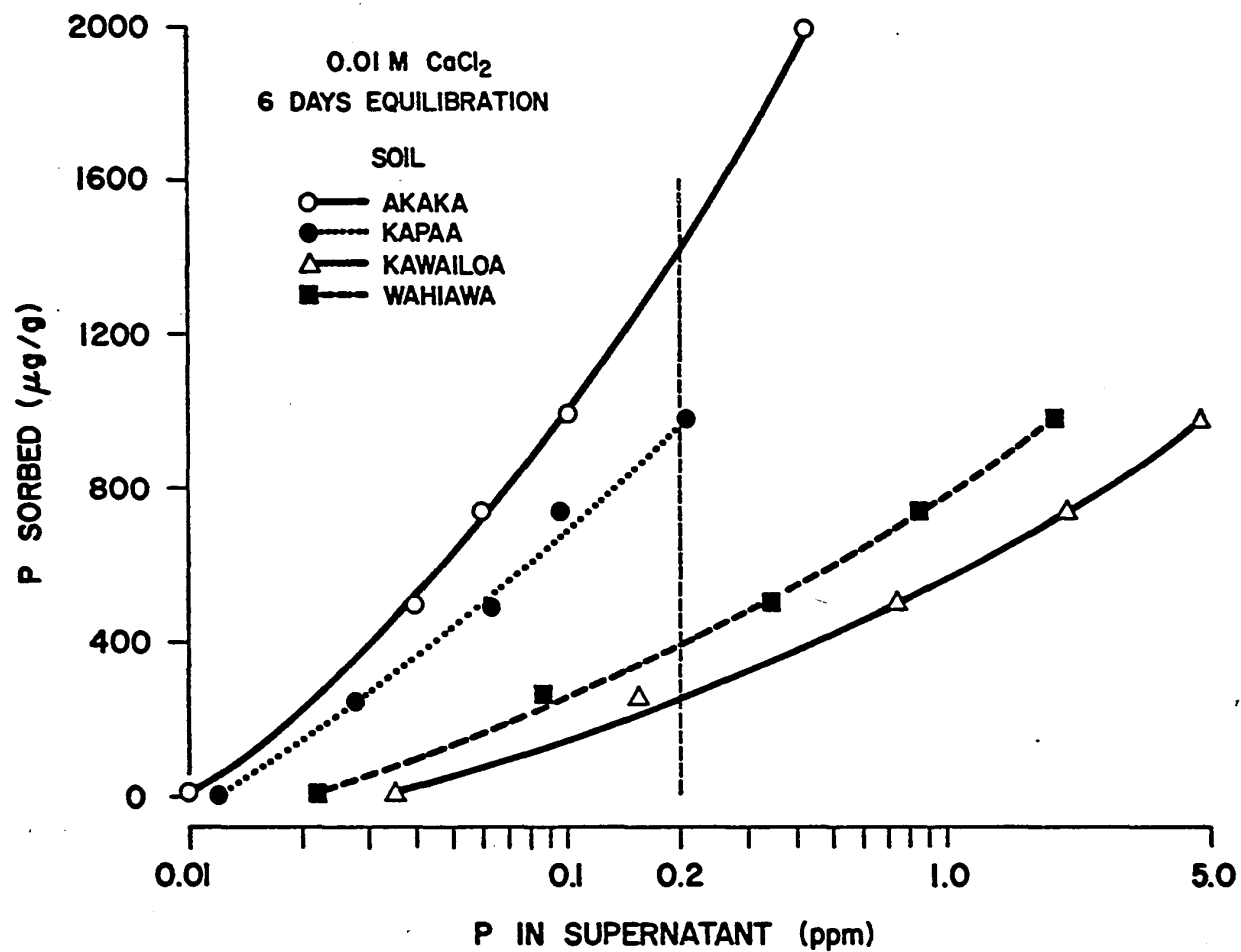


Fig. 11. Phosphorus Sorption by Four Hawaiian Soils  
(6 Days Equilibration).



Wahiawa soil than by the Kawaihoa soil may have been due to some ash influence in the former and hydrated Fe or high organic matter coatings on the latter. Greater P sorption by the Kapaa soil than by the Wahiawa soil was attributed to its high gibbsite content.

Silicon Release: Several opinions exist as to the nature of phosphorus-silicon interactions in soils. Evidence with regard to the displacement of silicate by phosphate ions was presented by Mattson (1931), Low and Black (1947) and others. The exact nature of this displacement is still obscure.

The effect of P sorption on the solubility of native Si was studied by equilibrating soils with serial rates of P added as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  in 0.01 M  $\text{CaCl}_2$ . Silicon was determined in the supernatant solution. Native Si release from soils increased with increasing amounts of P sorption (Figs. 12 and 13, Appendix Table 31). Silicon release as P sorbed was in the following order: Wahiawa > Kapaa > Akaka. The Kawaihoa soil changed little as P was sorbed. The greatest Si release was from the kaolinitic Wahiawa soil and the least from the non-crystalline Akaka soil. When P was adsorbed, the bauxitic Kapaa soil released more Si than the non-crystalline Akaka soil. The relatively great effect of P on Si release by the Wahiawa soil may be explained in terms of partial dissolution and release of Al and Si from the kaolin crystals during P sorption. These results

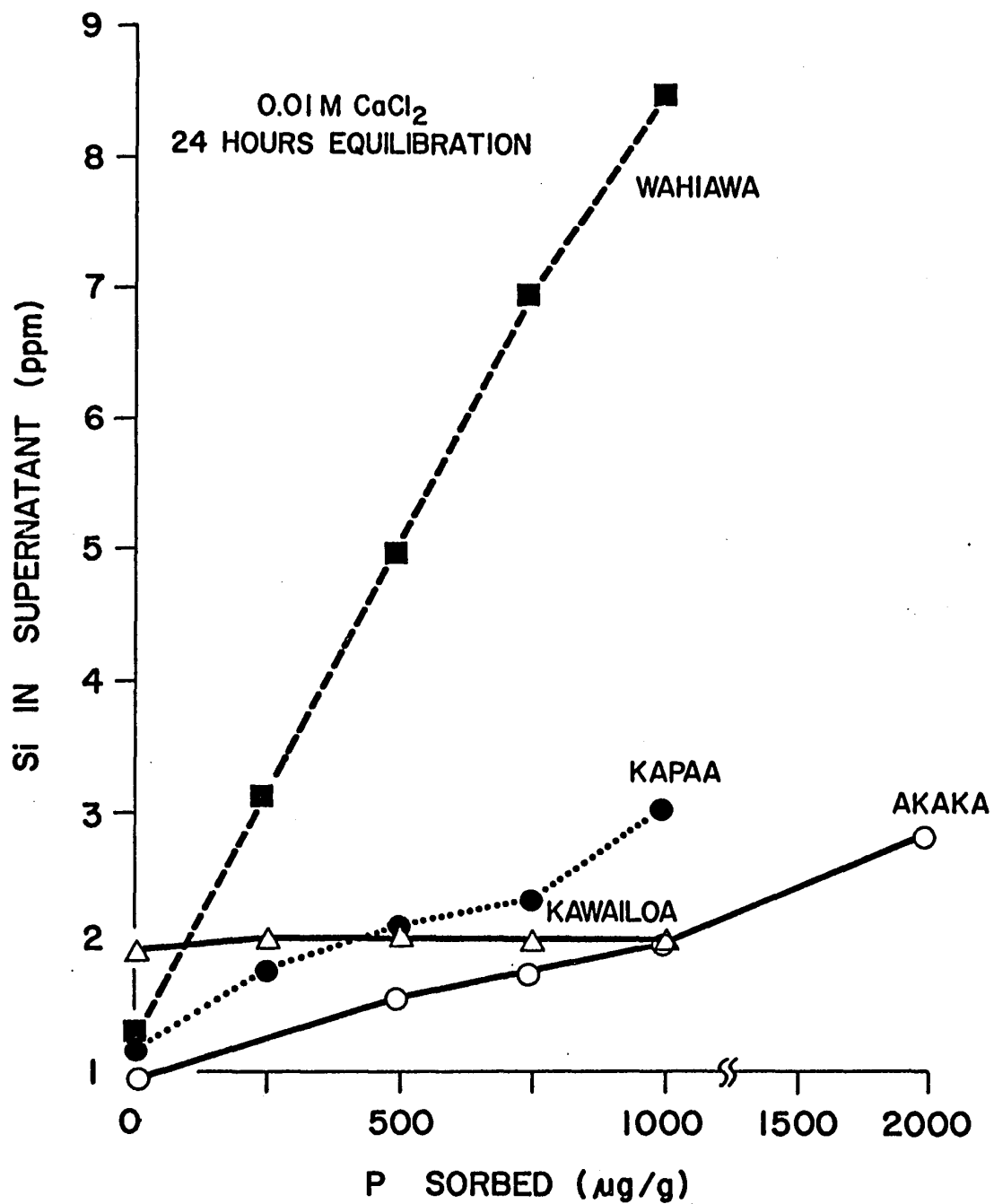


Fig. 12. Effect of Phosphorus Sorption on Native Silicon Release by Four Hawaiian Soils (24 Hours Equilibration).

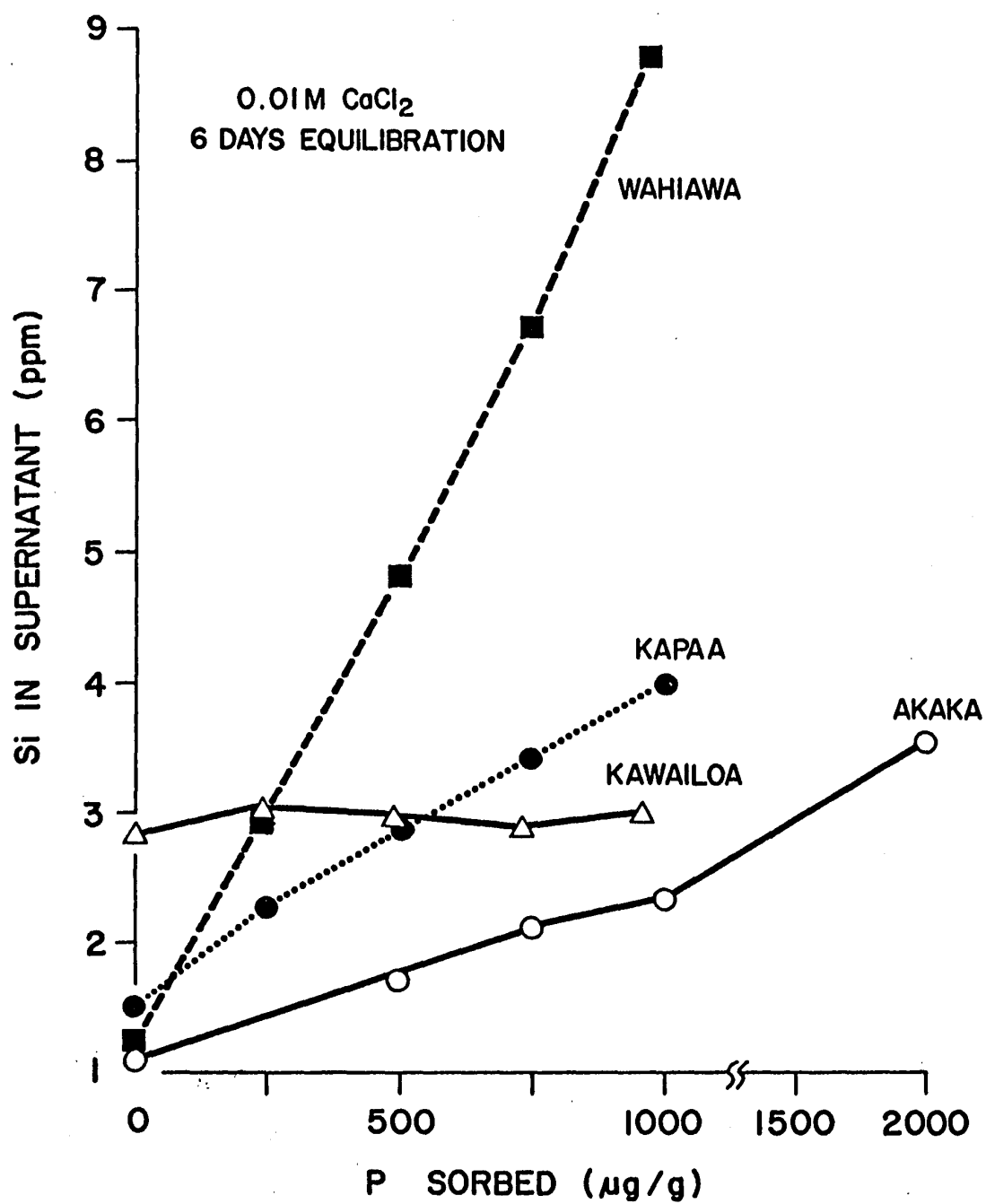


Fig. 13. Effect of Phosphorus Sorption on Native Silicon Release by Four Hawaiian Soils (6 Days Equilibration).

conform with the statement of previous workers that phosphate induces decomposition of kaolinite (Mattson, 1931; Low and Black, 1947; Reifenberg and Buckwold, 1954).

The Kawaihoa soil, although kaolinitic, is presumed to be coated with Fe and aluminosilicate gels. It may be possible that most P sorption by this soil was on the gel coatings. As a result there was very little contact between lattice Si and sorbed P. Silicon release by this soil was thought to be contributed mostly by the sorbed Si on the gel coatings. Adsorption of P on the coatings prevented any further dissolution of lattice Si.

Release of native Si due to P sorption was very little affected by increasing the equilibration time. It can be seen by comparing Figures 12 and 13 that by increasing the equilibration period from 24 hours to six days a proportionate increase in Si release was not obtained. However, the concentration of Si in soil solutions increased by about one ppm in all soils. These results suggest that during the initial stage while P sorption was high a considerable amount of Si was released by exchange with phosphate. Additional immobilization of P may be mostly precipitation reactions and have little effect on the structure of soil minerals.

#### Phosphorus-Silicon Interaction in Soils

The availability to plants of P and Si, both applied and native, is influenced by their concentrations in soil solutions.

In most cases found in the literature, responses to silicate have been attributed to increased availability of P to plants. However, the nature of P-Si interactions in soils has not been investigated in detail.

Soils were equilibrated with graded amounts of P and Si added simultaneously as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  and  $\text{CaSiO}_3$ . Phosphorus and Si remaining in solution were determined. Desorption was effected by equilibrating samples with distilled water and determining P and Si in the equilibrium solution.

Silicon decreased P sorption and P decreased Si sorption by soils (Figs. 14 to 21, Appendix Table 32). The effect of P on Si sorption was greatest. In general P sorption decreased with increasing rates of Si application, but the Akaka soil was an exception in that only the first increment of Si decreased P sorption a little.

In relative terms, applied Si decreased P sorption in the following order: Kawaihoa > Wahiawa > Kapaa > Akaka. This sequence is the same as that for concentration of P remaining in solution when P was equilibrated with the soils. The effect of Si on P sorption was greatest at high P levels. Phosphorus sorption at 0.2 ppm P in the supernatant solution was decreased by 47, 39, 24, and 9 percent by Si application in the Kawaihoa, Wahiawa, Kapaa and Akaka soils, respectively. Ikawa (1956) treated soils with sodium silicate for one week and then

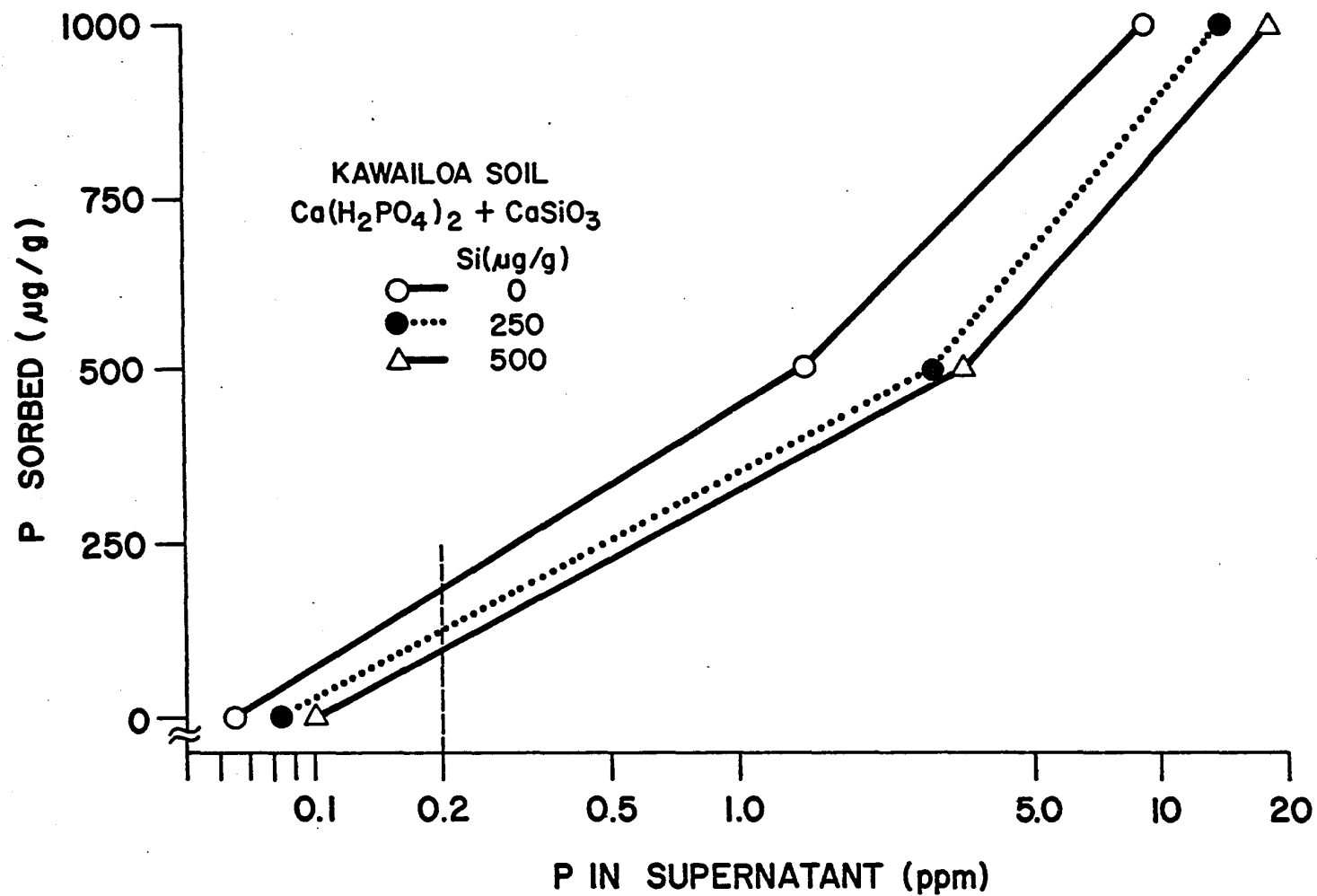


Fig. 14. Effect of Added Silicate on Phosphorus Sorption by Kawaihoa Soil.

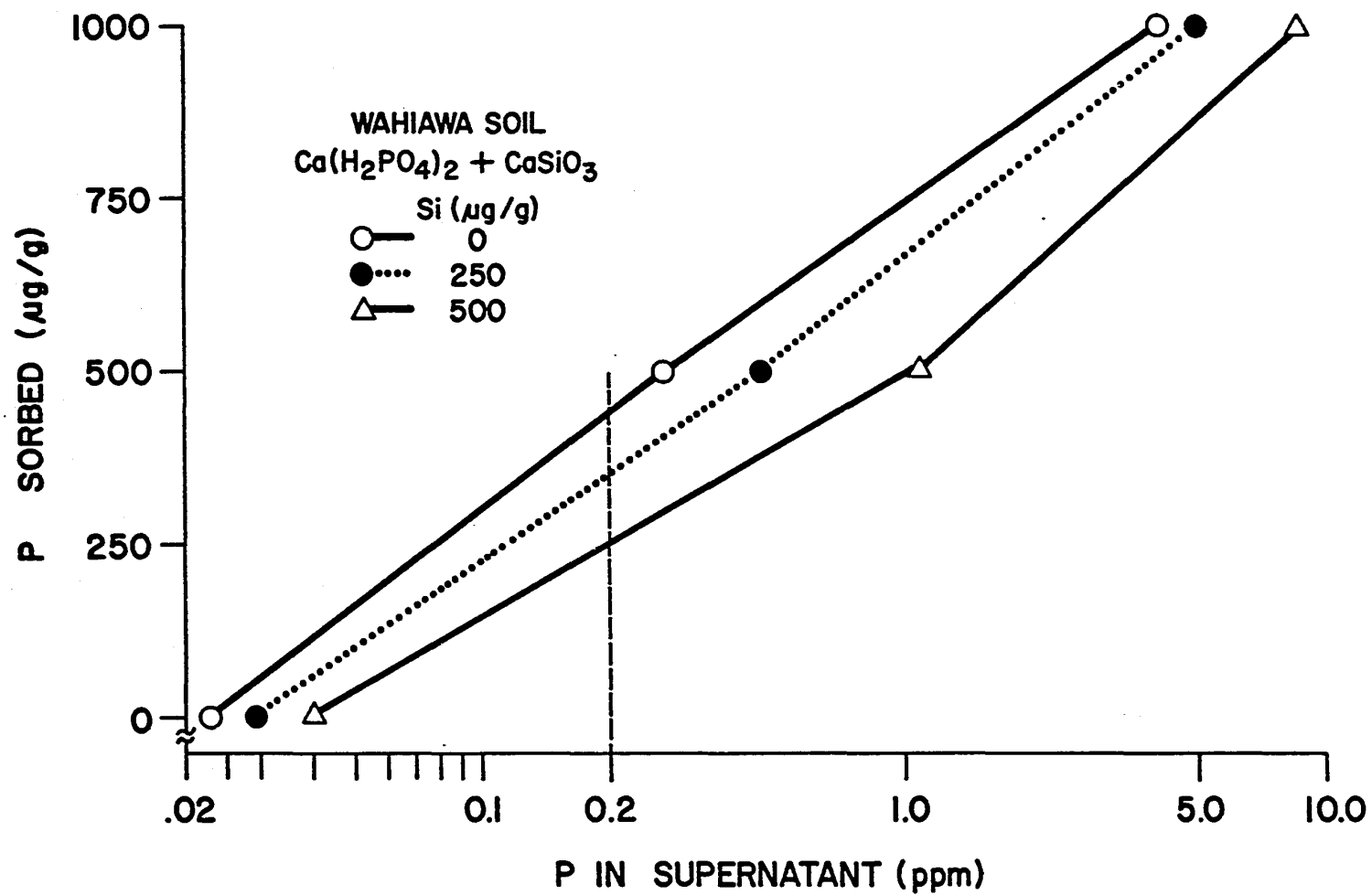


Fig. 15. Effect of Added Silicate on Phosphorus Sorption by Wahiawa Soil.

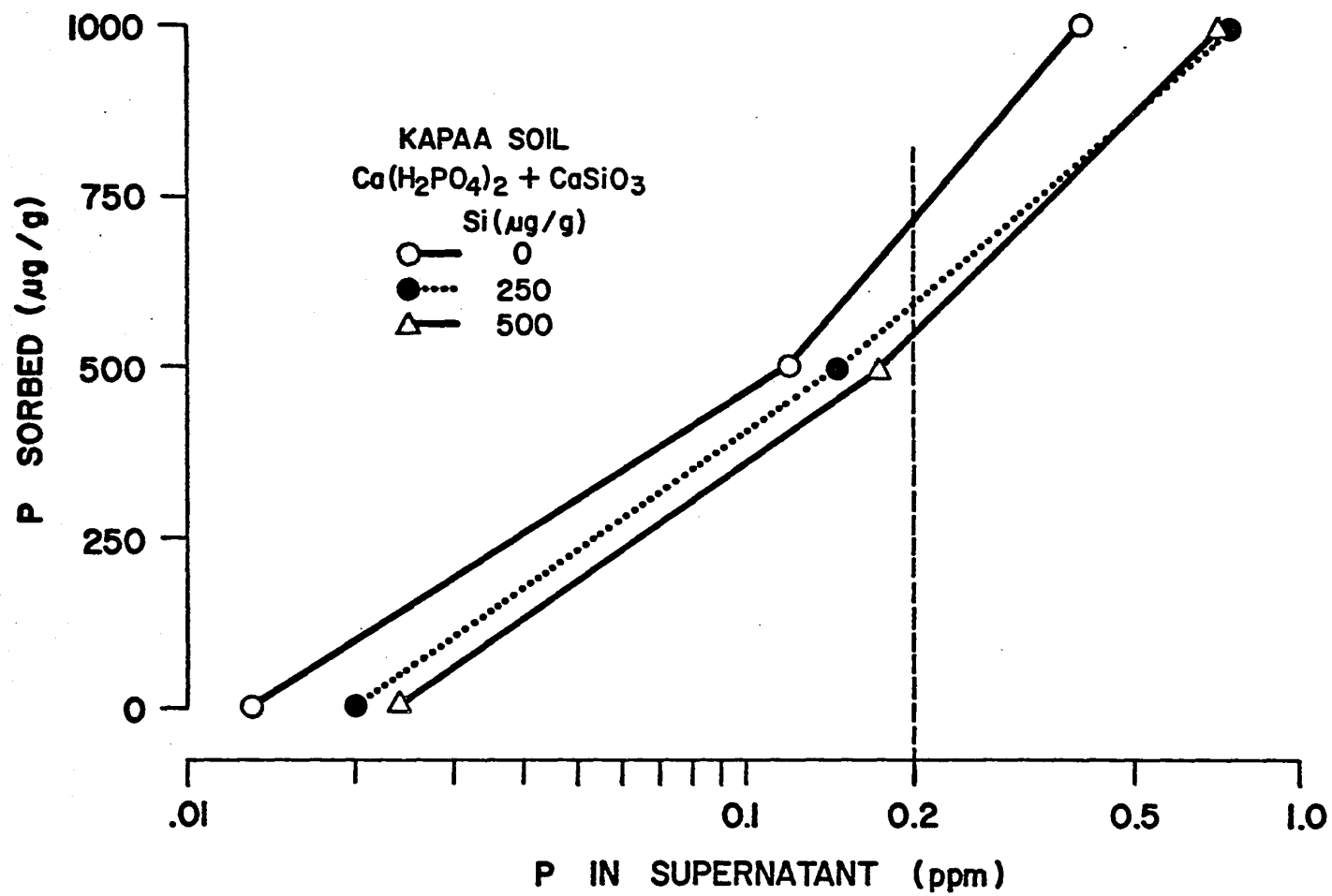


Fig. 16. Effect of Added Silicate on Phosphorus Sorption by Kapaa Soil.



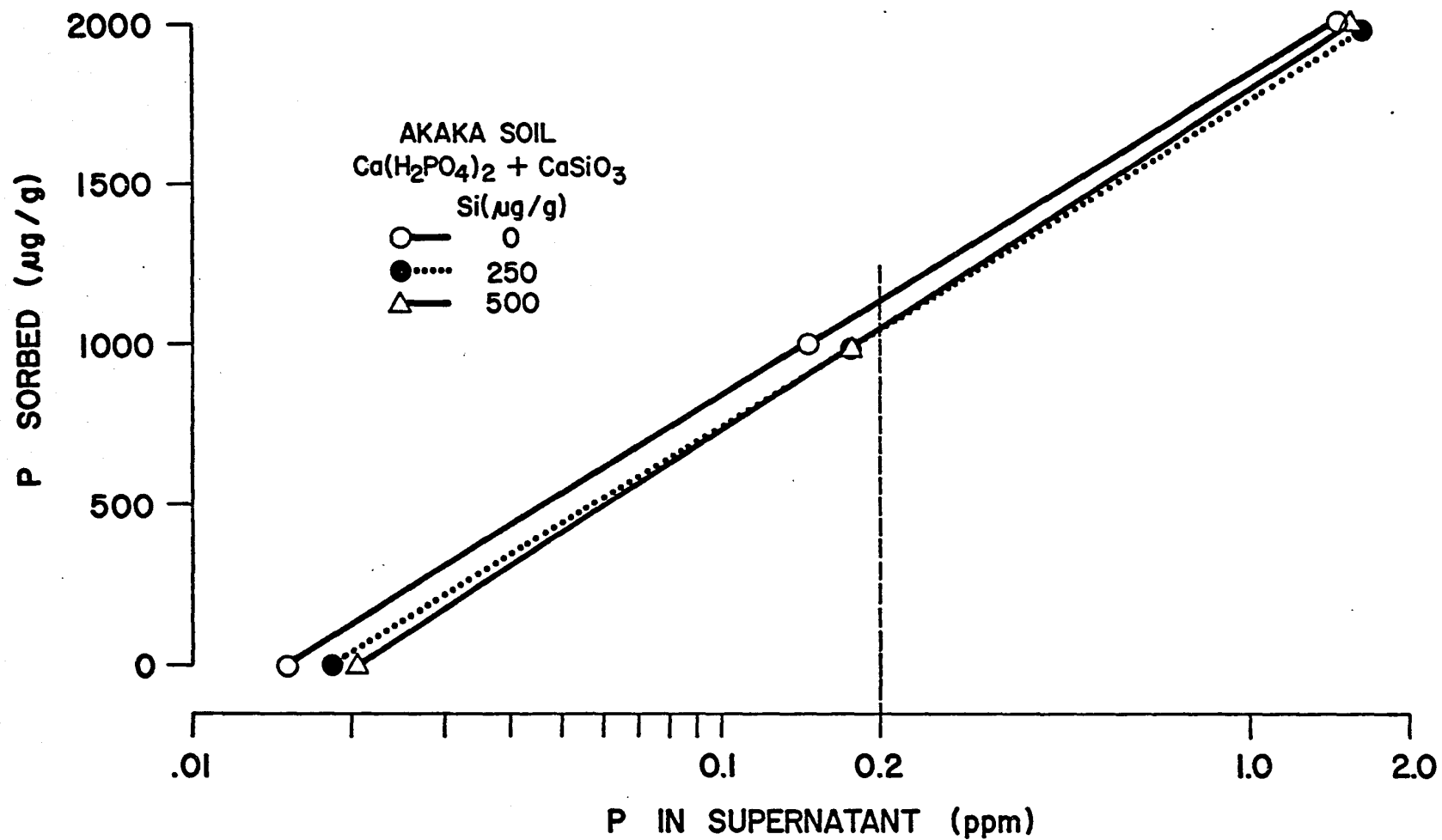


Fig. 17. Effect of Added Silicate on Phosphorus Sorption by Akaka Soil.

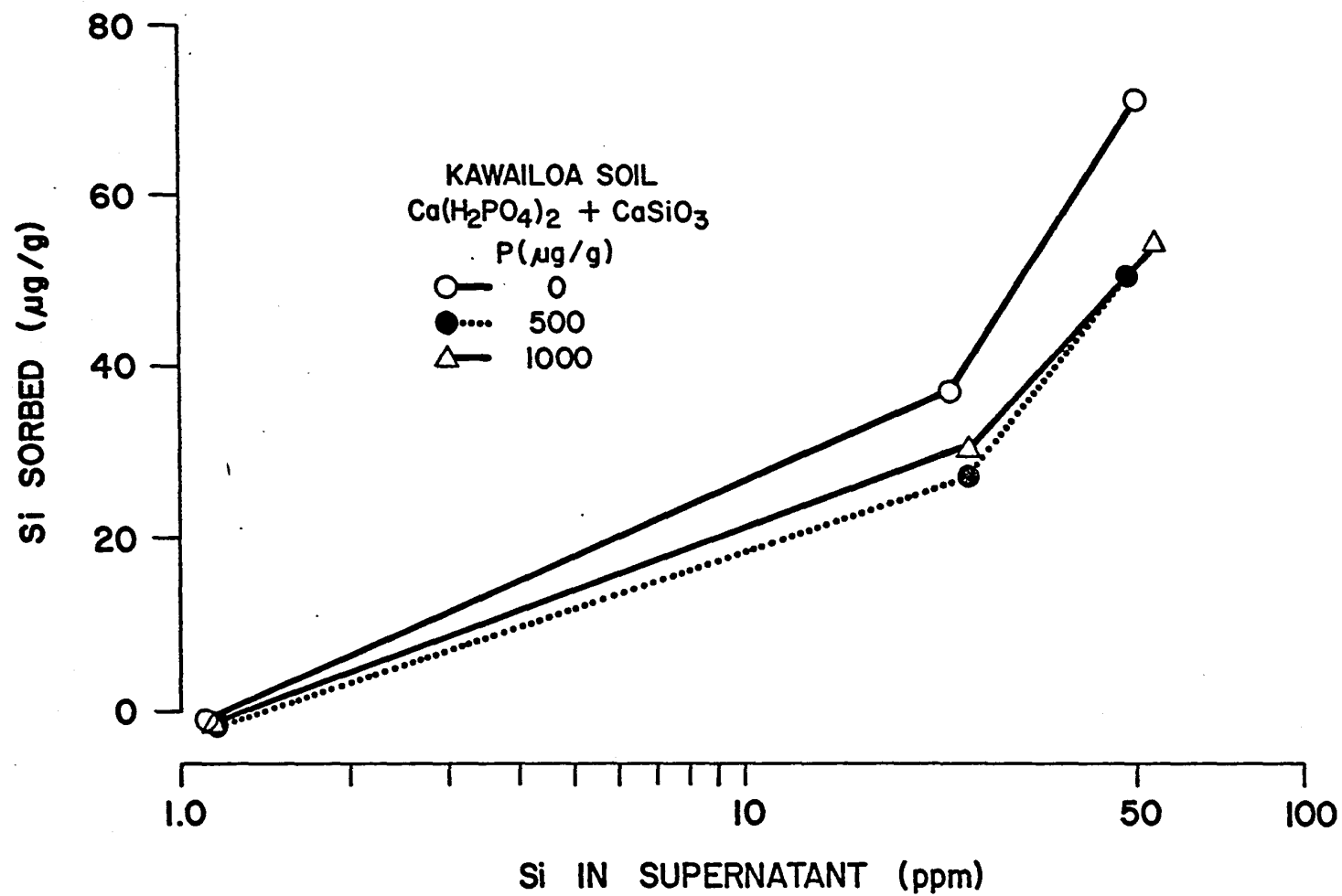


Fig. 18. Effect of Added Phosphorus on Silicon Sorption by Kawaihoa Soil.

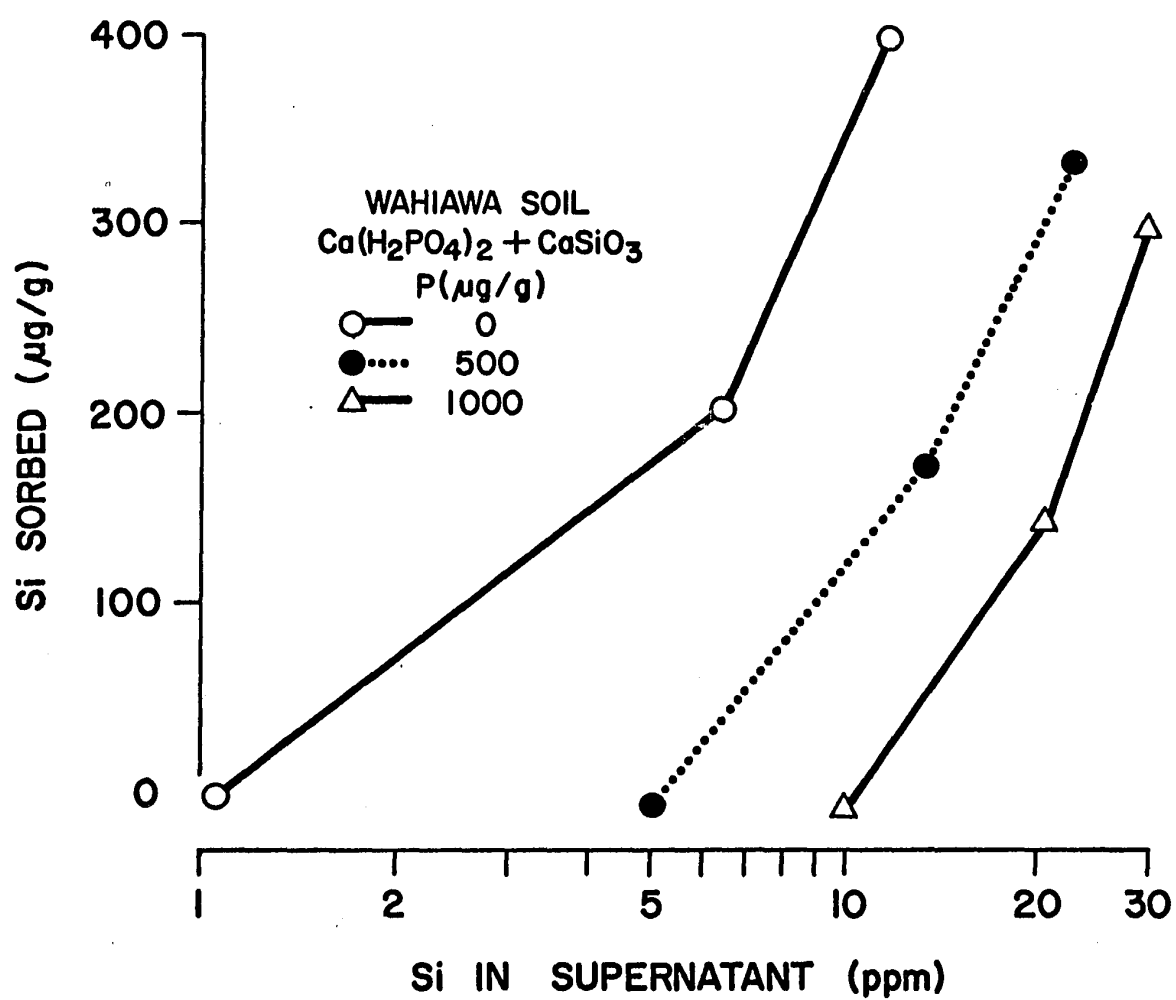


Fig. 19. Effect of Added Phosphorus on Silicon Sorption by Wahiawa Soil.

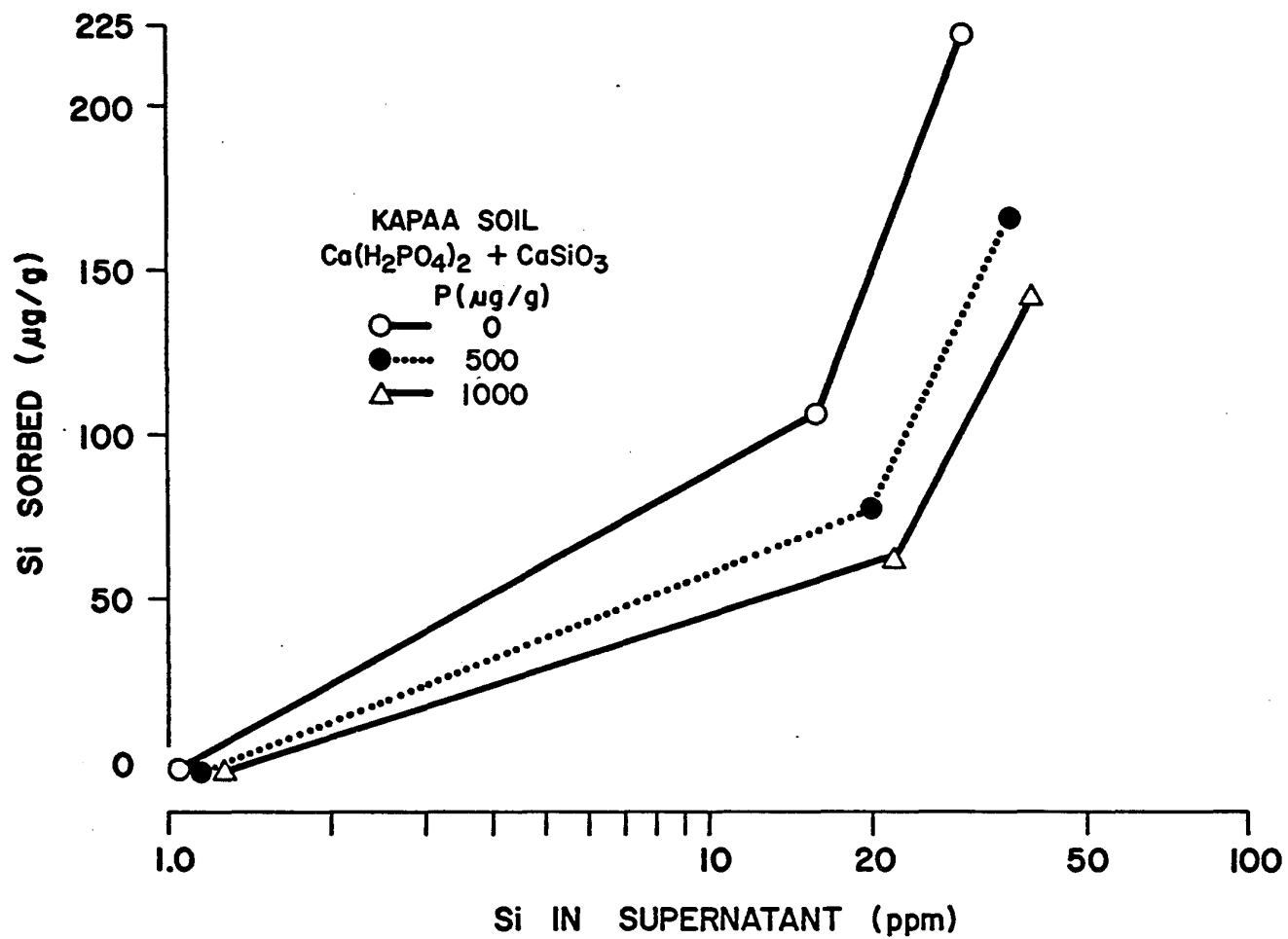


Fig. 20. Effect of Added Phosphorus on Silicon Sorption by Kapaa Soil.

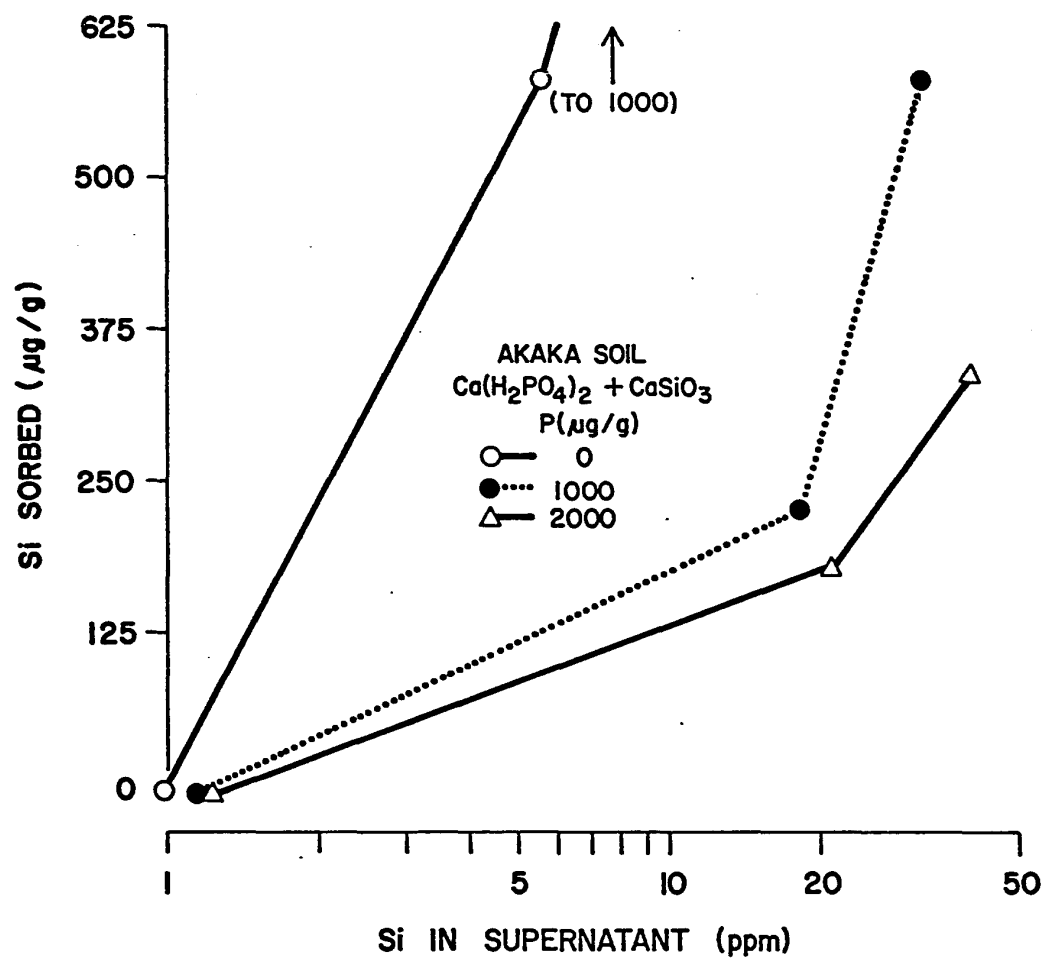


Fig. 21. Effect of Added Phosphorus on Silicon Sorption by Akaka Soil.

equilibrated with P. The silicate treatment decreased P fixation and increased acid extractable soil P.

Silicon sorption decreased with increasing rates of P application. The effect was most pronounced at high Si levels.

Silicon sorption was most affected in soils which sorbed much P. Silicon sorption by soils as a result of P application decreased in the order: Akaka > Wahiawa > Kapaa > Kawaihoa, which was also the sequence of Si sorption. The sorption curves for the Akaka soil diverge, while for the Wahiawa soil they converge with increasing Si. The Si sorption isotherms for the Wahiawa soil are shifted to the right, possibly as a result of release of native Si from the soil during P sorption.

Although the sorption mechanism is not known, these results suggest that either the sorption sites for P and Si are similar, if not the same, or it may be an immobilization of active Fe and Al in soils in the presence of P and/or Si. This is indicated by the decreased sorption of one element in the presence of the other. The greater influence of P on Si sorption than of Si on P sorption by soils is an indication of greater affinity of the sorption site for P. Sorption, therefore, seems to be influenced by valence-bond and concentrations of the adsorbates in soil solutions. The present investigation indicates that P availability in soils may be increased by silicate applications. Raupach and Piper (1959) obtained temporarily increased availability of P in lateritic soils by

silicate applications.

The relatively great effect of Si on P sorption in the Kawaihoa soil was associated with low P sorption capacity and high Si solubility in this soil. Concentration of Si in soil solutions is an important factor in decreasing P sorption by soils. Phosphorus sorption was affected relatively little by Si in the Akaka soil. Although sorption was decreased 100 ppm P by an application of 250  $\mu\text{g}$  Si/g soil, the initial sorption by this soil was very high (1150  $\mu\text{g}$  P/g soil at 0.2 ppm P in solution). This small effect may be explained in view of both high P and high Si sorption by the soil.

The Kapaa, Wahiawa and Kawaihoa soils sorbed 725, 425 and 187  $\mu\text{g}$  P/g soil, respectively, when no Si was added. Sorption was decreased 175  $\mu\text{g}$  P/g soil by Si application to the Kapaa and Wahiawa soils and 87  $\mu\text{g}$  P/g soil for the Kawaihoa soil. Percentage decrease in sorption was lower for the first two soils.

The effect of P on Si sorption is mostly associated with the P sorption capacity of soils. The greatest effect was observed in the Akaka soil and the least in the Kawaihoa soil. Both P and Si sorption were high for the Akaka soil. Sorption was decreased by P more effectively in the soils which sorbed high Si than in those which sorbed low Si.

### Phosphorus and Silicon Desorption

Phosphorus desorption from soils increased in the presence of sorbed Si, but Si desorption decreased in the presence of sorbed P except for the Wahiawa soil (Figs. 22 to 25, Appendix Table 33). Phosphorus desorption was greater per unit Si applied at 250 ppm Si than at 500 ppm Si. Phosphorus desorption was most affected by applied Si at high levels of P. The effect of Si on P desorption was small in the Akaka soil.

These results suggest that increasing Si sorption does not necessarily mean that there will be a large P desorption. Influence of Si on P desorption seems to be related to the nature of soil minerals on which P and Si are sorbed. The effect of Si on P desorption was greater in the kaolinitic soils than in the gibbsitic soil or hydrated oxide gels. These results indicate that P sorption by kaolin is more reversible than by crystalline gibbsite or hydrated oxide gels. The effect of Si on P desorption seems to be related to the bonding energy with which P is sorbed on different adsorbents or the formation of insoluble P compounds in soils. This may also depend on the nature of the silicate compound formed in soils. Both P and Si may be more tightly held by gibbsite and amorphous oxide gels than by kaolin. The loosely bound Si on kaolin may facilitate P desorption more easily than the strongly bound Si on hydrated oxides or gibbsite crystals. Formation of more insoluble silicate compounds with gibbsite or



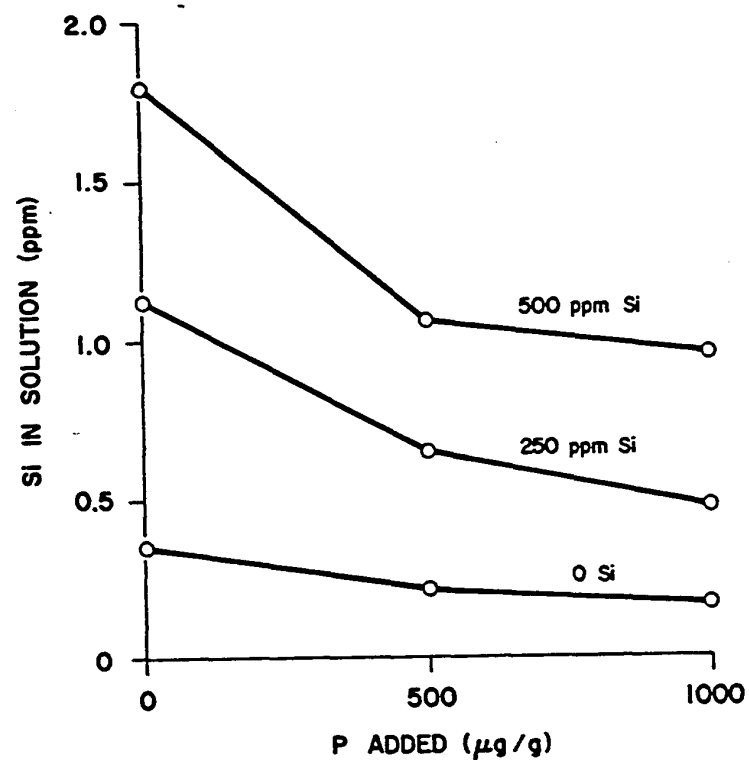
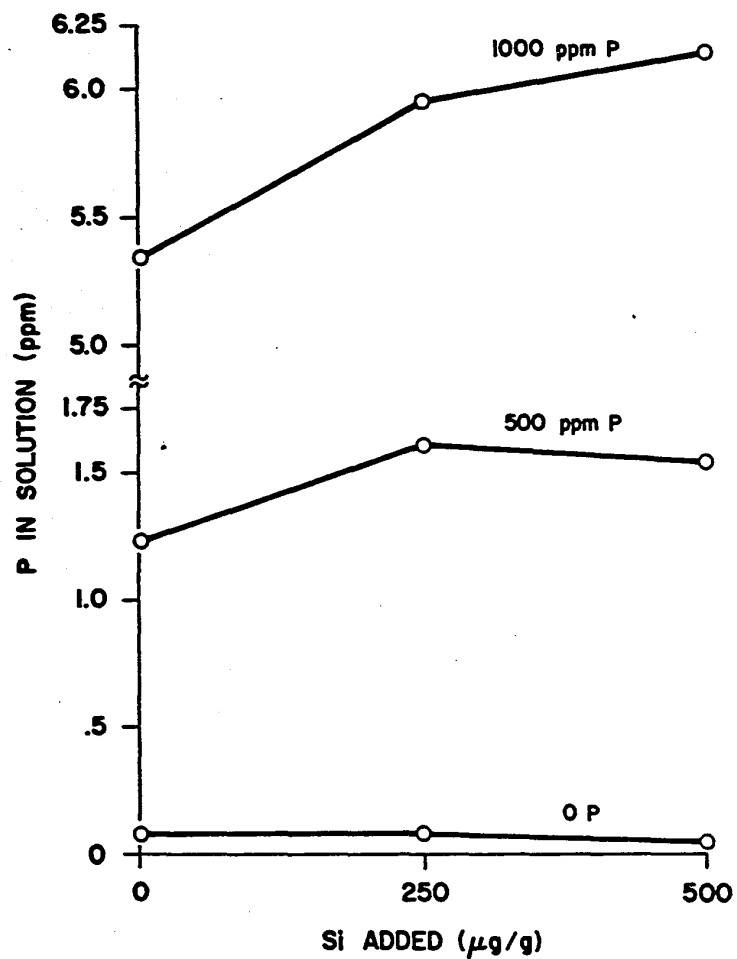


Fig. 22. Phosphorus-Silicon Interaction on the Desorption of Phosphorus and Silicon from Kawaihoa Soil.

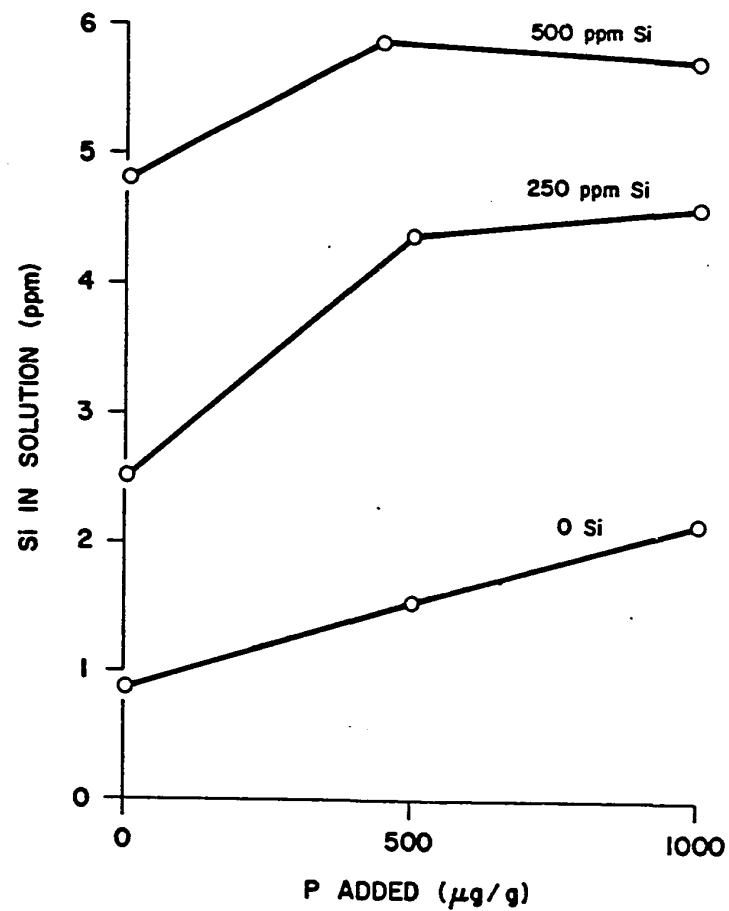
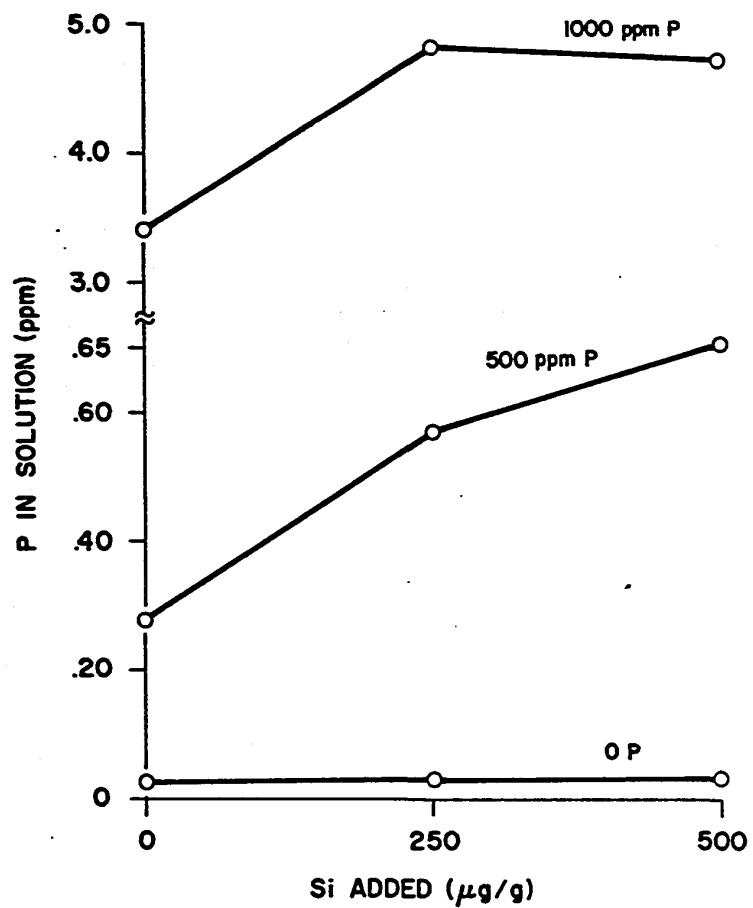


Fig. 23. Phosphorus-Silicon Interaction on the Desorption of Phosphorus and Silicon from Wahiawa Soil.

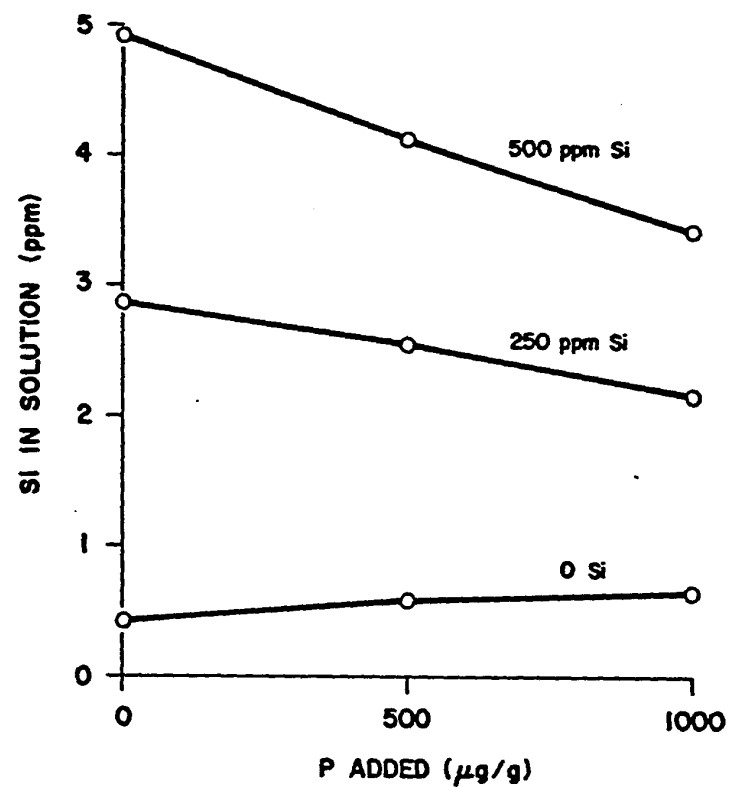
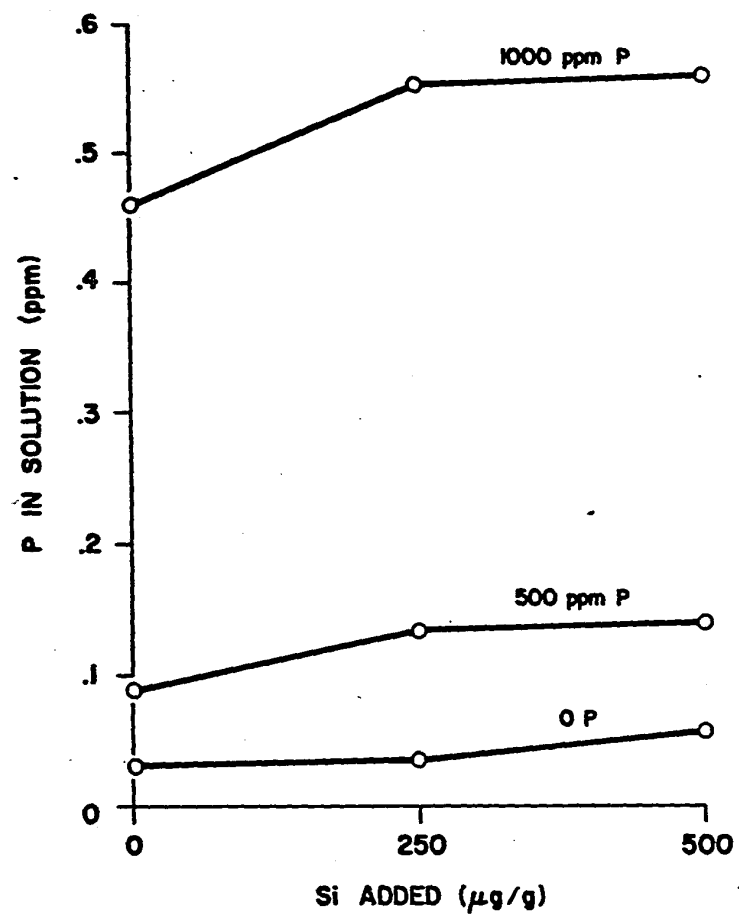


Fig. 24. Phosphorus-Silicon Interaction on the Desorption of Phosphorus and Silicon from Kapaa Soil.

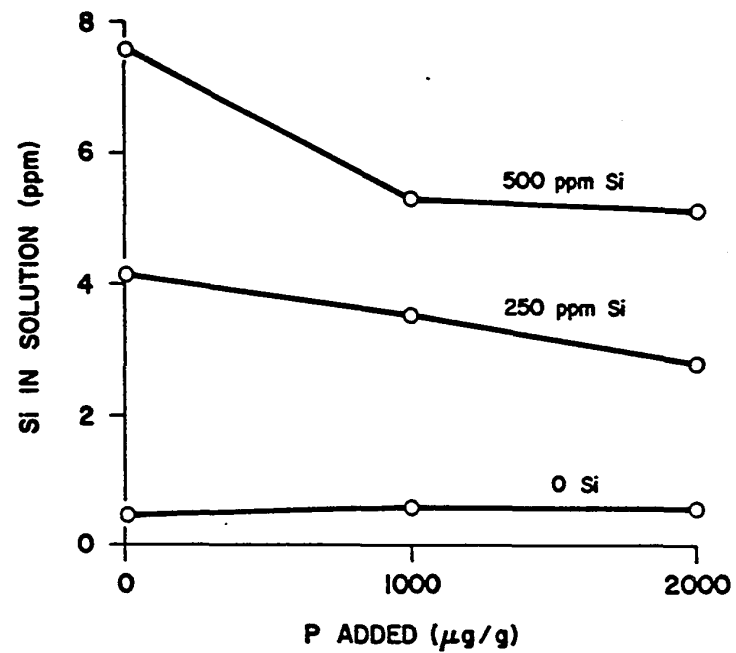
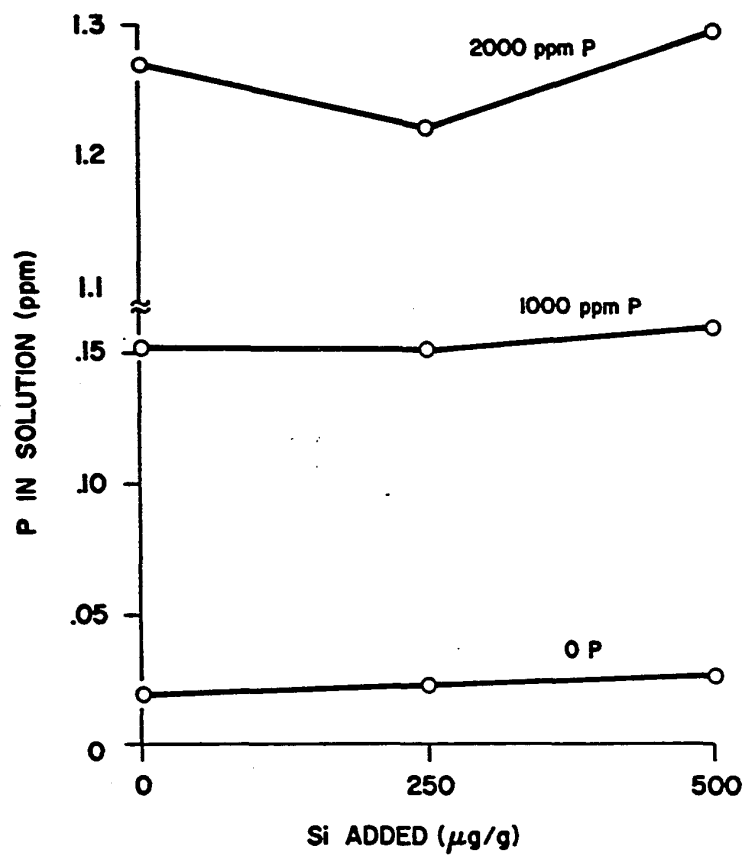


Fig. 25. Phosphorus-Silicon Interaction on the Desorption of Phosphorus and Silicon from Akaka Soil.

amorphous oxides may also be responsible for the low desorption effect of Si in these soils.

It is difficult to understand why desorption of Si from soils decreased in the presence of sorbed P. Progressive desorption of Si in the Wahiawa soil with increasing P levels may be due to dissolution on native Si by inter-crystalline P sorption.

#### Effect of Silicon on the Phosphorus Level of Soil Solution

During Continued Depletion of Phosphorus from Soil Solution: It has been demonstrated in the previous section that P sorption by soils can be decreased and P in solution can be increased by applications of soluble silicate. These studies were extended to see what effect Si has on the P status of soil solutions while P is being depleted from soil solutions.

Soils were allowed to sorb P from  $\text{Ca}(\text{H}_2\text{PO}_4)_2$  solutions with or without Si. Desorption was then carried out by equilibrating samples with distilled water four times in succession. Phosphorus was determined in the equilibrium solutions after each desorption.

Phosphorus concentrations in equilibrium solutions decreased with repeated desorption, but the concentration of P in soil solution was maintained at a high level in the presence of sorbed Si during continued desorption (Figs. 26 and 27, Appendix Tables 34 and 35). In both soils the effect of Si was more pronounced at high P levels than at low P levels. Silicon concentrations

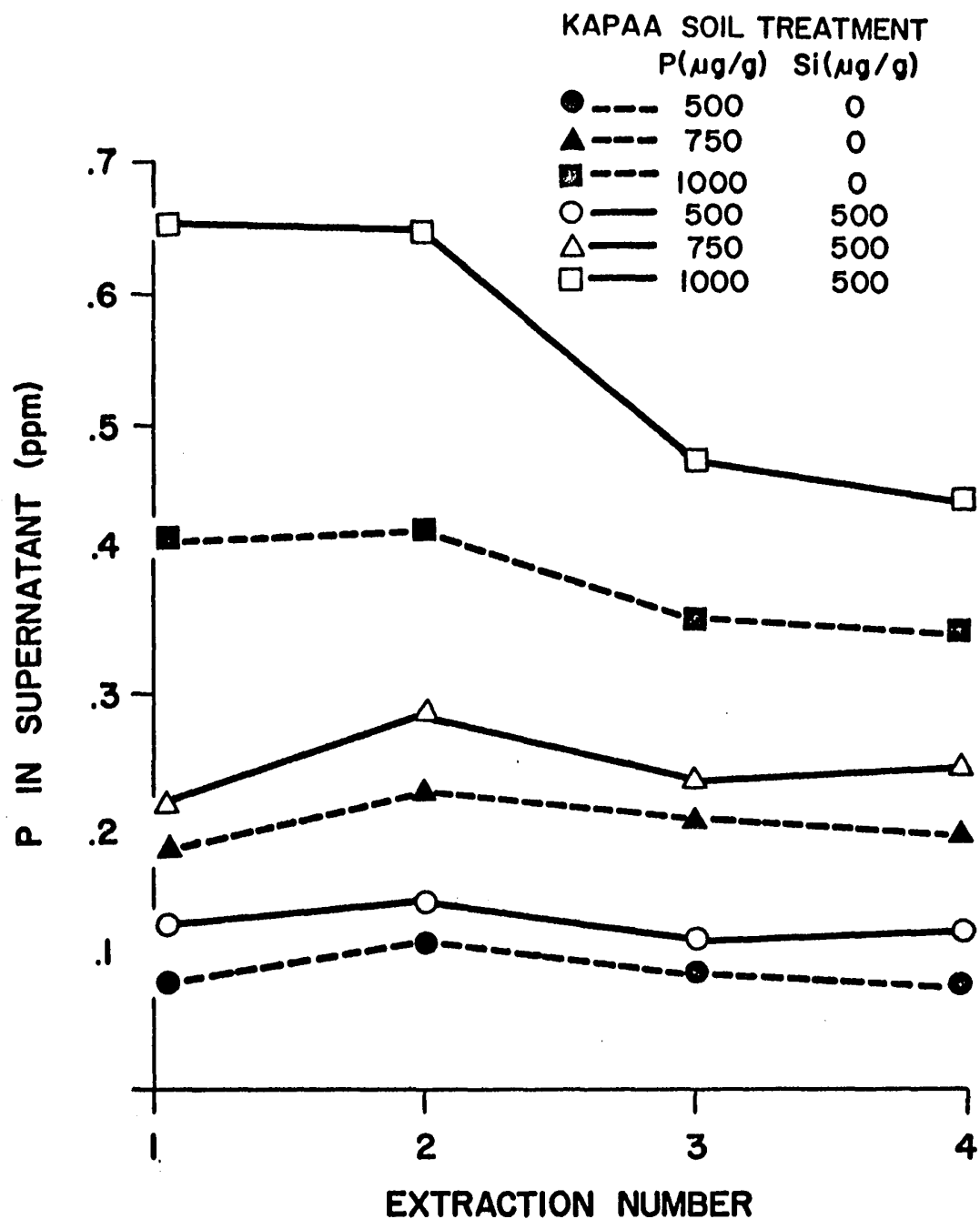


Fig. 26. Desorption of Phosphorus by Successive Extractions of Kapaa Soil in Relation to the Amounts of Phosphate and Silicate Previously Applied.

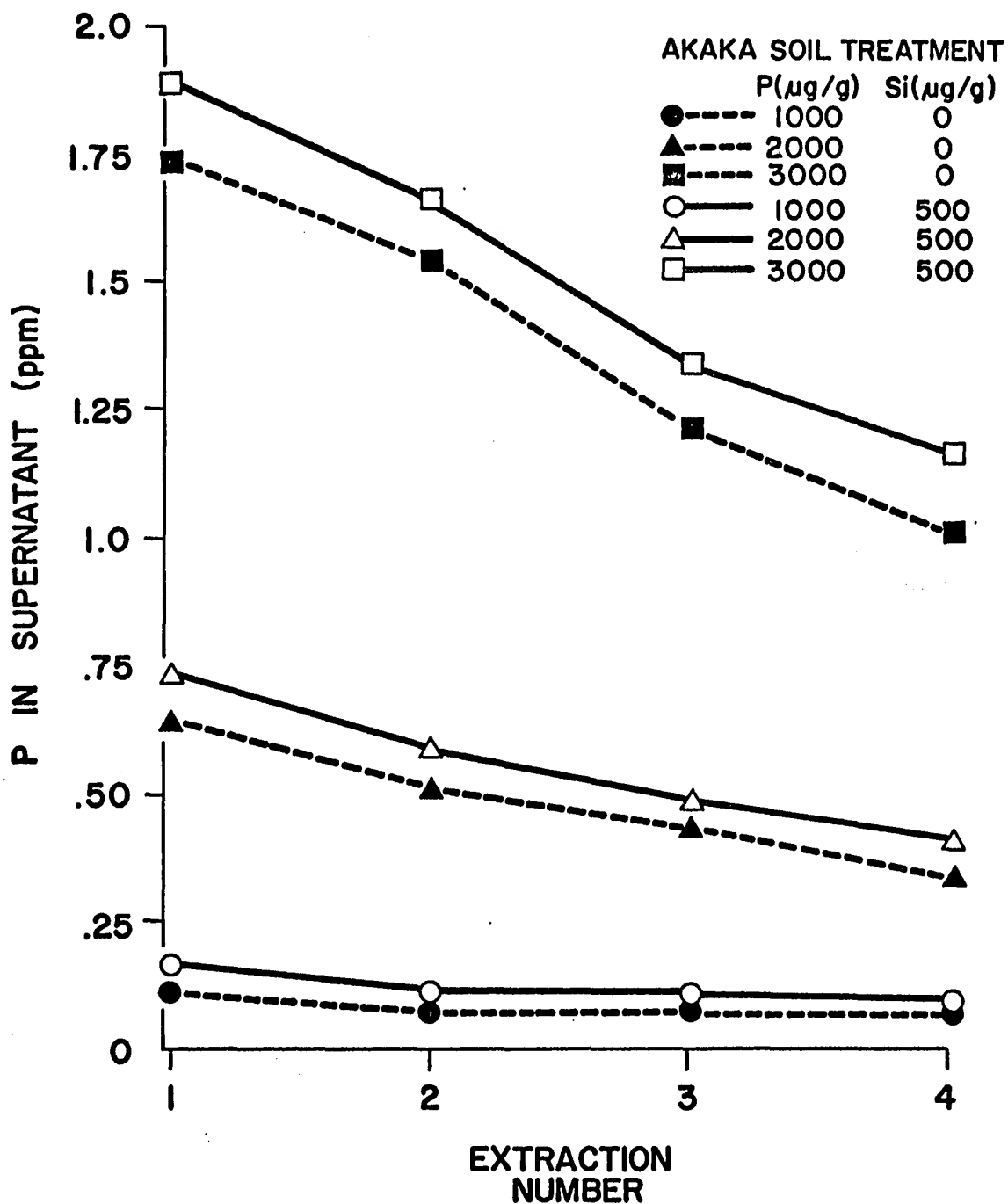


Fig. 27. Desorption of Phosphorus by Successive Extractions of Akaka soil in Relation to the Amounts of Phosphate and Silicate Previously Applied.

decreased with successive extractions and also with increasing P levels. The results of this investigation suggest that silicate, when applied to soils, not only decreases P sorption capacities of soils but also helps to maintain the P concentrations of soil solutions during P depletion.

## PHASE II

### Effect of Silicate, Phosphate and Soil pH on Phosphorus Sorption by Kapaa Soil

The phosphorus sorption study was extended to samples from field plots established to study phosphate-silicate-pH interactions on yield and nutrient uptake by sugarcane.

Phosphorus sorption by surface soils decreased with increasing amounts of P and Si initially applied (Figs. 28 to 31, Appendix Table 36). Sorption by sub-soils was much greater than sorption by surface soils (Fig. 32). In surface soil samples sorption was greater at pH 5.5 than at pH 6.2. This agrees with most concepts of P solubility in soils. Silicate decreased P sorption more effectively at pH 5.5 than at pH 6.2. However, the residual effect of P was most pronounced at the highest pH level.

Phosphorus requirements of surface soils were decreased 225 lbs P per acre by increasing applied P level from 100 to 1000 lbs P per acre at both pH levels ( $\text{lbs/A} = \text{ppm} \times 1.5$ )



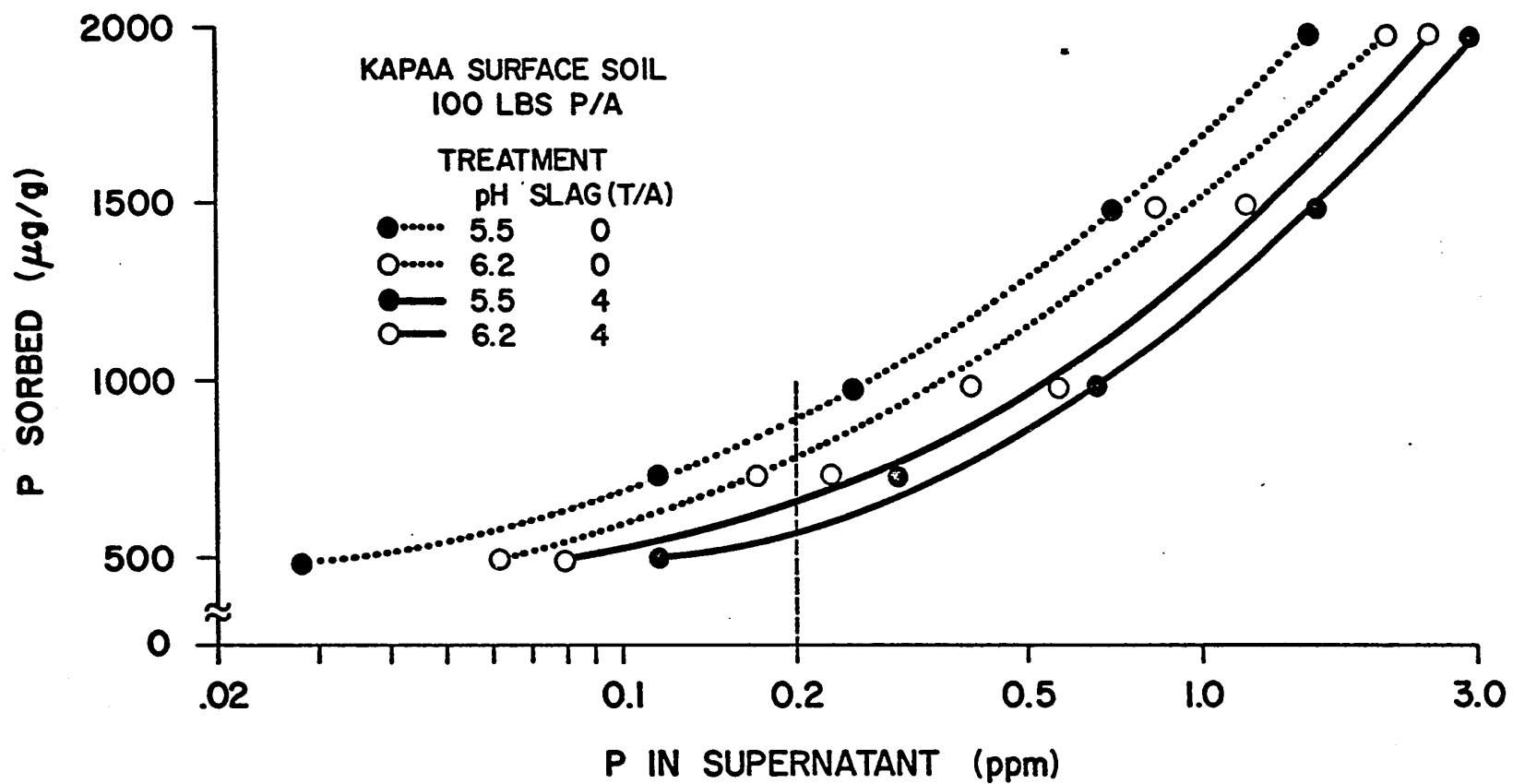


Fig. 28. Silicate X pH Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Surface Soil (100 lbs. P/A).

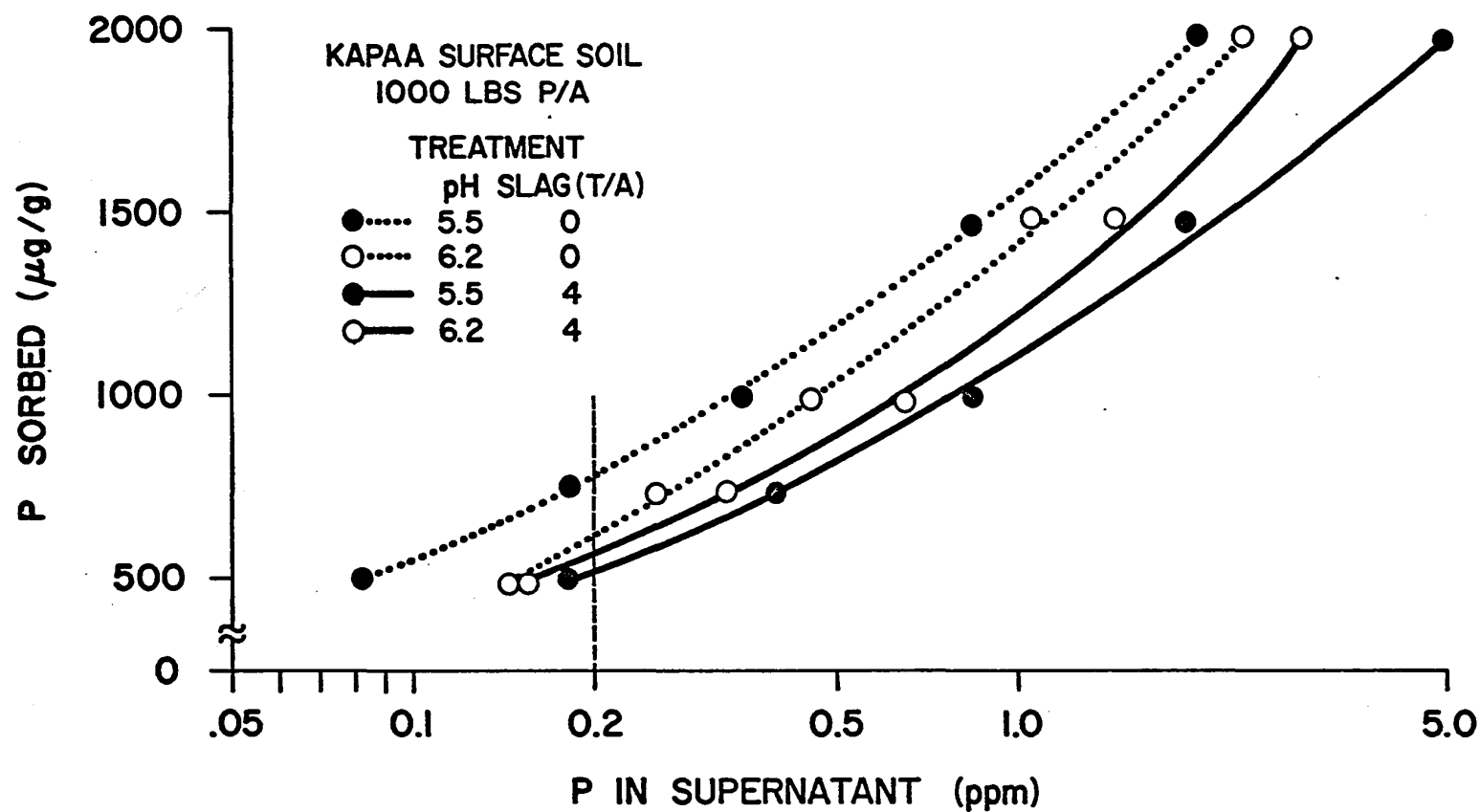


Fig. 29. Silicate X pH Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Surface Soil (1000 lbs. P/A).

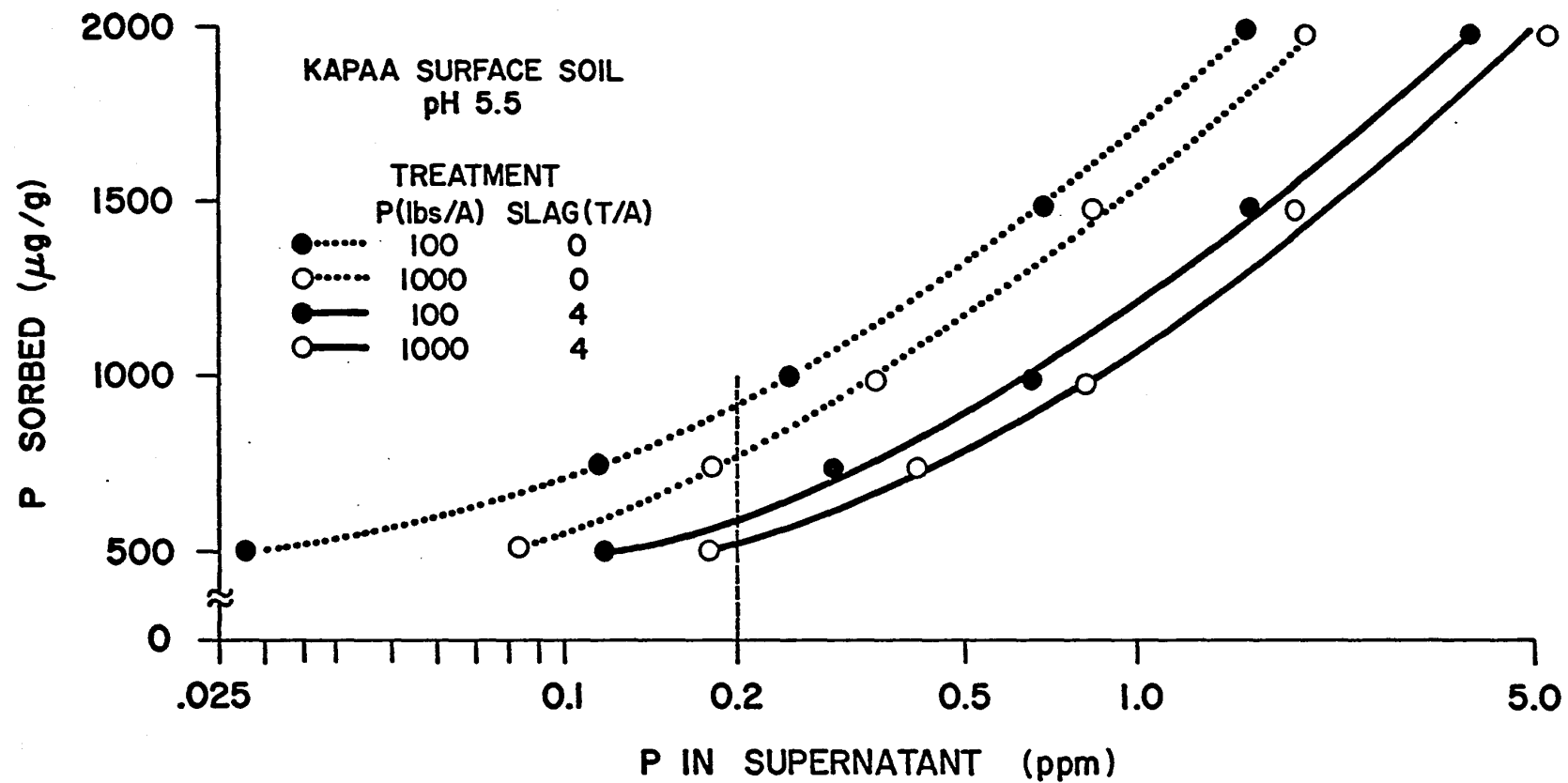


Fig. 30. Phosphate X Silicate Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Surface Soil (pH 5.5).

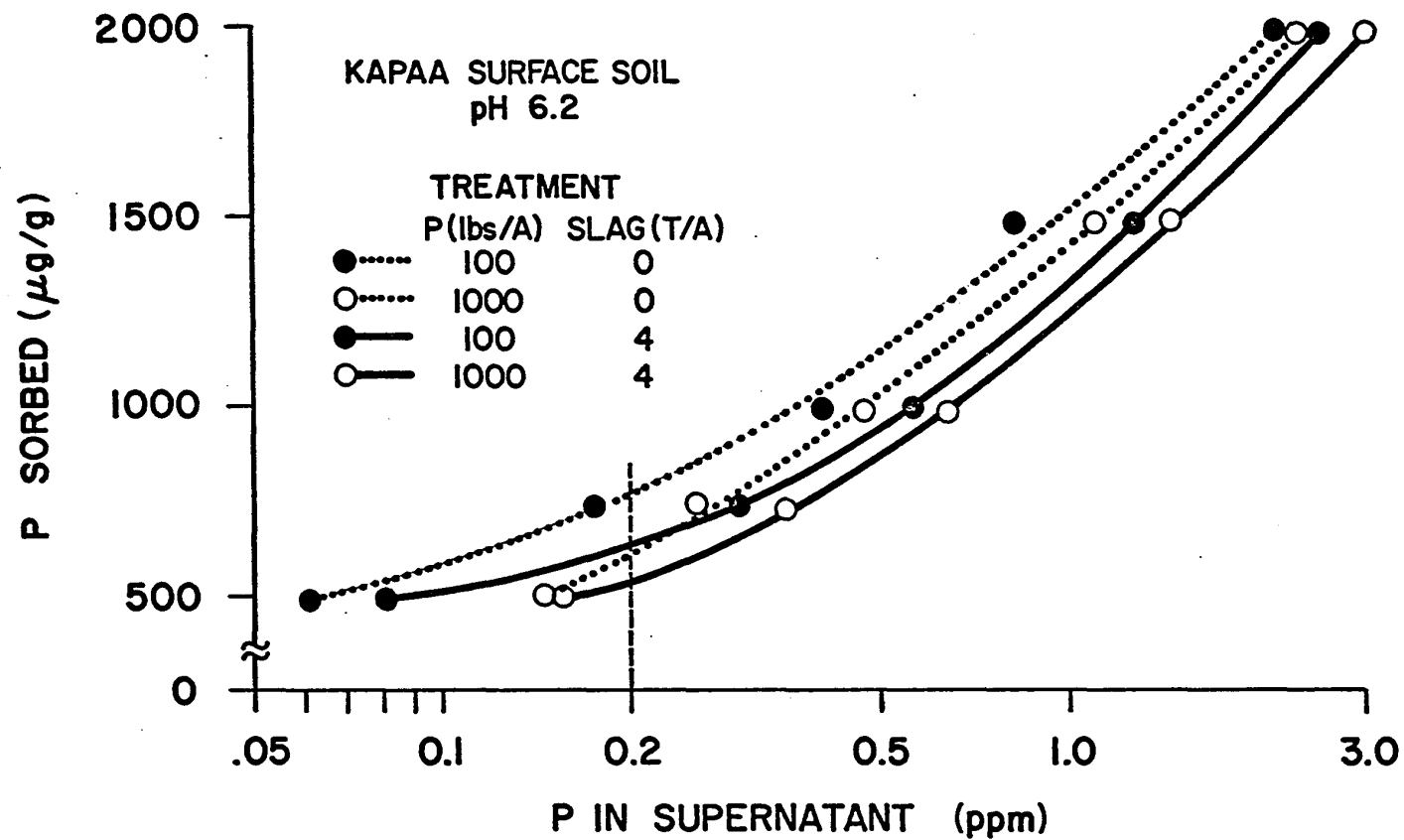


Fig. 31. Phosphate X Silicate Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Surface Soil (pH 6.2).

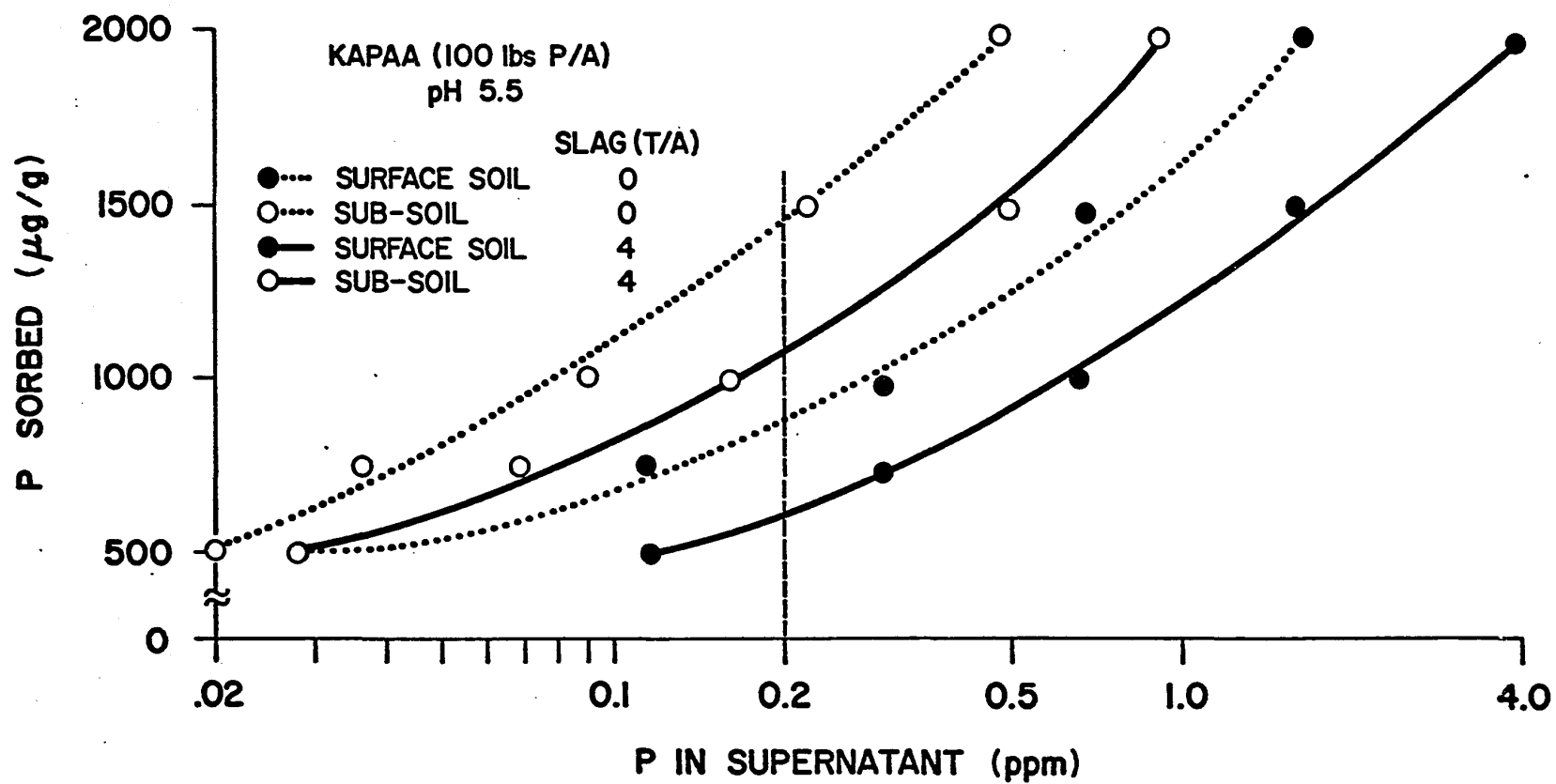


Fig. 32. Effect of Surface Applied Silicate on Phosphorus Sorption by Kapaa Surface Soil and Sub-Soil.

nine months after phosphate applications. However, sorption was greater at pH 5.5 than at pH 6.2. So in relative terms, P was more effective at high pH level than at low pH level in decreasing P requirements of the soil. Relatively greater effects of P at high pH than at low pH may be explained by increased P solubility at high soil pH.

Phosphorus sorption was decreased 375 lbs P per acre by an application of 1,000 lbs P plus 4 tons of slag per acre at pH 5.5. Similar applications of P plus Si decreased P sorption only 75 lbs P per acre when soil pH was 6.2. The effect of slag was even greater at the 100 lbs P per acre level. The difference at pH 5.5 was 450 lbs P per acre, and for pH 6.2 was 225 lbs P acre. The effects of P and Si were not additive.

Among the three factors tested silicon had the greatest effect in decreasing P requirements of surface soil samples. The effect of Si was most pronounced at low pH. It may be recalled that solubility of Si in soils increases with decreasing soil pH. Silicate effects on P sorption was also affected by rates of applied P. There was an inverse relationship between the rates of applied P and the effect of applied silicate. One of the explanations for the negative effect of high P rates may be the nucleation effect of phosphate crystals at high P levels. It is speculated that in case of massive phosphate applications the precipitated phosphate crystals serve as nuclei which initiate precipitation of P from

succeeding applications (R. L. Fox, personal communication).

This nucleation effect may have been more pronounced in the presence of applied silicate and may be responsible for the relative ineffectiveness of Si at high P levels.

The overall effect of silicate applications on P sorption may be explained by: (i) partial saturation of the sorption sites by  $\text{Si(OH)}_4$  and/or (ii) inactivation of ionic Fe and Al by the formation of insoluble compounds with silicates.

These laboratory studies indicate that P availability could be increased by adding slag to the soil without changing soil pH or applied P levels. These studies also suggest that applications of large amounts of phosphates to high P fixing soils may be beneficial for the succeeding crops. This conclusion has been borne out in field trials where applications of phosphate fertilizer had residual effects even after nine years on crop yields for the bauxitic Kapaa soil of Kauai (Younge and Plucknett, 1965, 1966; Fox et al., 1968).

The effects of P applied to surface soils on P sorption by sub-soils were negligible (Figs. 33 and 34). At the low P level P sorption by the sub-soils was decreased 300 lbs P per acre by increasing surface soil pH from 5.5 to 6.2. The sub-soil effect of pH modification of the surface soils was indistinguishable at the high P level. Additions of P and Si together to surface soils decreased P sorption by sub-soils by 450 lbs P per acre.

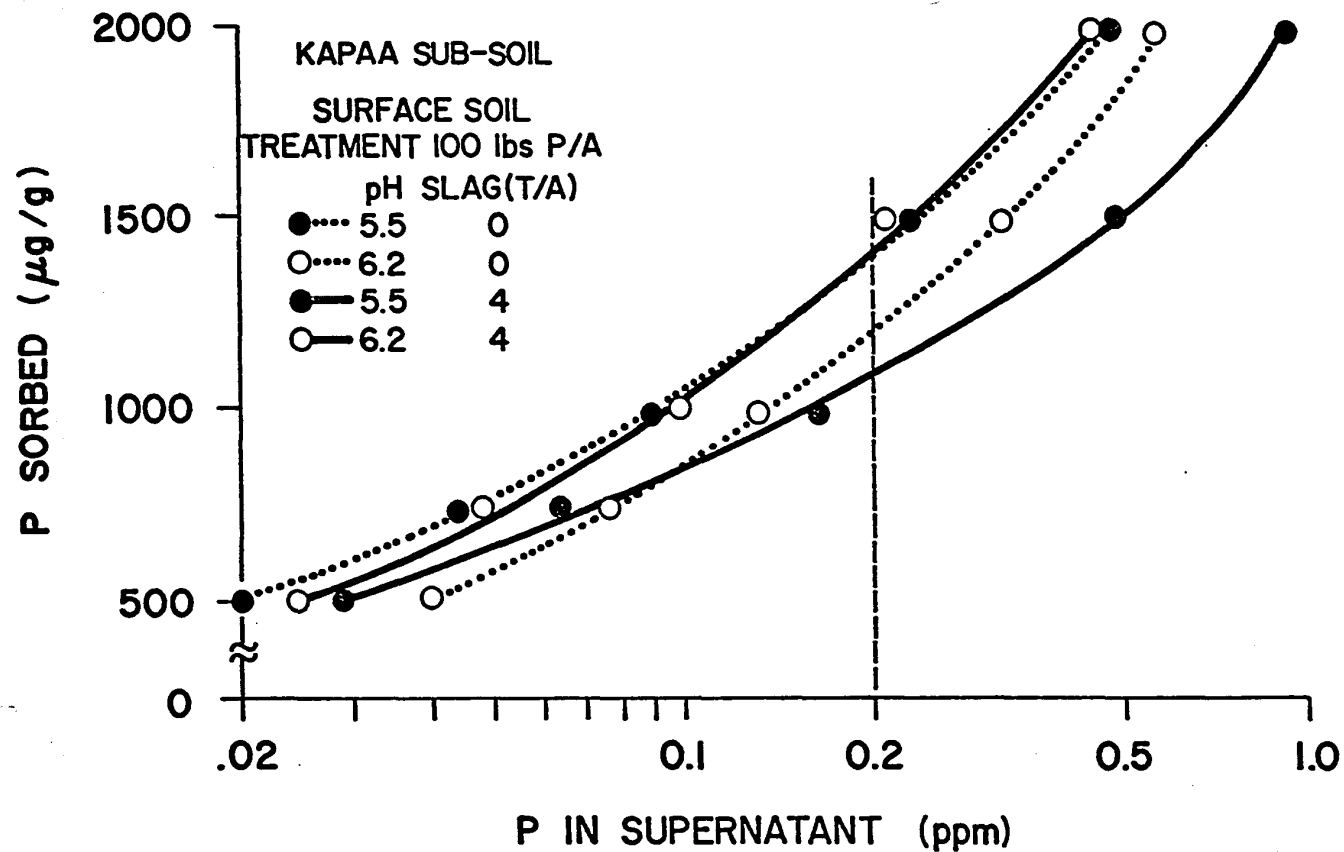


Fig. 33. Silicate X pH Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Sub-Soil (100 lbs. P/A).



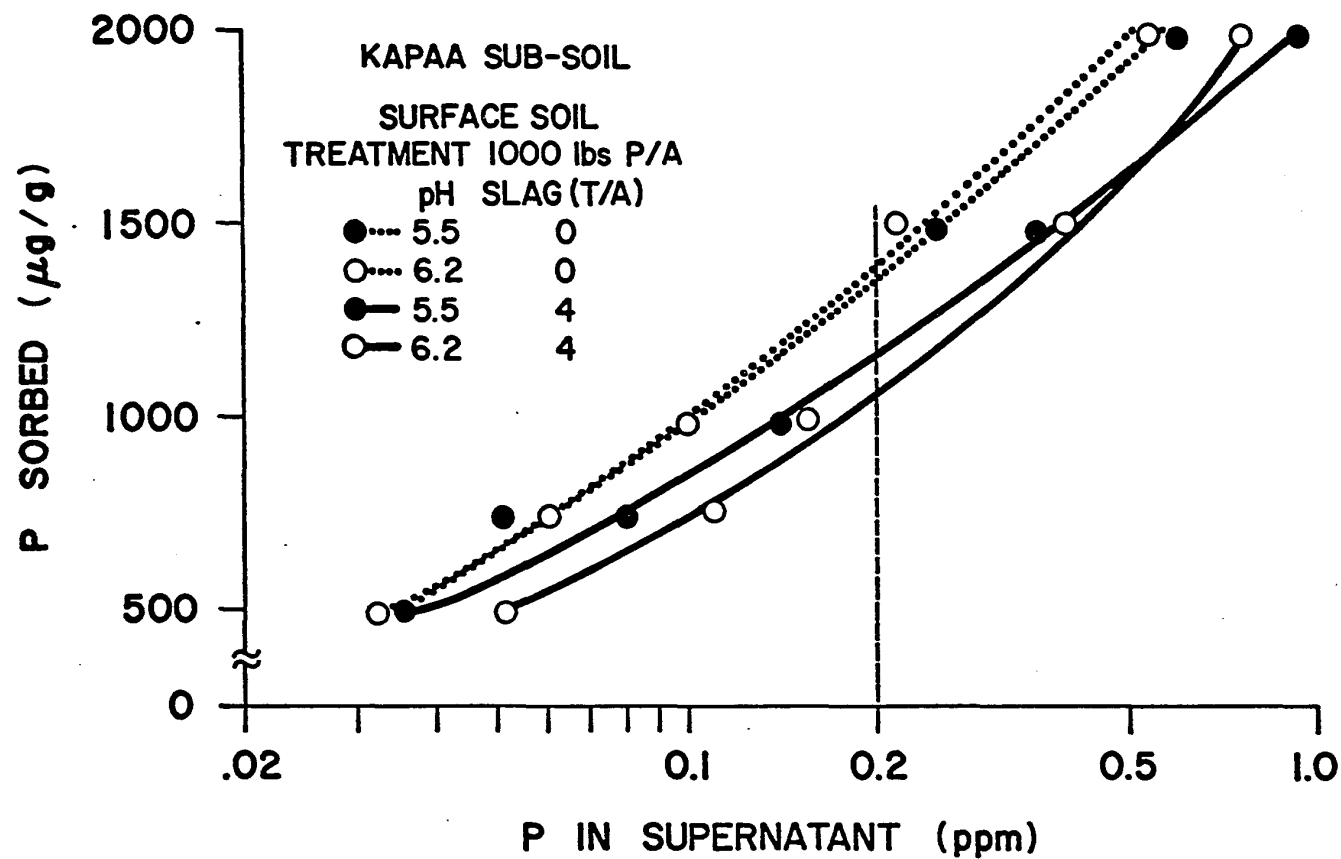


Fig. 34. Silicate X pH Interaction (Surface Applied) on Phosphorus Sorption by Kapaa Sub-Soil (1000 lbs. P/A).

This effect was noticeable only at high pH. However, at the high P level, P and Si together decreased P sorption at both pH levels.

The ability of silicate applied to surface soils, at low surface soil pH, to decrease P sorption by sub-soils may be due to one or all of the following: (i) high solubility of Si in the surface soils at low pH and subsequent movement of Si to the sub-soil, (ii) mobilization of sulfur from the surface soils and partial saturation of the sorption sites by  $\text{SO}_4^{=}$  ions, and (iii) precipitation of ionic Fe and Al in the sub-soil by Si.

The comparative ineffectiveness of Si at high pH may be due to the following: (i) decreasing the solubility of applied Si at high pH and thus restricting Si movement to the sub-soil, (ii) flocculation of colloidal silica in the surface soil in the presence of excess  $\text{CaCO}_3$ , and (iii) increased activity of Ca in the sub-soil due to Ca movement from the surface soil. It may be recalled that  $\text{CaCO}_3$  was added to the surface soils to adjust soil pH to 6.2. Increased activity of Ca depresses P concentrations in soil solutions of many soils (R. L. Fox, unpublished data). Flocculation of colloidal silica in the presence of excess  $\text{CaCO}_3$  was demonstrated by Khan (1960).

### Residual Effects of Slag Applications on Phosphorus Sorption by Akaka Soil

Residual effects of slag applications on P requirements by Akaka soil were evaluated by P sorption isotherms. Seven years after slag applications, phosphorus sorption by surface soils was decreased about 100 ppm P by increasing the rates of silicate from zero to 8 tons of slag per acre (Figs. 35 and 36, Appendix Table 37). The decrease in P requirements resulting from slag applications was three times greater in sub-soil samples than in surface soil samples. However, sorption by sub-soils was much greater than sorption by surface soils. The very small effect of Si on P sorption by Akaka soil was demonstrated in an earlier section. This small effect of Si was explained by the high P and high Si sorption capacity of the hydrated oxide gels. Apparently Si moved in the Akaka soil as was demonstrated for other Latosols in laboratory leaching experiments.

### Extractable Soil Phosphorus

The effect of silicate, phosphate and soil pH on extractable P, after nine months of cropping a Kapaa soil with sugarcane, was evaluated. The Modified Truog extractant was used. Extractable P in surface soil samples increased with increasing rates of silicate, initially applied (Fig. 37, Appendix Table 38). Increases due to phosphate were greater than increases due to

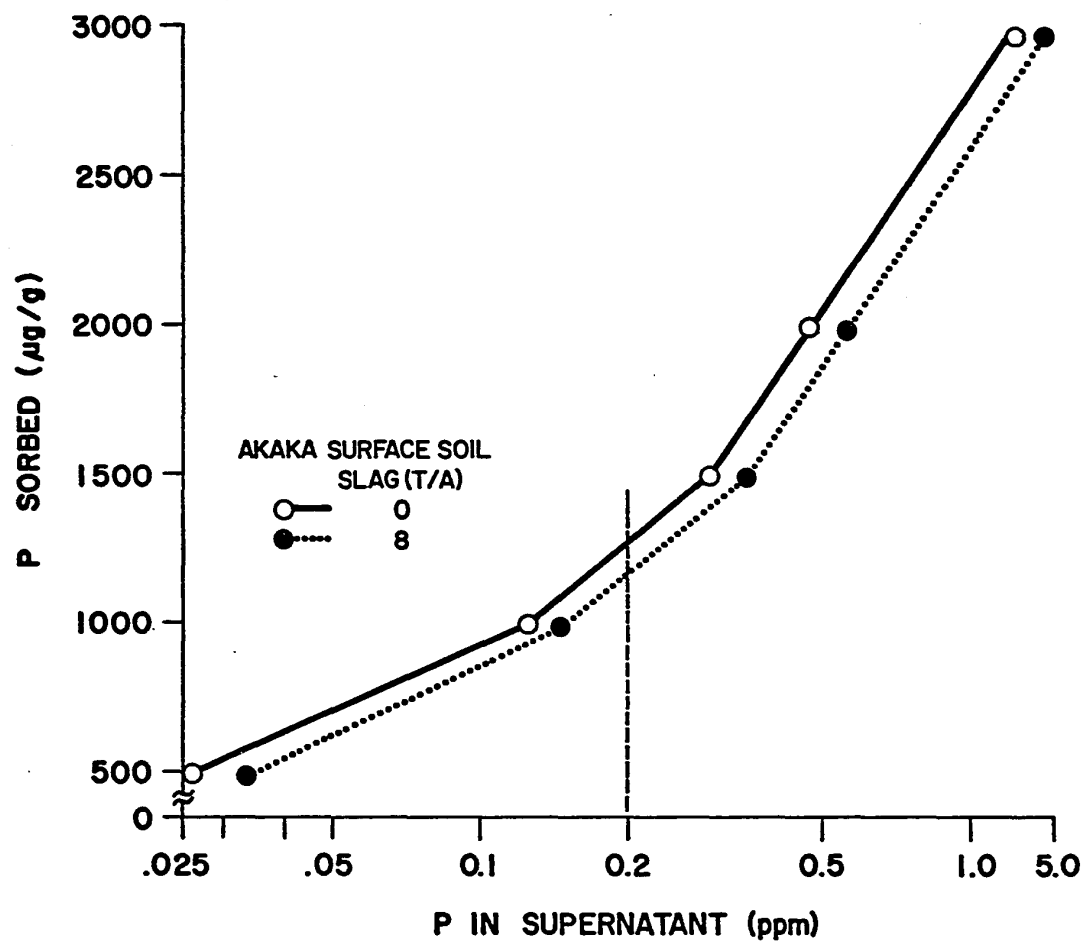


Fig. 35. Residual Effects of Field Applied Silicate on Phosphorus Sorption by Akaka Surface Soil.

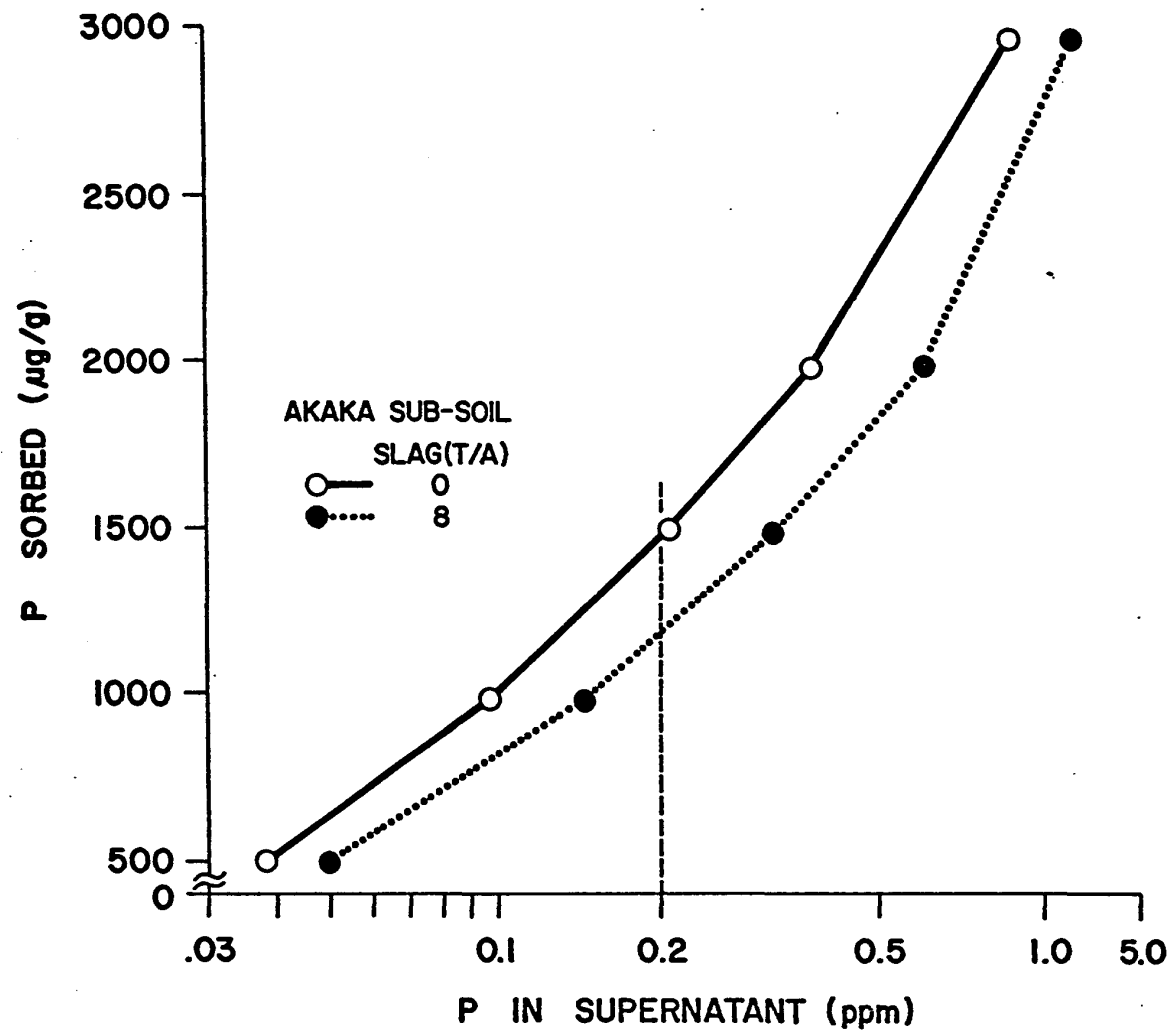


Fig. 36. Residual Effects of Field Applied Silicate on Phosphorus Sorption by Akaka Sub-Soil.

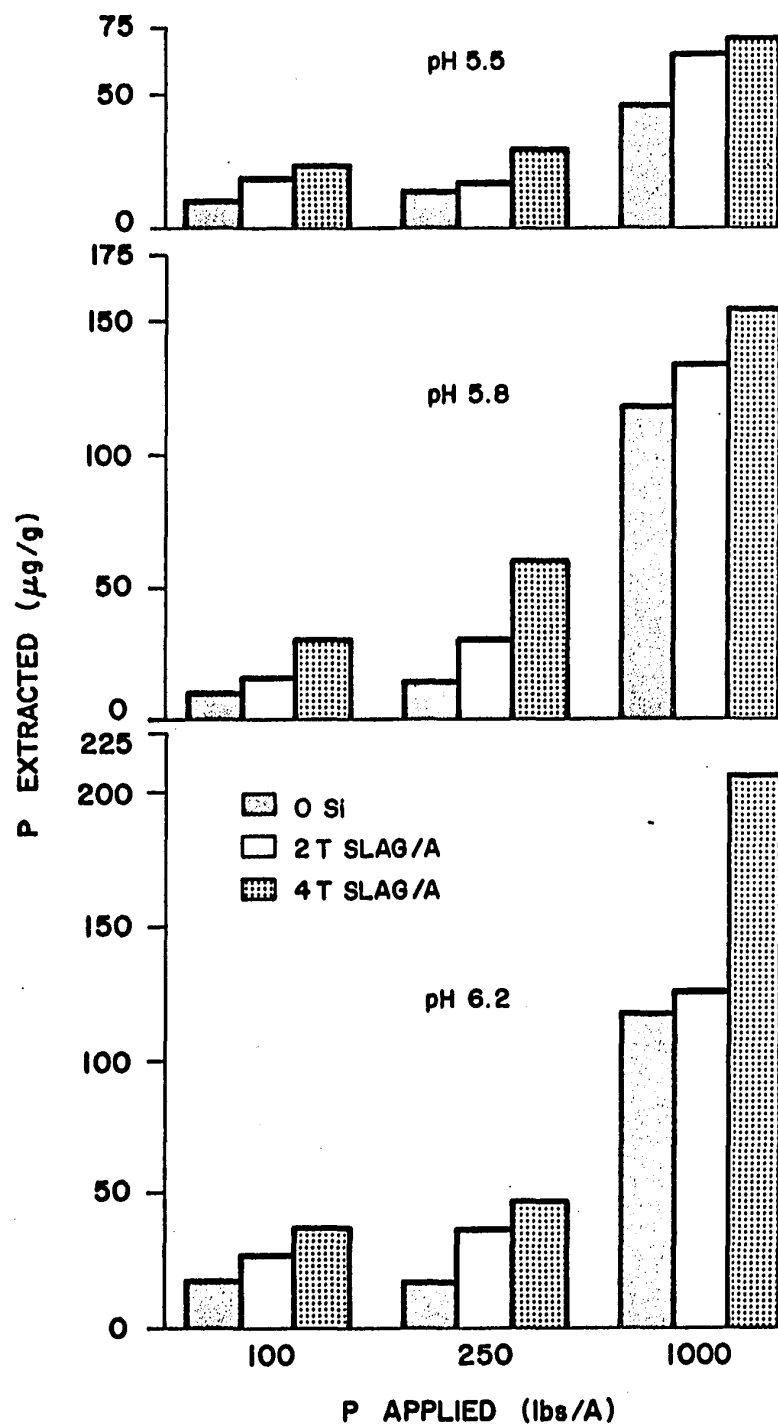


Fig. 37. Effects of Phosphate, Silicate and pH on Phosphorus Extracted from Kapaa Surface Soil Using Modified Truog Extractant.

silicate. Phosphorus extraction was highest at the highest pH level. Silicate was relatively more effective in increasing extractable P at low P levels. Extraction of P was greatest at pH 6.2. Within limits, decreasing solubility of Fe and Al and increasing solubility of P with increasing pH may be responsible for the highest extractability of P at the highest pH level or perhaps there was calcium phosphate in isolated zones in the soil. This would be readily extracted by Truog extractant.

Extractable P in the sub-soil samples (6-12 inches depth) also increased with increasing silicate and phosphate applied initially to surface soils (Fig. 38, Appendix Table 38). However, values for sub-soil samples were much smaller than values for surface soil samples. Extractability of P in the sub-soil samples increased with silicate applied to the surface soils irrespective of surface soil pH. At all silicate levels phosphorus extracted from the sub-soil samples was greatest at the highest surface soil pH.

Restricted movements of P in soils is well known. This raises the question how increasing amounts of phosphate applied to surface soil increased extractability of P in the sub-soil samples. This is probably the result of pH change and silicate effects rather than the direct effect of P leaching.

Mean effects of silicate decreased with increasing surface soil pH. Increased solubility of Si at low pH in the surface soil and subsequent Si leaching to the sub-soil may be one explanation

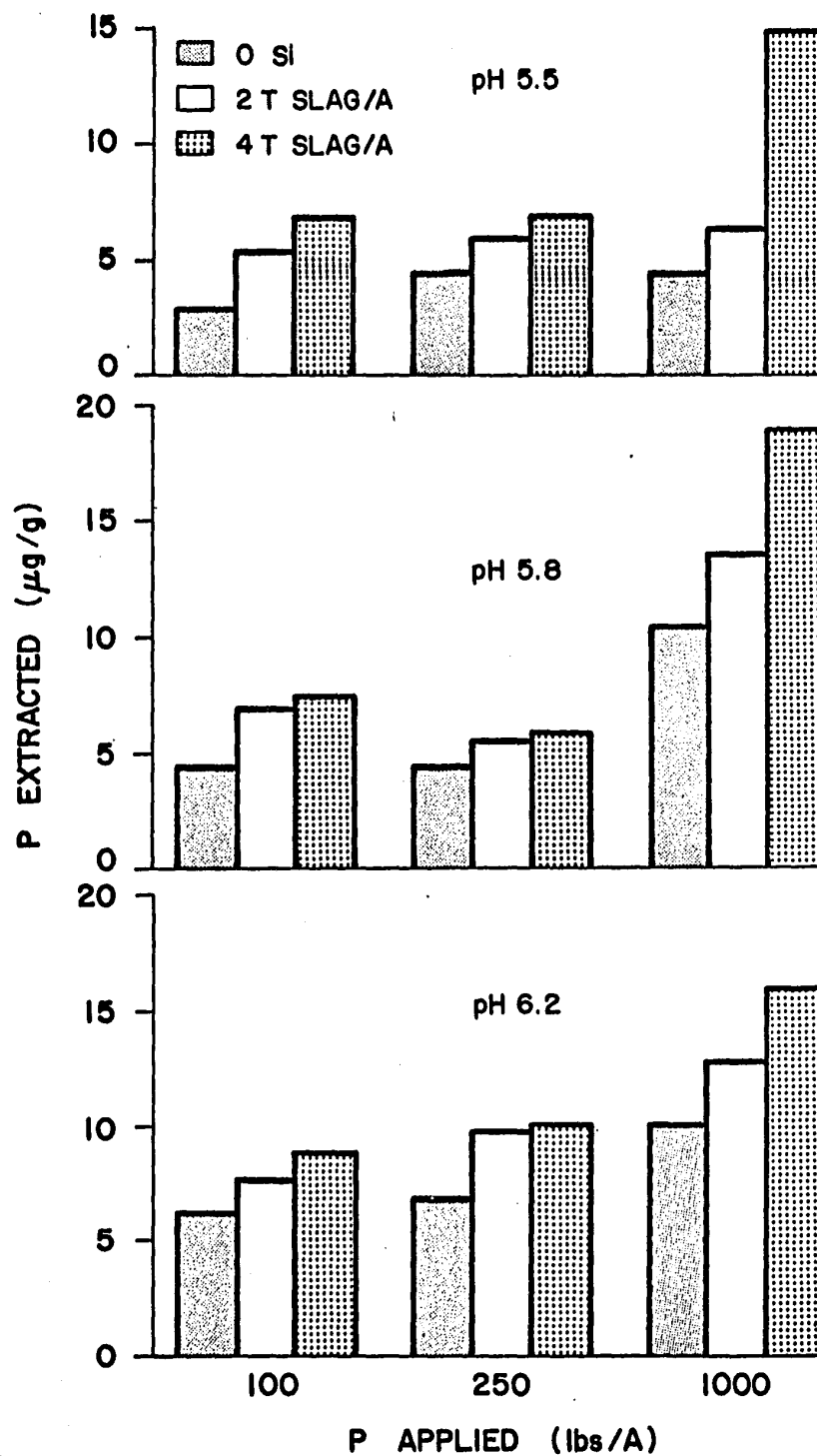


Fig. 38. Effects of Phosphate, Silicate and pH on Phosphorus Extracted from Kapaa Sub-Soil Using Modified Truog Extractant.



for the large effect of silicate on P extraction from the sub-soil samples at low surface soil pH. Another explanation may be leaching of sulfate to the sub-soil (sulfur was added to the high silicate plots to depress soil pH to 5.5) and modification of sub-soil P status by exchange. The mean effect of pH was positively correlated with extractability of P from the sub-soil samples. It was shown before that P extraction from surface soils increased with increasing soil pH, which may be due to increased P solubility at the higher pH.

#### Silicon Movement in Soils by Unsaturated Flow

Soils in short columns were treated with  $\text{CaSiO}_3$  and leached with distilled water to study Si movement. Control columns were leached with distilled water and differences between Si concentration of the control and the treated columns are reported as applied Si in the effluents.

Silicon movement was faster in Paaloa soil than in Lahaina or in Kapaa soil (Fig. 39). Applied Si first appeared in the effluents of the Paaloa, Lahaina and Kapaa soils when the effluent volumes were 120, 240 and 480 ml, respectively. The highest concentration of Si was in the effluent from the Paaloa soil and the lowest in the effluent from the Kapaa soil. By the time the Paaloa soil reached equilibrium the Kapaa soil reached about one-half equilibrium, and the Lahaina soil reached only about one-third

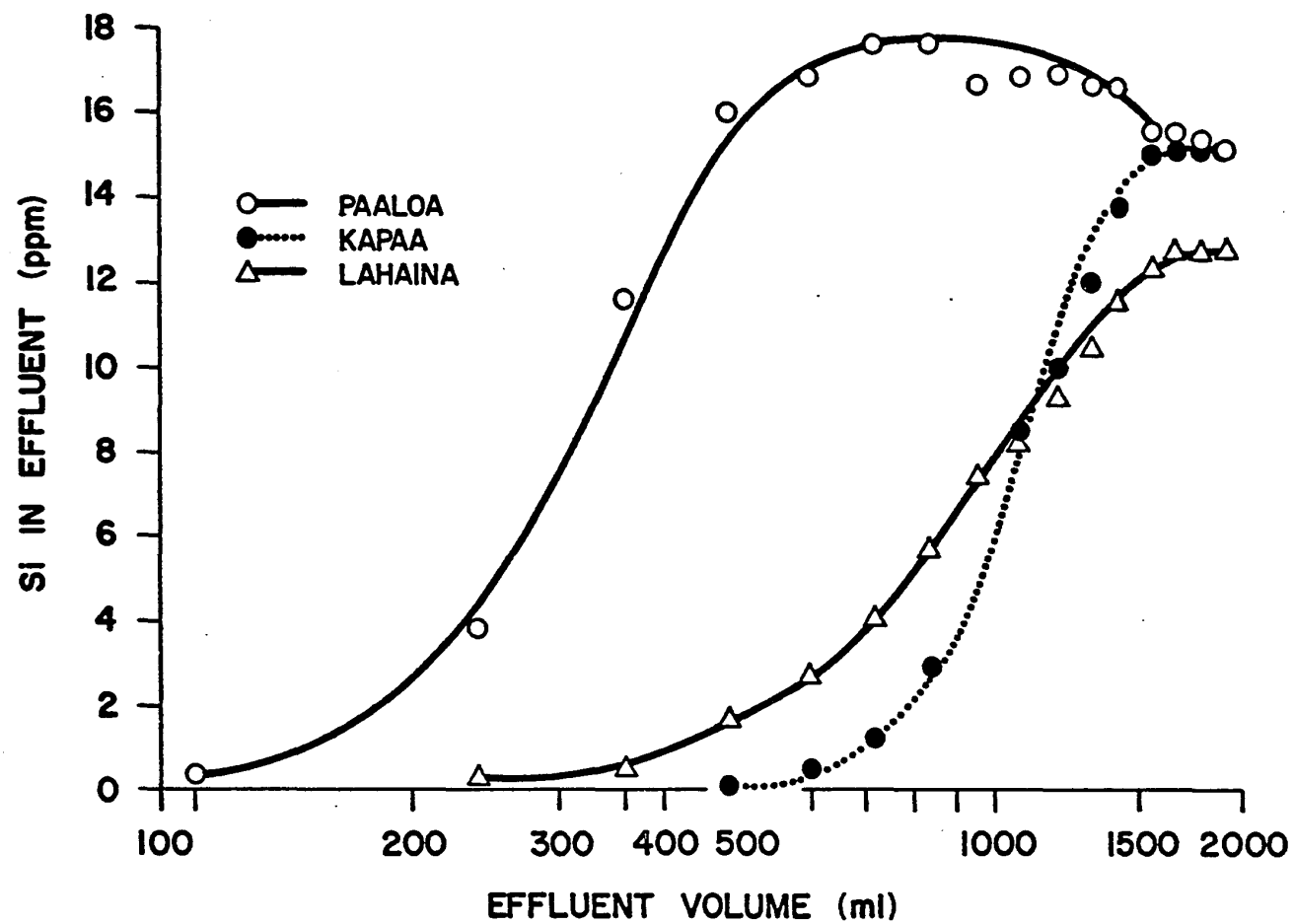


Fig. 39. Silicon Movement Through Four Inch Soil Columns in Relation to Amounts of Leaching.

equilibrium. Equilibrium concentrations in the effluents varied between 12 and 18 ppm Si.

Differences in equilibrium concentrations of Si in the effluents of these soils may be explained as follows: (i) differences in soil pH affecting solubility Si in the soils, and (ii) differential sorption of added Si by these soils. The rates at which the soils attained equilibrium correspond to their sorption capacities. It may be recalled that Si sorption by the Kawaihoa soil, a soil related to the Paaloa soil, was much smaller than sorption by the Kapaa or Wahiawa soils. The Lahaina soil is similar to the Wahiawa soil. Both belong to the Low Humic Latosol group. However, Lahaina contains more soluble Si than Wahiawa, since the former developed under lower rainfall than the latter.

Concentrations of Si in the leachate were between 12 and 18 ppm. The solubility of  $\text{CaSiO}_3$  in distilled water is about 140 ppm Si. Apparently a large fraction of added soluble Si was retained by these soils during its movement through soil columns. Changes in the concentration of soluble Si can occur during water percolation through soils (Miller, 1967). The sigmoid shapes of the breakthrough curves conform to the theory of miscible displacement of solutes in soils (Neilson and Biggar, 1962). According to this theory, characteristic shifting of breakthrough curves to the right is explained by chemical reaction, precipitation or exchange of the solute with soil particles, and that to the left

by any process which may increase solute concentration or cause incomplete mixing throughout the entire soil solution. Repulsion of anions from negatively charged clays may also translate breakthrough curves to the left. Although all the curves are to the right of one pore volume (140 cc), the curve for the Paaloa soil is far to the left of the curves for the Lahaina and Kapaa soils.

The amount of Si leached through the Paaloa soil by passing two liters (70 cm) of water through the column was twice as much as through the Lahaina or Kapaa soils (Table 2).

Fractionation of the soil columns indicated that in the Kapaa soil approximately 12 percent of added Si remained in water soluble form and 12 percent in phosphate extractable form. About 42 percent of the total water soluble fraction leached out of the column. In calculating the net phosphate extractable fraction, it was assumed that the water soluble fraction in the soil column was also phosphate extractable. The water soluble fractions for the Lahaina and Paaloa soils were 17 and 16 percent, respectively, and the phosphate extractable fraction for both the soils was 1.6 percent.

More water soluble Si was retained by the columns of the Lahaina soil than by the other two soils (Fig. 40, Appendix Table 39). Greatest phosphate extractable Si was recovered from the Kapaa soil and least from the Paaloa soil. Most of the soluble Si was retained in the top two inches of the soil columns.

Table 2. Fraction of Added Silicon Remaining in Water Soluble and Phosphate Extractable Forms During Leaching Through Soil Columns (320 mg Si Added)

Soil	Water Soluble				Phosphate Extractable	
	Si in Leachate (mg)	Si in Column (mg)	Total (mg)	Fraction of Added %	Si in Column (mg)	Fraction <sup>1/</sup> of Added %
Kapaa	16	22	38	12	60	12
Lahaina	15	39	54	17	44	1.6
Paaloa	30	20	50	16	25	1.6

$$\frac{1}{\text{Fraction Phosphate Extractable}} = \frac{\text{P Extractable Si-Water Soluble Si in Column}}{320} \times 100$$

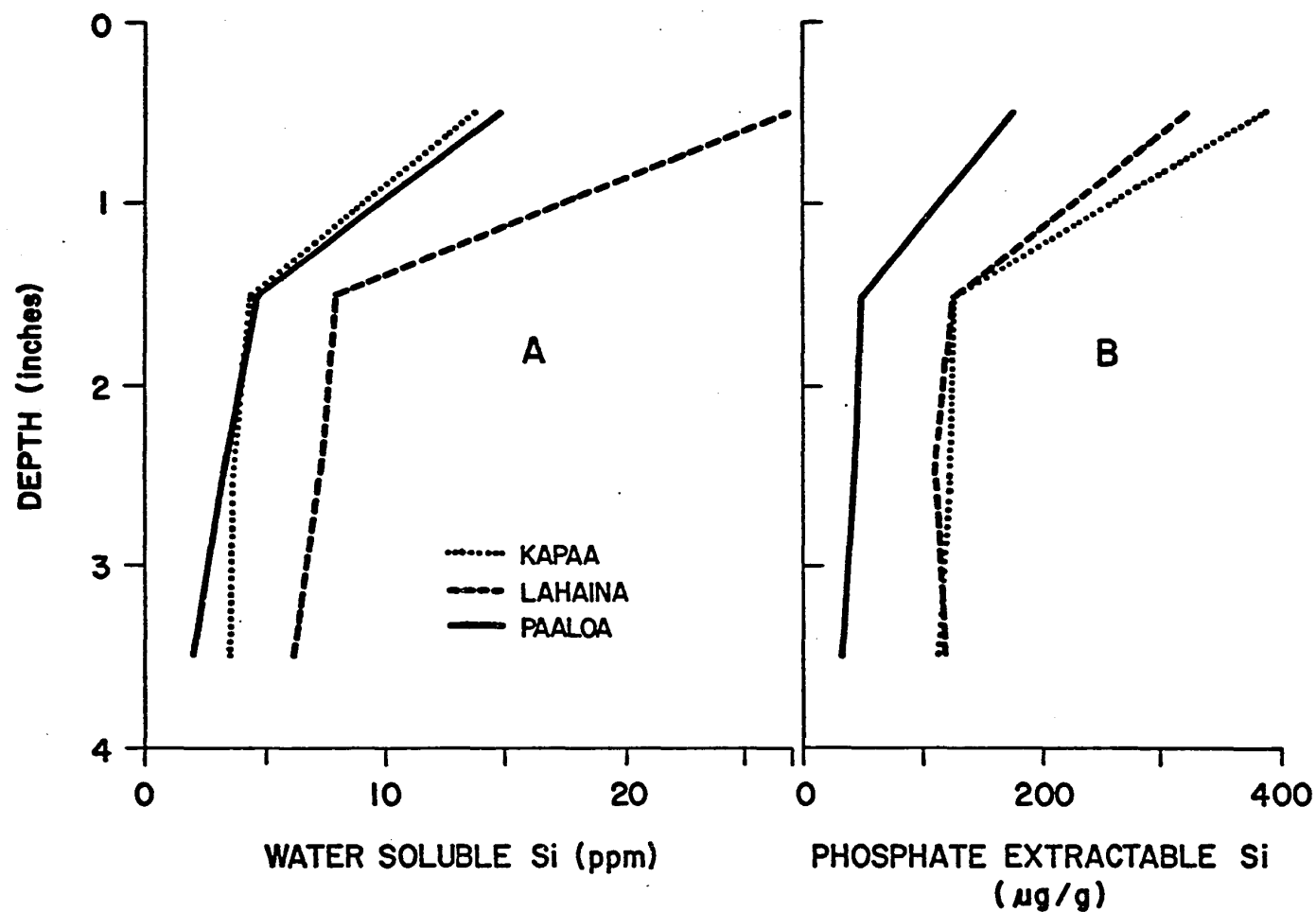


Fig. 40. Distribution of Added Silicon (320 mg Si Added) in Four Inch Soil Columns After Leaching With Two Liters of Distilled Water.

The large retention of Si in this section of the soil columns may have been caused by the presence of solid phase  $\text{CaSiO}_3$  applied on top of the soil columns.

These results indicate that a considerable amount of Si applied to soils may be lost by leaching. The extent of leaching will be determined by soil properties and the amount of water percolating through soil profiles.

#### Silicon Movement in Kapaa Soil by Saturated Flow

Silicon movement in soils may be influenced by the presence of other ions. The results of Si movement, presented in the previous section, initiated interest in a study of the influence of composition of displacing liquids on Si movement. Calcium silicate solution (20 ml of 50 ppm Si) was supplied to soil columns that were preleached with water or 0.01 M  $\text{CaCl}_2$ , and Si was displaced with distilled water or 0.01 M  $\text{CaCl}_2$ . Each 20 ml effluent was analyzed for Si.

Calcium chloride solution was more effective than water in displacing Si (Fig. 41). The  $\text{CaCl}_2$  curve peaked sharply at 3.5 ppm Si and the water curve at 2 ppm Si when the effluent volume was about 100 ml. The effects of the two displacing liquids on Si displacement were noticed even before introducing Si solutions into the soil columns when the water effluent contained 0.75 ppm Si, while the  $\text{CaCl}_2$  effluent contained 1.3 ppm Si.

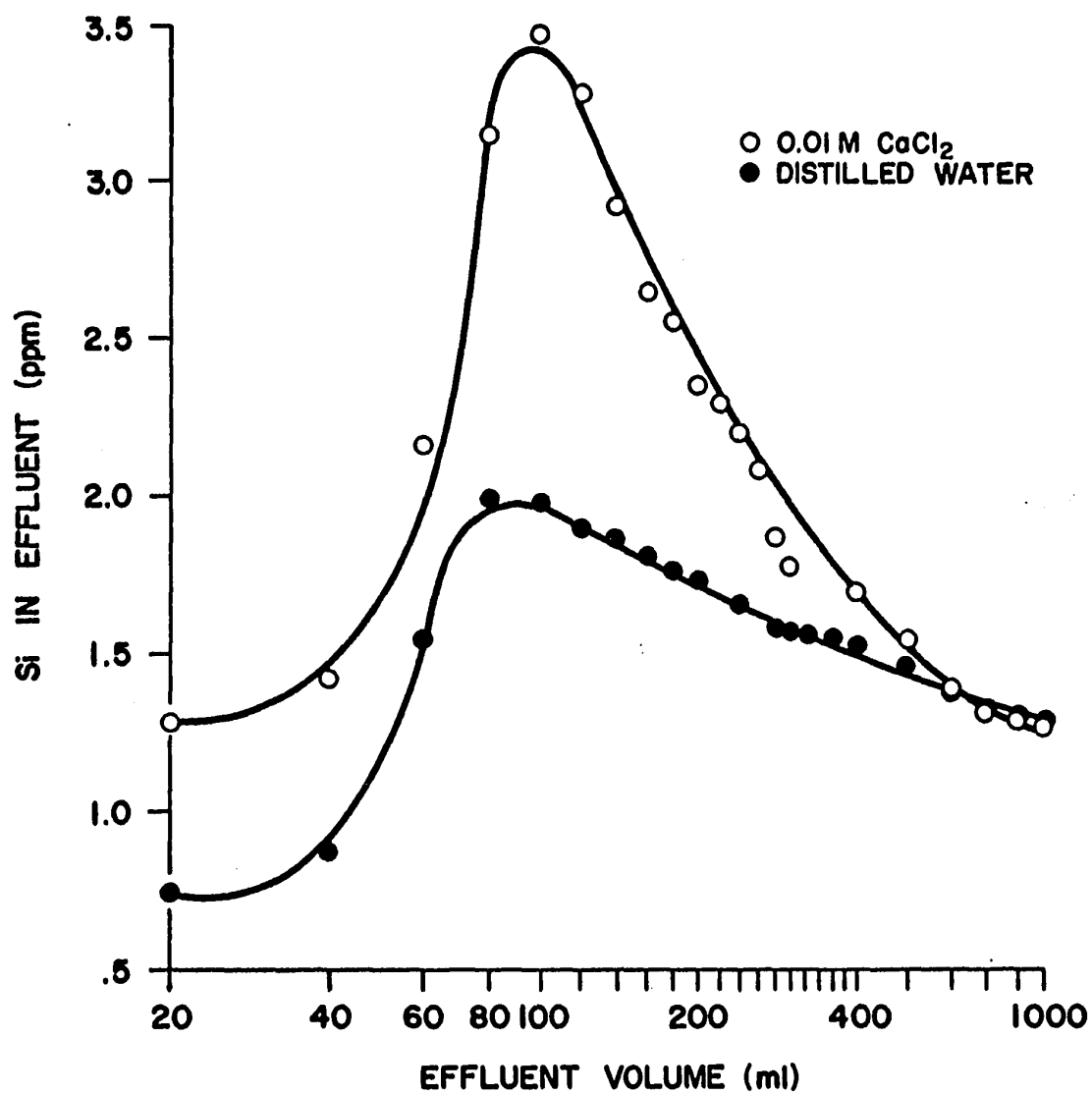


Fig. 41. Effect of Composition of Displacing Solution and the Amount of Leaching on Silicon Movement in Four Inch Columns of Kapaa Soil (Saturated Flow).



However, at the end of the experiment both effluents contained 1.25 ppm Si.

The greater effect of  $\text{CaCl}_2$  solution than water on Si displacement in soils can be explained by the influence of  $\text{CaCl}_2$  on pH. The pH of the  $\text{CaCl}_2$  effluents were between 4.7 and 5.0, while that for the water effluents varied from 5.8 to 6.2.

Exchange of silicate for chloride is a remote possibility. Fox et al. (1967), in an equilibration study, found little difference between Si extracted by water and by a chloride solution, although sulfate, phosphate and acetate extracted more Si than water.

Total amounts of Si leached out of the columns were 1.50 and 1.75 mg Si for the water and  $\text{CaCl}_2$  columns, respectively. Since each column was supplied with only one mg Si, an appreciable fraction of Si in the effluents must have come from the soil itself. Although more Si leaching was effected by  $\text{CaCl}_2$  solution than by water, no appreciable difference was noticed in the distribution of water soluble Si in the soil columns at the end of the experiment (Table 3).

It may be concluded that Si movement in soils may be increased by the presence of other ions, if the presence of the ions depresses soil pH. Ions such as chloride have little effect per se which is an indication that displacement of Si by phosphate or sulfate is not a simple anion exchange involving Coulombic forces. The nature of Si in soil solutions leads to the same

Table 3. Distribution of Water Soluble Silicon  
in Four-Inch Soil Columns After Leaching the Columns  
with Sixty-Seven Centimeters of Water  
or 0.01 M Calcium Chloride Solution<sup>1/</sup>  
(One mg Si Added as  $\text{CaSiO}_3$  Solution)

Column Section	Depth cm.	Column I (Water)	Column II ( $\text{CaCl}_2$ )
a	0 - 2	0.45	0.53
b	2 - 4	0.64	0.70
c	4 - 6	0.70	0.77
d	6 - 8	0.74	0.77
e	8 - 10	0.75	0.73

<sup>1/</sup>Values are ppm Si in a 1:10 water extract.

conclusion.

### Silicon Movement in the Field

The silicon movement study was extended to established field plots. Effects of silicate, phosphate and soil pH on Si movement in Kapaa soil profiles, nine months after slag applications, and distribution of Si in Akaka soil profiles, five years after slag applications was investigated.

Silicon Movement in Kapaa Soil: Both water soluble and phosphate extractable Si in the profiles of the Kapaa soil increased with increasing rates of silicate initially applied (Fig. 42, Appendix Tables 40 to 43). Most of the applied Si was concentrated in the upper 12 inches. Some Si may have moved to 24 inches in the profiles during the nine months after slag applications. Distribution of Si in the profiles was not proportional to the amounts of slag applied. This may be accounted for by: (i) A considerable fraction of soluble Si may have leached out of the zone sampled since more than 100 inches of rain fell during the nine months after slag was applied. (ii) Some soluble Si was taken up by the sugarcane crop (Teranishi, 1968). Some soluble Si was precipitated by Fe and Al oxides of the soil.

A greater proportion of Si in the profiles was retained as phosphate extractable rather than the water soluble form. It was shown earlier that Si sorption by Kapaa soil is high. High

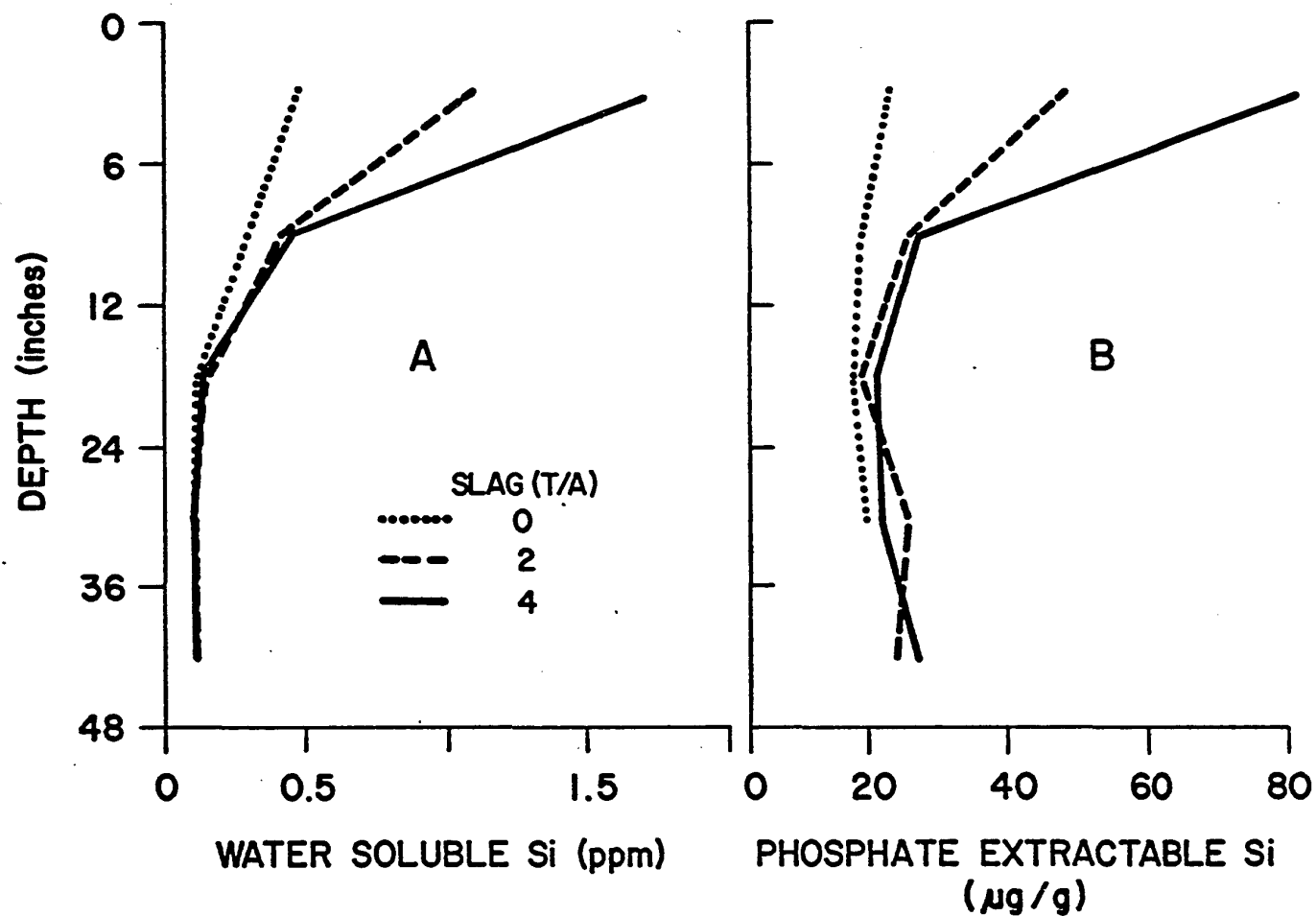


Fig. 42. Distribution of (A) Water Soluble and (B) Phosphate Extractable Silicon in Kapaa Soil Profiles as Influenced by Rates of Applied Silicate. Values are Means of Three pH Levels and Three Phosphate Rates.

phosphate extractable Si may be associated with high Si sorption properties of the soil.

The distribution of Si in the profiles was influenced by soil pH. In general, more soluble Si was found in profiles where topsoil had been limed to pH 5.8 than in profiles where topsoil had been limed to pH 5.5 or 6.2. This does not fit the pattern, indicated earlier, of an inverse relationship between soil pH and the solubility of Si in soils.

Phosphate extractable Si usually was greater in profiles which had the highest pH. However, for the treatment, 1,000 lbs P plus 4 tons of slag, both water soluble and phosphate extractable Si were retained most at pH 5.8 (Fig. 43). In general, Si in the profiles decreased with increasing amounts of P initially applied (Appendix Tables 42 and 43). The decrease was greater at high pH than at low pH. However, there was some increase in both water soluble and phosphate extractable Si in the profiles of the zero silicate plots in the presence of phosphate.

Decreased Si in the profiles with increasing levels of P may be due to the following: (i) Increased solubility of Si in the presence of P and consequent leaching of Si, and (ii) greater removal of Si from the phosphate plus silicate plots by the sugarcane crop due to better growth.

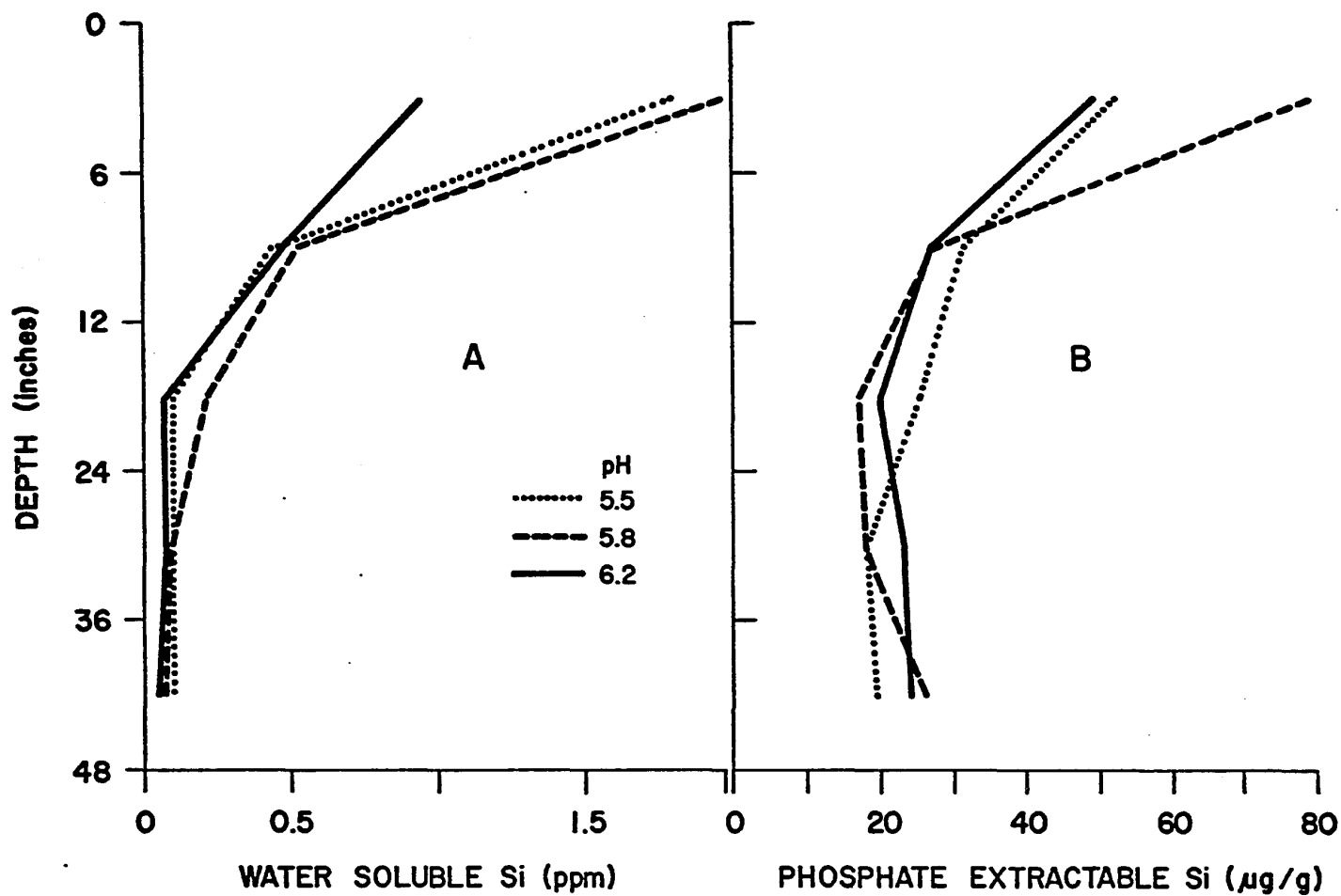


Fig. 43. Distribution of (A) Water Soluble and (B) Phosphate Extractable Silicon in Kapaa Soil Profiles as Influenced by Surface Soil pH (100 lbs. P + 4 Tons of Slag/A).

Silicon Movement in Akaka Soil: Water soluble Si in the profiles of the Akaka soil increased with increasing amounts of slag applied five years before (Fig. 44, Appendix Table 44). Although most Si was concentrated in the top six inches of the profiles, considerable amounts of Si was detectable to 24 inches. Phosphate extractable Si also increased with amounts of slag applications. This fraction was detectable to 36 inches (Fig. 45). Earlier sections have emphasized that Si sorption by Akaka soil is high and a considerable amount of sorbed Si could not be desorbed by distilled water (Appendix Table 35). It is not surprising, then, to find that phosphate extraction accounted for more added Si than did water extraction.

Evidence that a considerable fraction of added Si (applied 5 years earlier) remained in phosphate extractable form is presented in Table 4. Extraction of Si from the high slag (8 tons per acre) treatment, by repeated extractions with a phosphate solution, was 80 percent more than from the check. A similar trend was also observed in sub-soil samples, although the net recoveries over check were much less than in the surface soil samples.

These results indicate that soils that sorb large amounts of Si may retain Si in the profiles in "exchangeable" or difficultly soluble forms, which with time and changes in soil chemical conditions, especially with changing soil pH, may be converted into

Table 4. Effect of Silicate Applications on the Recovery  
of Phosphate Extractable Silicon  
(Five Years After Slag Application)  
from Akaka Soil by Repeated Extractions<sup>1/</sup>

Silicate Applied Tons of Slag/A	<u>Extraction Number</u>				Total	Extraction Over Check
	1	2	3	4		
<u>Topsoil</u>						
0	88	104	96	137	425	-
2	164	136	133	138	570	145
4	230	174	137	161	703	278
6	258	178	142	167	745	320
8	270	173	153	174	769	344
<u>Sub-Soil</u>						
0	83	103	94	125	404	-
2	116	118	94	118	446	42
4	133	120	111	123	487	84
6	147	129	125	157	557	154
8	187	133	144	128	592	188

<sup>1/</sup> Values are ppm Si on O.D. soil basis.



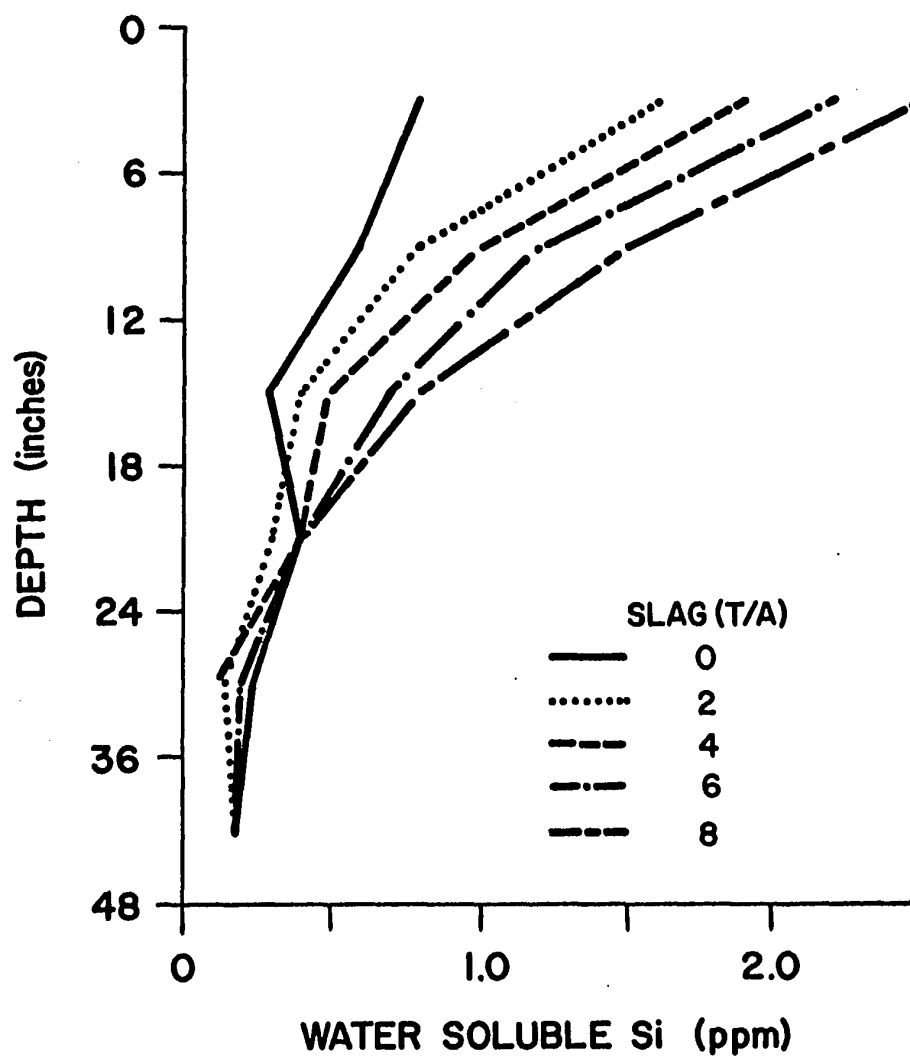


Fig. 44. Distribution of Water Soluble Silicon in Akaka Soil Profiles as Influenced by Silicate Applications Made Five Years Earlier.

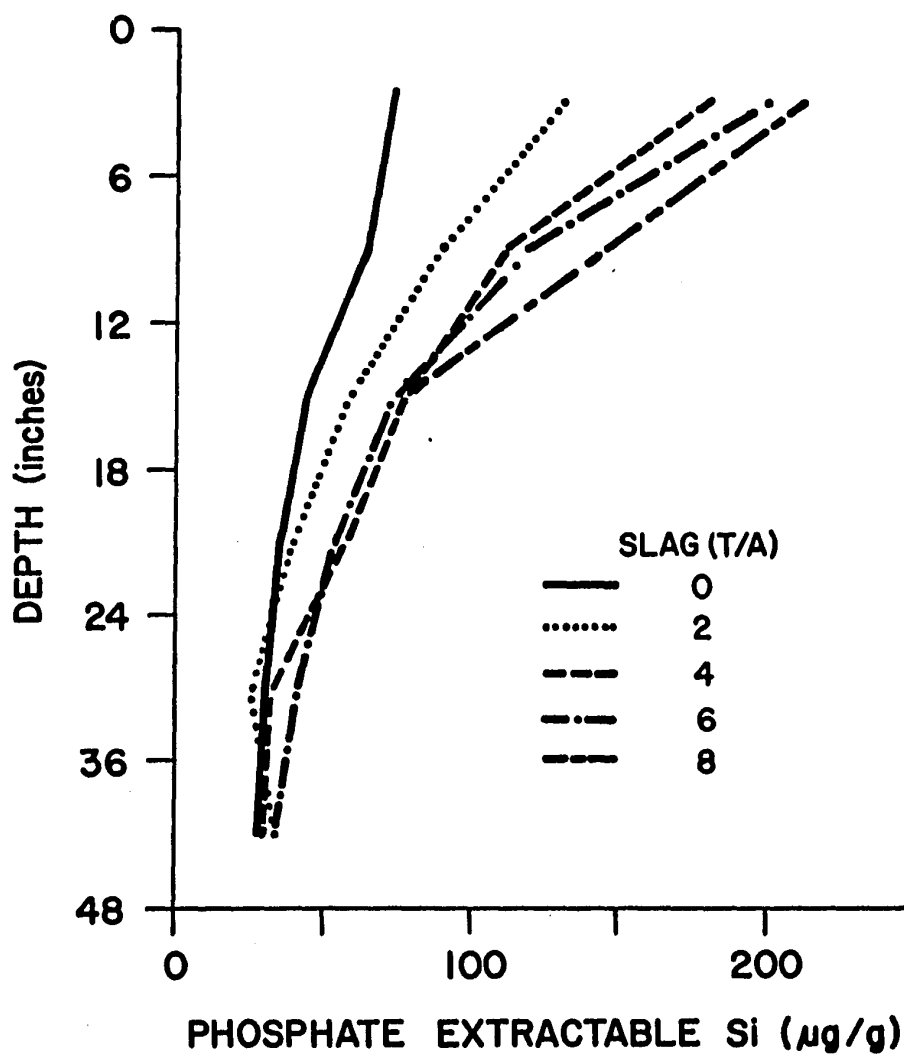


Fig. 45. Distribution of Phosphate Extractable Silicon in Akaka Soil Profiles as Influenced by Silicate Applications Made Five Years Earlier.

water soluble form and be readily available for plants or lost through leaching.

It may be concluded from the above investigations that solubility and movement of Si in soils is a function of the nature of the colloidal fraction, amount of silicate applied, the quantity of water passing through soil profiles and soil pH. Movement may be influenced by the presence of other anions, especially phosphate which increase the solubility of silicon in soils.

#### Exchangeable Soil Aluminum in Soil Profiles

Exchangeable soil Al in profiles of Kapaa soil decreased with slag applications (Table 5). Liming decreased exchangeable Al still further. Increasing the rates of phosphate applications did not affect the exchangeable Al status of the Kapaa soil profiles. The most striking feature in this investigation is the distribution of exchangeable Al in the soil profiles. Exchangeable Al was concentrated in the top 12 inches. The check topsoil contained 10 times more exchangeable Al than the sub-soil. Below 24 inches very little Al exists in the exchangeable form.

Similar trends were observed in the profiles of the Akaka soil (Table 6). An application of 8 tons of slag per acre decreased exchangeable Al 95 percent even five years after slag applications. Exchangeable Al values for the Akaka soil were much smaller than for the Kapaa soil.

Table 5. Distribution of Exchangeable Soil Aluminum in Kapaa Soil Profiles as Influenced by Phosphate, Silicate and Lime Applications<sup>1,2/</sup>

Depth in Inches	Profiles				
	Check pH 4.8	100 lbs P/A		1,000 lbs P/A	
		4 T Slag/A pH 5.5	4 T Slag/A + CaCO <sub>3</sub> pH 6.2	4 T Slag/A pH 5.5	4 T Slag/A + CaCO <sub>3</sub> pH 6.2
0 - 6	63.5	10.0	5.0	11.0	9.0
6 - 12	6.5	11.0	8.0	15.0	0.5
12 - 24	1.0	1.0	2.5	1.5	1.0
24 - 36	0.5	0.3	0.5	0.3	0.3
36 - 48	0.3	0.5	0.3	0.5	0.2

<sup>1/</sup> Values are ppm Al on O.D. soil basis. <sup>2/</sup> Samples from three replicates were composited.

Table 6. Distribution of Exchangeable Soil Aluminum <sup>1,2/</sup>  
in Akaka Soil Profiles as Influenced by Silicate Applications

Depth in Inches	Profiles	
	Check	8 Tons Slag/A
0 - 6	5.0	0.25
6 - 12	3.5	1.00
12 - 18	3.0	0.75
18 - 24	0.5	1.25
24 - 36	0.1	0.25
36 - 48	0.1	0.13

<sup>1/</sup> Values are ppm Al on O.D. soil basis.

<sup>2/</sup> Samples from four replicates were composited.

The decrease in exchangeable Al by silicate applications may be explained by an increase in soil pH, the formation of insoluble aluminosilicate compounds in soils or precipitation of Si on the hydrated Al oxides. The effect of lime may be mainly precipitation of Al in the form of insoluble oxides or hydroxides. These results suggest that aluminum toxicity in plants grown on highly weathered aluminous soils may be effectively decreased by applications of soluble silicates or silicate plus lime.

### PHASE III

#### Interaction Effects of Phosphorus and Silicon on Silicon and Phosphorus Uptake by Plants from Culture Solutions

Conflicting evidence still exists as to the nature of P-Si interactions which affect the P nutrition of plants. Some research indicates that the interaction is in the plant, while other studies suggest interaction in the soil. This study was undertaken to investigate possible interactions between Si and P as these influence P and Si absorption by plants from culture solutions.

A split-root technique was used to grow five plant species. Roots of the same plant were divided into two approximately equal parts and placed into adjacent chambers. Each chamber was provided with one of five combinations of Si and/or P (tagged with  $^{32}\text{P}$ ) in 1/4 strength Hoagland solution. The Si-P combinations were as follows: (i) None (no P or Si), (ii) Si alone,

(iii) P alone, (iv) P and Si together, and (v) P and Si separated. The absorption of P and Si by plants was measured.

Supplying Si and P from the same chamber gave the greatest P concentrations in lettuce, Mimosa and corn but least in rice and sugarcane (Table 7). Phosphorus and Si supplied from separate chambers decreased P concentrations in Mimosa, corn and rice but increased the P concentration in lettuce. However, the differences were not statistically significant except for corn. When the zero P and the zero Si treatments were included in the statistical analysis both P and Si concentrations in the plants differed significantly among the five treatments. In most cases treatment effects differed widely among replications. However, P-Si interactions gave some discernible patterns in the uptake of Si and P.

Additions of Si to culture solutions either together with or separated from P drastically decreased P absorption by rice. The decrease was greatest when both Si and P were in the same chamber. These results suggest that Si has a synergistic effect on P absorption by the plants which accumulate little Si (lettuce and Mimosa), while it has an antagonistic effect of P absorption by species that accumulate large amounts of Si (rice and sugarcane). Phosphorus absorption by corn was increased in the presence of Si significantly, although corn accumulates considerable Si.

Table 7. Phosphorus and Silicon Composition of Plants as Influenced by Phosphorus-Silicon Interactions in Culture Solutions<sup>1/</sup>

Treatment	Dry Matter (g/pot)	Total P		Tagged P (ppm)	Silicon (ppm)
		(ppm)	(mg/pot)		
<u>Lettuce</u>					
None	3.7	2210	8.3	-	176
Si alone	4.0	2350	9.6	-	196
P alone	4.5	3086	14.0	1030	136
P + Si separated	4.2	3240	13.5	1090	170
P + Si together	4.4	3260	14.2	1260	120
<u>Mimosa</u>					
None	4.6	3000	9.5	-	43
Si alone	5.2	1970	10.2	-	90
P alone	6.2	2836	17.0	965	40
P + Si separated	6.3	2820	17.7	935	80
P + Si together	5.6	3290	18.4	1160	70
<u>Rice</u>					
None	5.0	1230	6.2	-	184
Si alone	4.6	1300	5.9	-	7300
P alone	4.1	2675	10.8	1465	280
P + Si separated	4.7	2395	11.4	1180	6690
P + Si together	4.1	2430	10.0	1120	7236
<u>Corn</u>					
None	1.7	845	1.4	-	160
Si alone	1.3	850	1.1	-	2410
P alone	1.9	910	1.7	80	162
P + Si separated	1.9	900	1.7	73	1750
P + Si together	2.0	945	1.9	90	2185

<sup>1/</sup> Values are means of three replicates.



Table 7. Phosphorus and Silicon Composition of Plants as Influenced by Phosphorus-Silicon Interactions in Culture Solutions<sup>1/</sup> (Continued)

Tissues	P/Si Conc. (ppm)	Treatment				
		None	Si Alone	P Alone	P + Si Separated	P + Si Together
Sugarcane						
Mature Cane	Total P	202	172	515	416	364
	Tagged P	-	-	338	266	246
	Silicon	182	630	146	490	380
Immature Cane	Total P	580	530	1660	1600	1825
	Tagged P	-	-	1180	1140	1250
	Silicon	64	3780	60	2530	2390
Leaf 1	Total P	930	1025	2790	2626	2626
	Tagged P	-	-	1960	1710	1860
	Silicon	43	3630	52	3500	2975
Leaves 2 and 3	Total P	520	540	1836	1575	1580
	Tagged P	-	-	1210	1000	912
	Silicon	120	5700	100	4860	3600
Lower Leaves	Total P	400	430	1110	1125	1080
	Tagged P	-	-	620	610	570
	Silicon	174	3360	200	2975	2600
Secondary Shoots	Total P	645	610	2670	2910	2810
	Tagged P	-	-	1960	2210	1640
	Silicon	56	4120	50	5270	5160
Total	Yield (g/pot)	80	77	81	89	88
	Total P (mg/pot)	23	22	102	96	97
	Tagged P (mg/pot)	-	-	65	59	61
	Silicon (mg/pot)	10	175	10	166	133

<sup>1/</sup>Values are means of three replicates.

In all species Si concentrations in the plants were greatest when Si was supplied alone. Greatest Si absorption was by rice and least by lettuce. Silicon concentrations of lettuce, Mimosa and sugarcane were depressed most when P and Si were supplied from the same chamber, indicating antagonistic effects of P on Si absorption by these species. For rice and corn the greatest decrease occurred when Si and P were supplied from separate chambers, indicating that P was still synergistic to Si absorption by rice and corn. In corn, P concentrations differed significantly between the treatments, P and Si together, and P and Si separated, by Duncan's Multiple Range test. Silicon concentrations in lettuce differed significantly only between the treatments, Si alone, and P and Si together.

Phosphorus absorption by corn was very low compared to that by other species. The corn seedlings were raised in a growth chamber under low light intensity, while other species were raised outside under full sunlight. As a result the corn seedlings were weak. The very low P uptake by corn may have resulted from low carbohydrate metabolism. From a general knowledge of normal Si composition of corn, it seems that low light intensity may have inhibited Si absorption by corn. Fox et al. (1969) suggested that Si deposition in sugarcane was associated with growth.

Sugarcane was separated into six different plant parts to

investigate the effects of P-Si interactions on Si and P distribution in different tissues. The greatest concentration of P was in leaf No. 1 and least was in mature cane stalks. Secondary shoots contained even more P than primary shoots. Silicon concentrations were greatest in leaves 2 and 3 and least in mature cane tissues. Again, the secondary shoots contained more Si than the primaries. Both total P concentrations and total Si concentrations differed significantly among treatments and among tissues. Furthermore, when P and Si concentrations in individual tissues were tested by Duncan's Multiple Range test most of the tissues differed significantly from each other.

Silicon depressed P concentrations in all plant parts except immature cane. Silicon was more effective in depressing P concentrations in the tissues when applied together with P than when they were separated from each other. Concentrations of Si in the younger tissues were consistently depressed by P.

The distribution of P in various plant parts indicates that P always moves to the actively growing regions. Even in this short experimental period (7 days) 5 to 10 times more P was translocated to the actively growing tissues than to the older leaves and storage tissues (indicated by  $^{32}\text{P}$  activities in respective tissue). In contrast, Si seems to be very immobile in the plant. This is indicated by the progressive decrease in Si concentrations from the oldest to the youngest tissues in the check plants. The lowest

Si concentration was 43 ppm Si in leaf No. 1 and the highest was 182 ppm in the mature cane stalks. When plants were provided with Si alone, Si concentration in leaf No. 1 rose from 43 to 3626 ppm Si, while in the mature cane stalks the increase was from 182 to 630 ppm. There was a much greater increase in Si concentrations of leaves 2 and 3 than the lower leaves and mature cane stalks. Leaves 2 and 3 were fully open and almost mature, while leaf No. 1 was still immature and partly unrolled. All of them were metabolically active.

These results suggest that Si accumulation in sugarcane is affected by metabolic activities of the tissues. Comparatively high Si concentrations of the immature cane and leaf No. 1 which take little part in transpiration but are metabolically highly active supports this contention.

Tanaka and Park (1966) suggested that Si distribution in rice plants is controlled by the metabolic activities of the organs and also by the rate of transpiration. Yoshida et al. (1962) believe that Si distribution within rice plants is related to the transpiration stream, and that Si is concentrated and precipitated as a result of transpiration.

The results of the present investigation are in agreement with those of Fox et al. (1969), who suggested that Si deposition in sugarcane is associated with growth. These investigators reported that total and soluble Si was higher in the metabolically

active tissues (leaf sheaths and leaf blades). Soluble Si was highest in the least mature tissue.

The presence of P in culture solutions decreased Si concentrations in all plant parts of sugarcane. Greatest decrease occurred when both P and Si were supplied from the same chamber. Similar effects were observed in lettuce and Mimosa. Ganssmann (1962) proposed that P decreased Si concentrations in plants due to increased dry matter yields. The results of the present investigation do not agree with the above statement, since it is unlikely that P increased plant growth appreciably during this experiment. In most cases Si concentrations decreased even though total dry matter yields were not changed very much.

Silicon is known to be present in solution as uncharged monosilicic acid,  $\text{Si}(\text{OH})_4$  below pH 7 (Iler, 1955), and it is considered to be in this form in soil solutions (McKeague and Cline, 1963; Beckwith and Reeve, 1964). It is generally assumed that the mechanism by which ions are absorbed by plants is associated with electrochemical cell potentials contributed by cations and anions of plant cells, but Barber and Shone (1966) indicated that the absorption of nonpolar  $\text{Si}(\text{OH})_4$  by plants is an active process.

It is well established that active accumulation or exclusion of one or more ions may bring about differences in electrical potential which may cause ions to move passively against a concentration gradient (Dainty, 1962). This theory explains neither

increased P uptake due to Si absorption by plants nor exclusion of Si due to P absorption, since P is absorbed as an anion ( $\text{H}_2\text{PO}_4^-$  or  $\text{HPO}_4^{=}$ ), while Si is absorbed as nonpolar  $\text{Si}(\text{OH})_4$ , which should not affect electrical potential in the plant cell. Moreover, exclusion of Si due to P sorption is a rather common phenomenon, while the influence of Si on P absorption varies with species. It may, therefore, be concluded that the positive or negative interaction effects of Si and P on their uptake by plants are either inherent in the species or are involved in P metabolism of the plant rather than being a simple absorption phenomenon. That leaf phosphatase, amylase, peroxidase and phenol oxidase in sugarcane can be suppressed by Si has been indicated by Alexander (1968). Alexander also demonstrated that Si increased sucrose accumulation in sugarcane leaf and immature storage tissues by invertase suppression.

Upward and Lateral Transport of Phosphorus and Silicon in Plants: The transport ratios of absorbed P indicate that translocation of tagged P from fertilized roots to unfertilized roots was much smaller than the movement from roots to tops (Table 8). This was true for all species. The transport ratio was calculated as follows:

$$\text{Transport Ratio} = \frac{^{32}\text{P}/\text{total P concentration in tissue}}{^{32}\text{P}/\text{total P concentration in fertilized roots}}$$

In relative terms, the greatest translocation of  $^{32}\text{P}$  from

Table 8. Transport Ratios<sup>1/</sup> of <sup>32</sup>P in Plant Parts  
as Influenced by Phosphorus-Silicon Interactions  
in Culture Solutions<sup>2/</sup>

Tissues	Treatment		
	P Alone	P and Si Separated	P and Si Together
<u>Lettuce</u>			
Fertilized Roots	1.00	1.00	1.00
Tops	0.56	0.56	0.67
Unfertilized Roots	0.21	0.18	0.17
<u>Mimosa</u>			
Fertilized Roots	1.00	1.00	1.00
Tops	0.60	0.64	0.84
Unfertilized Roots	0.19	0.24	0.23
<u>Rice</u>			
Fertilized Roots	1.00	1.00	1.00
Tops	1.12	0.85	0.83
Unfertilized Roots	0.41	0.31	0.50
<u>Corn</u>			
Fertilized Roots	1.00	1.00	1.00
Tops	0.48	0.45	0.50
Unfertilized Roots	0.33	0.28	0.27
<u>Sugarcane</u>			
Fertilized Roots	1.00	1.00	1.00
Tops (Leaves):			
Leaf 1	0.96	0.92	1.00
Leaves 2 and 3	0.90	0.91	0.84
Lower Leaves	0.77	0.76	0.76
Unfertilized Roots	0.46	0.48	0.47

$$\text{1/ Transport Ratio} = \frac{^{32}\text{P}/\text{total P concentration in tissue}}{^{32}\text{P}/\text{total P concentration in fertilized roots}}$$

2/ Values are means of three replicates.

fertilized roots to tops occurred in plants that accumulate considerable Si and the least translocation occurred in plants that accumulate little Si. The greatest transport of  $^{32}\text{P}$  from fertilized roots to tops occurred in sugarcane and the least in lettuce. These results indicate that in some plants Si may stimulate P movement.

In lettuce and Mimosa,  $^{32}\text{P}$  transport from fertilized roots to tops was greatest when both Si and P were supplied from the same chamber, indicating an influence of Si on upward transport of P in these species. Yet these are the species that take up little Si. Unfortunately concentrations of soluble Si in these species are not known. In rice and sugarcane the presence of Si together with or separated from P did not affect upward transport of  $^{32}\text{P}$ .

Lateral translocation of  $^{32}\text{P}$  (translocation from fertilized to unfertilized roots) was very little affected by the supply of Si from the culture media. However, in rice lateral transport of  $^{32}\text{P}$  was depressed when Si and P were supplied from separate chambers. These results suggest that the effect of Si is primarily associated with upward translocation of phosphorus in plants.

When plants were grown without intentional Si additions root Si was greater than Si in tops in all species except sugarcane (Table 9). When Si was supplied to the plants, plants which accumulate Si (rice, sugarcane and corn) absorbed and



Table 9. Increase or Decrease in Concentrations of Added Silicon in Plant Parts as Influenced by Phosphorus-Silicon Interactions in Culture Solutions<sup>1/</sup>

Tissues	Treatment									
	Check		Si Alone		P Alone		P and Si Separated		P and Si Together	
	Gross Si Conc. (ppm)	Net Si Increase (ppm)	Ratio <sup>2/</sup>		Conc. (ppm)	Ratio	Conc. (ppm)	Ratio	Conc. (ppm)	Ratio
<u>Lettuce</u>										
Fertilized Roots	-	+227	+1.0		+27	+1.0	+156	+1.0	+24	+1.0
Tops	176	+20	+0.09		-40	-1.5	-6	+0.04	-60	-2.5
Unfertilized Roots	194	+198	+0.87		+10	+0.4	+136	+0.9	+56	+2.3
<u>Mimosa</u>										
Fertilized Roots	-	+181	+1.0		+8	+1.0	+63	+1.0	+81	+1.0
Tops	43	+48	+0.3		+2	+0.3	+39	+0.6	+25	+0.3
Unfertilized Roots	64	+18	+0.1		+16	+2	+23	+0.4	+36	+0.4
<u>Rice</u>										
Fertilized Roots	-	+1210	+1.0		+8	+1.0	+205	+1.0	+7	+1.0
Tops	184	+7116	+5.9		+95	+12	+6500	+31.7	+7050	+1000
Unfertilized Roots	630	+1018	+0.8		+18	+2.2	-53	-0.3	+60	+8.4
<u>Corn</u>										
Fertilized Roots	-	+292	+1.0		+3	+1.0	+190	+1.0	+165	+1.0
Tops	157	+2250	+7.7		+5	+1.6	+1590	+8.4	+2030	+12.3
Unfertilized Roots	170	+190	+0.7		+3	+1.0	+14	+0.7	+222	+0.1

<sup>1/</sup> Values are means of three replicates.

<sup>2/</sup> Ratio =  $\frac{\text{Net Si concentration in tissue}}{\text{Net Si concentration in fertilized roots}}$

Table 9. Increase or Decrease in Concentrations of Added Silicon in Plant Parts as Influenced by Phosphorus-Silicon Interactions in Culture Solutions<sup>1/</sup> (Continued)

Tissues	Treatment									
	Check		Si Alone		P Alone		P and Si Separated		P and Si Together	
	Gross Si Conc. (ppm)	Net Si Increase (ppm)	Ratio <sup>2/</sup>		Conc. (ppm)	Ratio	Conc. (ppm)	Ratio	Conc. (ppm)	Ratio
<u>Sugarcane</u>										
Fertilized Roots	-	+776	+1.0	+15	+1.0	+510	+1.0	+404	+1.0	
Tops: Leaf 1	43	+3580	+4.6	+9	+0.6	+3460	+6.8	+2930	+7.3	
Leaves 2 and 3	123	+5590	+7.2	-23	-1.5	+4740	+9.3	+3480	+8.6	
Lower Leaves	174	+3190	+4.1	+30	+2.0	+2800	+5.5	+2434	+6.0	
Unfertilized Roots	50	+43	+0.06	+4	+0.3	+41	+0.08	+9	+0.02	

<sup>1/</sup>Values are means of three replicates.

<sup>2/</sup>Ratio =  $\frac{\text{Net Si concentration in tissue}}{\text{Net Si concentration in fertilized roots}}$

transported to tops considerable amounts of Si, while in plants, which accumulate little Si (lettuce and Mimosa) most of the absorbed Si remained in the roots whether in the vascular tissue, in cells or in free spaces was not determined.

In the presence of P, supplied either together with or separated from Si, both accumulation and lateral transport of Si were depressed. This was true for all species irrespective of their Si status.

Effect of Varying Ratios of Silicon and Phosphorus in Culture Solutions on the Yield, and Phosphorus and Silicon Status of Sugarcane

Sugarcane was grown for four months in water culture at four levels of P (0, 0.2, 0.5 and 1 ppm P) and four levels of Si (0, 0.2, 2 and 5 ppm Si). Nutrient solutions were renewed once each week. Dry matter yields and uptake of P and Si were measured at two months and at four months.

Total sugarcane yields of the combined harvests increased with increasing levels of P and Si supplied (Table 10). Yield increases were roughly proportional to P supply and analysis of variance indicated that they were highly significant. Effects of P levels on yields differed significantly from each other by Duncan's Multiple Range test. Silicon did not increase yields significantly. The highest Si concentration (5 ppm Si) had an adverse effect on

Table 10. Interaction of Silicon and Phosphorus  
in Culture Solutions on Yield, and  
Phosphorus and Silicon Uptake by Sugarcane<sup>1/</sup>

Treatments		Dry Matter Yield g/pot	Total P Uptake mg/pot	Total Si Uptake mg/pot
Phosphorus (ppm)	Silicon (ppm)			
0	0	25.3	9.9	17.8
	0.2	28.6	10.4	33.6
	2	26.2	7.5	109.5
	5	42.6	12.4	294.6
0.2	0	55.1	20.5	28.2
	0.2	52.2	19.0	43.0
	2	67.6	23.2	174.0
	5	55.6	19.7	329.6
0.5	0	89.4	38.0	39.2
	0.2	105.5	45.6	49.0
	2	101.5	39.5	151.0
	5	90.9	37.3	277.0
1.0	0	151.5	64.6	46.6
	0.2	150.7	70.7	54.3
	2	156.0	74.2	165.8
	5	160.4	69.8	338.9

<sup>1/</sup> Values are means of the combined harvests.

cane growth at low P levels. At the highest P level (1 ppm P) cane yields were increased at all levels of applied Si. Increased yields were always associated with increased P uptake.

Although 0.2 ppm P has been taken as a standard P concentration in soil solutions for normal plant growth, it was not feasible to maintain this concentration constant in the culture solutions. It is certain that the plants were phosphorus starved. Even plants growing at the highest P level (1 ppm P) contained only about 50 percent of the normal P concentration of sugarcane.

Silicon uptake by sugarcane increased with increasing Si levels in culture solutions irrespective of P supply and this increase was highly significant. However, concentrations of Si in sugarcane decreased with increasing levels of P in culture solutions (Tables 11 and 12). There was a highly significant phosphorus X silicon interaction on Si content of plants, and Si uptake was significantly decreased by the highest P level.

Phosphorus uptake of the combined harvests was roughly proportional to P supply. There was no consistent trend between total P uptake and Si supply at low P levels. However at the highest P level, P uptake tended to increase with increasing Si supply, but total P uptake was depressed at the highest Si level. There was a significant P X Si interaction in P concentrations but not in total P uptake.

Table 11. Interaction of Silicon and Phosphorus in Culture Solutions on Yield, and Phosphorus and Silicon Composition of Sugarcane at Two Months<sup>1/</sup>

Treatment		Dry Matter Yields g/pot	Phosphorus		Silicon	
Phosphorus (ppm)	Silicon (ppm)		ppm	mg/pot	%	mg/pot
0	0	6.0	500	3.0	0.11	6.8
	0.2	9.7	526	5.1	0.13	12.7
	2	8.8	398	3.5	0.15	13.3
	5	13.4	403	5.4	0.72	96.9
0.2	0	14.3	517	7.4	0.08	11.4
	0.2	11.9	530	6.3	0.16	19.4
	2	21.3	484	10.3	0.31	66.5
	5	14.8	500	7.4	0.73	107.3
0.5	0	24.7	558	13.8	0.08	18.7
	0.2	24.0	604	14.5	0.08	19.3
	2	15.2	565	8.6	0.27	40.5
	5	21.6	560	12.1	0.40	86.0
1.0	0	41.0	578	23.7	0.04	16.0
	0.2	38.7	625	24.1	0.05	18.5
	2	37.2	656	24.4	0.14	51.2
	5	37.4	594	22.2	0.31	116.0

<sup>1/</sup> The values are means of two replicates.

Table 12. Interaction of Silicon and Phosphorus on Yield,  
and Phosphorus and Silicon Composition of Sugarcane  
at Four Months<sup>1/</sup>

Treatment		Dry Matter Yield g/pot	Phosphorus		Silicon	
Phosphorus (ppm)	Silicon (ppm)		ppm	mg/pot	%	mg/pot
0	0	17.7	395	6.5	0.07	10.6
	0.2	17.2	323	5.0	0.14	19.0
	2	15.8	257	3.7	0.61	86.0
	5	76.7	265	6.5	0.83	184.3
0.2	0	37.0	362	12.1	0.05	16.2
	0.2	36.4	366	11.9	0.07	21.0
	2	37.6	350	11.8	0.28	94.8
	5	37.0	350	11.6	0.58	189.5
0.5	0	59.9	412	22.7	0.04	19.6
	0.2	76.0	424	29.7	0.04	27.3
	2	80.0	395	28.9	0.13	97.5
	5	63.5	405	23.5	0.30	171.4
1.0	0	104.0	444	38.4	0.03	29.0
	0.2	105.6	448	44.0	0.03	37.9
	2	111.3	456	47.4	0.10	103.5
	5	116.0	413	44.9	0.19	205.3

<sup>1/</sup> Values are means of two replicates.

Sugarcane was harvested twice, at two months and at four months. At both stages dry matter yields and total P uptake were roughly proportional to P supply. At four months dry matter yields increased with increasing Si levels. The effect of Si on utilization of limited amounts of P was indicated in the sheath weights (Table 13 and Fig. 46). These results indicate that at low levels of P, Si may help make more efficient use of P. At higher levels of P there may be an effect from Si over and above its effect on P. Phosphorus concentrations in plants decreased with increasing Si supply at all P levels when the cane was four months old. However, at 0.5 and 1 ppm P levels total P uptake increased in the presence of Si due to increased cane growth. Silicon concentrations in sugarcane decreased with increasing rates of P supply. However, total Si uptake increased in the presence of P due to increased growth.

Both Si and P stimulated root growth (Table 14). Effects of P were more pronounced than the effects of Si. In general, Si increased root growth at all P levels, and at deficiency levels of P silicon treatments tended to give greater yield per unit P in the plant (Fig. 47). Phosphorus concentrations in the roots decreased with increasing levels of Si in the culture solutions at all P levels when the cane was two months old. However, at four months P concentrations in roots were increased with Si levels at the 0.5 and 1 ppm P levels. This may have been due



Table 13. Interaction of Silicon and Phosphorus in Culture Solutions on Phosphorus and Silicon Composition of Sugarcane Sheaths at Four Months<sup>1/</sup>

Treatment		Sheath Yield g/pot	Phosphorus		Silicon	
Phosphorus (ppm)	Silicon (ppm)		ppm	mg/pot	%	mg/pot
0	0	1.6	234	0.46	0.02	0.5
	0.2	1.7	189	0.34	0.12	2.0
	2	1.6	196	0.30	0.66	10.2
	5	2.4	181	0.43	0.85	20.0
0.2	0	3.7	255	0.95	0.02	0.6
	0.2	3.9	238	0.90	0.07	2.7
	2	3.8	288	1.10	0.34	12.8
	5	3.8	203	0.75	0.60	22.8
0.5	0	4.9	288	1.35	0.02	0.8
	0.2	5.6	288	1.60	0.04	2.4
	2	6.3	320	2.00	0.21	13.1
	5	5.7	270	1.55	0.34	19.6
1.0	0	6.4	398	2.55	0.02	1.6
	0.2	6.4	395	2.50	0.05	3.0
	2	6.4	399	2.45	0.15	11.2
	5	7.0	390	2.75	0.25	17.5

<sup>1/</sup> Values are means of two replicates.

Table 14. Interaction of Silicon and Phosphorus in Culture Solutions on Silicon and Phosphorus Composition of Sugarcane Roots<sup>1/</sup>

Treatment		Root Yield g/pot	Phosphorus		Silicon	
Phosphorus (ppm)	Silicon (ppm)		ppm	mg/pot	ppm	mg/pot
<u>At Two Months</u>						
0	0	3.6	225	0.81	80	0.3
	0.2	4.5	225	1.0	64	0.3
	2	4.6	150	0.7	352	1.6
	5	4.8	112	0.5	544	2.6
0.2	0	5.7	262	1.5	80	0.5
	0.2	6.5	240	1.6	70	0.5
	2	9.0	240	2.2	168	1.5
	5	7.0	150	1.1	400	2.8
0.5	0	8.5	338	2.9	90	0.8
	0.2	6.8	300	2.0	70	0.5
	2	5.5	260	1.4	104	0.6
	5	10.0	240	2.4	208	2.1
1.0	0	11.2	375	4.2	60	0.7
	0.2	11.4	315	3.6	50	0.6
	2	9.3	338	3.1	40	0.4
	5	11.7	300	3.5	152	1.8
<u>At Four Months</u>						
0	0	8.0	225	1.8	75	0.6
	0.2	8.3	240	2.0	272	2.3
	2	7.8	210	1.6	410	3.2
	5	13.6	220	3.0	310	4.2
0.2	0	10.2	340	3.5	72	0.7
	0.2	16.2	285	4.6	96	1.6
	2	15.4	315	4.9	336	5.2
	5	16.0	315	5.0	320	5.0
0.5	0	21.9	435	9.5	64	1.4
	0.2	22.1	360	8.0	152	3.4
	2	23.7	450	10.7	376	8.9
	5	23.4	488	11.4	240	5.6
1.0	0	26.8	450	12.0	70	1.9
	0.2	26.9	410	11.0	144	3.9
	2	27.1	690	18.8	196	5.3
	5	28.5	730	20.8	176	5.0

<sup>1/</sup> Values are means of two replicates.

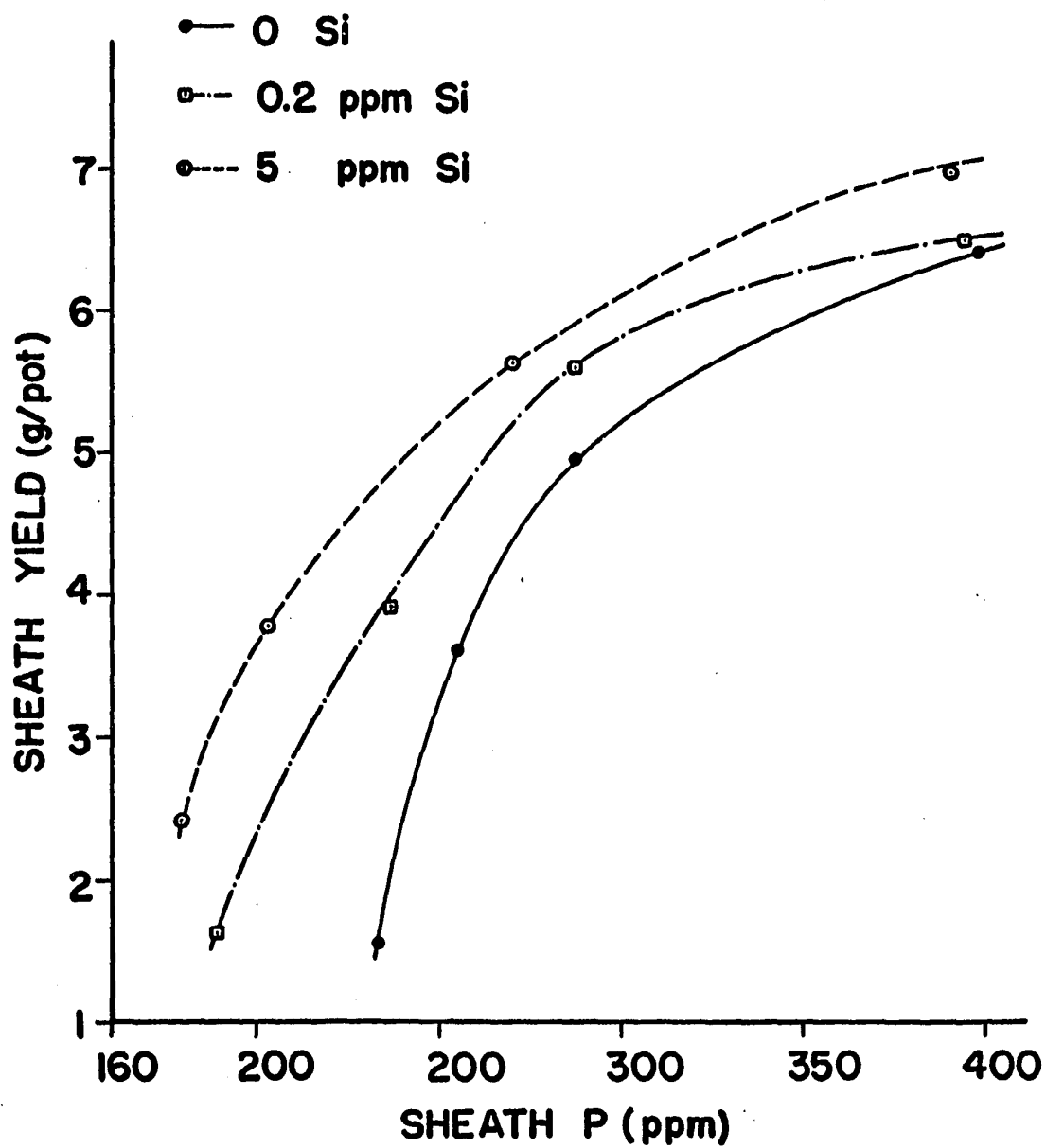


Fig. 46. Sugarcane Sheath Yields in Relation to Phosphorus Concentrations at Three Levels of Silicon in Solution.

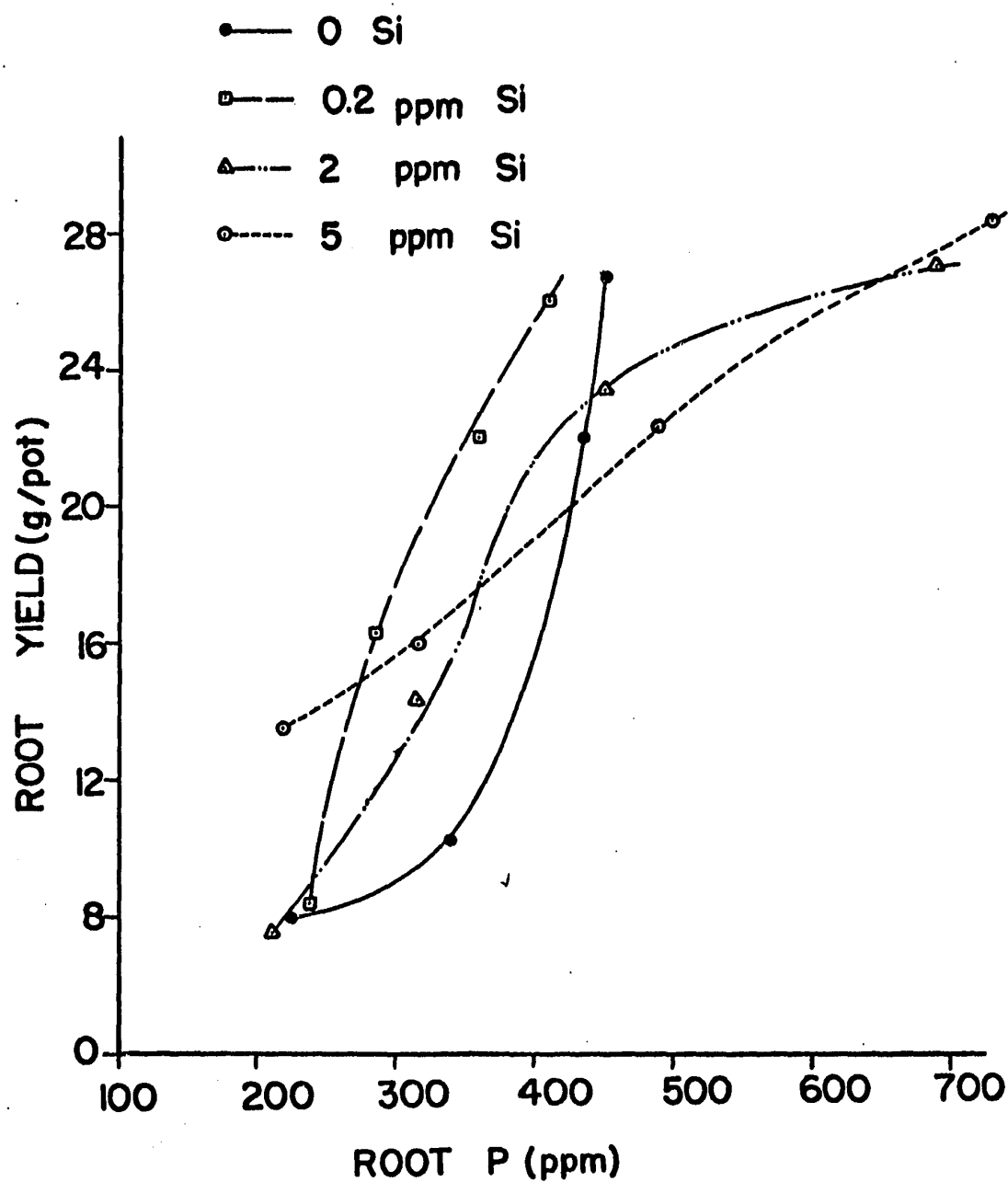


Fig. 47. Sugarcane Root Yields in Relation to Phosphorus Concentrations at Four Levels of Silicon in Solution.

to immobilization of P in the roots from excess Ca movement to the roots. Silicon concentration of the roots was depressed by the addition of P. This may be a dilution effect, since this was largely associated with better root growth in the presence of P.

## PHASE IV

### Effects of Placement on Phosphorus-Silicon Interactions

This study was conducted to evaluate manner of placement of P and Si on phosphorus-silicon interactions in soils and consequent influence on P and Si uptake by plants. Plants were grown in pots with the following silicate and phosphate placements: P banded, P and Si banded together, P and Si banded separately, P mixed with one-half of the soil, P and Si mixed together with one-half of the soil, and P and Si mixed separately with two-halves of the soil. The placement combinations are illustrated in Figure 48.

Yield: In general, lettuce, Mimosa, corn and rice yields were greatest when P and Si were banded together (Tables 15 to 20), while in sugarcane, yields were greatest when P and Si were placed apart (Tables 21 to 23). For lettuce and Mimosa band placements were superior to mixed placements. Analysis of variance showed that placement effects on lettuce yields were highly significant. Mimosa yields were only slightly increased by silicate applications with phosphate in the Kawaihoa and Wahiawa

Table 15. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Uptake by Lettuce Grown on Three Hawaiian Soils<sup>1/</sup>

Placement	Yield g/pot	Phosphorus mg/pot	Silicon mg/pot
<u>Akaka</u>			
P banded	8.9	27.0	1.63
P + Si banded together	9.3	30.2	3.31
P + Si banded separately	9.1	28.6	2.39
P mixed with 1/2 soil	7.0	20.7	1.24
P + Si mixed together	7.4	24.4	2.84
P + Si mixed separately	7.7	25.1	3.12
<u>Kawailoa</u>			
P banded	8.7	30.6	4.80
P + Si banded together	11.4	37.0	11.81
P + Si banded separately	12.2	41.0	11.63
P mixed with 1/2 soil	5.9	18.9	2.54
P + Si mixed together	10.9	36.2	12.83
P + Si mixed separately	8.4	26.9	7.97
<u>Wahiawa</u>			
P banded	10.5	34.7	7.50
P + Si banded together	10.7	33.9	10.65
P + Si banded separately	10.2	40.6	9.30
P mixed with 1/2 soil	10.3	33.0	6.35
P + Si mixed together	10.4	36.5	9.75
P + Si mixed separately	10.2	32.9	9.95

<sup>1/</sup> Values are means of combined harvests.

Table 16. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Lettuce Grown on Three Hawaiian Soils at Four Weeks<sup>1/</sup>

Placement	Yield g/pot	Phosphorus			Silicon	
		%	mg/pot	Fert. P % of Total	%	mg/pot
<u>Akaka</u>						
P banded	2.7	0.312	8.4	91	0.016	0.43
P + Si banded together	3.0	0.344	10.4	96	0.029	0.86
P + Si banded separately	2.9	0.332	9.5	94	0.026	0.74
P mixed with 1/2 soil	2.0	0.328	6.7	92	0.020	0.41
P + Si mixed together	2.2	0.332	7.3	95	0.029	0.64
P + Si mixed separately	2.1	0.316	6.5	94	0.035	0.77
<u>Kawailoa</u>						
P banded	2.1	0.348	7.3	93	0.038	0.08
P + Si banded together	2.9	0.280	10.9	92	0.081	0.23
P + Si banded separately	2.4	0.400	9.4	96	0.060	0.14
P mixed with 1/2 soil	1.5	0.437	6.6	94	0.033	0.05
P + Si mixed together	2.2	0.348	7.7	85	0.056	0.12
P + Si mixed separately	1.8	0.272	4.9	98	0.050	0.09
<u>Wahiawa</u>						
P banded	3.4	0.372	12.5	95	0.070	2.4
P + Si banded together	3.6	0.292	10.3	98	0.077	2.8
P + Si banded separately	3.2	0.463	14.8	94	0.085	2.7
P mixed with 1/2 soil	3.6	0.364	12.9	95	0.056	2.0
P + Si mixed together	3.7	0.365	13.5	97	0.066	2.5
P + Si mixed separately	3.5	0.373	12.9	92	0.071	2.5

<sup>1/</sup> Values are means of two replicates.

Table 17. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Lettuce Grown in Three Hawaiian Soils at Six Weeks<sup>1/</sup>

Placement	Yield g/pot	Phosphorus			Silicon	
		%	mg/pot	Fert. P % of Total	%	mg/pot
<u>Akaka</u>						
P banded	6.2	0.300	18.6	78	0.019	1.20
P + Si banded together	6.3	0.316	19.8	80	0.038	2.45
P + Si banded separately	6.2	0.308	19.1	70	0.026	1.65
P mixed with 1/2 soil	5.0	0.284	14.0	93	0.017	0.83
P + Si mixed together	5.2	0.328	17.2	76	0.042	2.20
P + Si mixed separately	5.6	0.336	18.6	84	0.043	2.35
<u>Kawailoa</u>						
P banded	6.6	0.354	23.3	88	0.060	4.0
P + Si banded together	8.5	0.310	26.2	79	0.110	9.5
P + Si banded separately	9.8	0.324	31.6	87	0.105	9.5
P mixed with 1/2 soil	4.4	0.266	12.3	84	0.050	2.0
P + Si mixed together	8.7	0.333	28.5	87	0.134	11.6
P + Si mixed separately	6.6	0.335	22.0	90	0.108	7.1
<u>Wahiawa</u>						
P banded	7.1	0.312	22.2	95	0.072	5.2
P + Si banded together	7.1	0.336	23.6	94	0.110	7.9
P + Si banded separately	7.0	0.373	25.8	98	0.094	6.6
P mixed with 1/2 soil	6.8	0.297	20.0	91	0.065	4.4
P + Si mixed together	6.7	0.343	23.0	90	0.108	7.3
P + Si mixed separately	6.8	0.298	20.0	93	0.113	7.5

<sup>1/</sup> Values are means of two replicates.



Table 18. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Mimosa Grown on Three Hawaiian Soils<sup>1/</sup>

Placement	Yield g/pot	Phosphorus			Silicon	
		%	mg/pot	Fert. P % of Total	%	mg/pot
<u>Akaka</u>						
P banded	17.6	0.192	33.7	80	0.020	3.6
P + Si banded together	17.0	0.196	33.2	86	0.017	2.8
P + Si banded separately	18.7	0.196	36.3	88	0.019	3.6
P mixed with 1/2 soil	18.3	0.217	39.8	92	0.020	3.6
P + Si mixed together	16.0	0.200	32.1	81	0.024	4.3
P + Si mixed separately	18.9	0.194	36.3	91	0.022	4.1
<u>Kawailoa</u>						
P banded	10.0	0.148	14.8	97	0.015	1.5
P + Si banded together	11.3	0.204	23.0	99	0.027	3.1
P + Si banded separately	10.3	0.156	16.1	93	0.017	1.8
P mixed with 1/2 soil	9.4	0.184	17.3	78	0.013	1.2
P + Si mixed together	10.6	0.163	17.3	88	0.021	2.2
P + Si mixed separately	9.6	0.175	16.8	87	0.021	2.1
<u>Wahiawa</u>						
P banded	8.1	0.180	14.6	95	0.012	1.0
P + Si banded together	8.8	0.184	16.9	88	0.024	2.1
P + Si banded separately	8.2	0.184	15.1	90	0.019	1.5
P mixed with 1/2 soil	6.6	0.172	11.4	81	0.014	0.9
P + Si mixed together	7.8	0.192	15.4	79	0.023	1.8
P + Si mixed separately	7.4	0.168	12.4	89	0.017	1.3

<sup>1/</sup> Values are means of two replicates.

Table 19. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Corn Grown on Three Hawaiian Soils<sup>1/</sup>

Placement	Yield g/pot	Phosphorus			Silicon	
		%	mg/pot	Fert. P % of Total	%	mg/pot
<u>Akaka</u>						
P banded	18.2	0.147	26.7	71	0.287	52.0
P + Si banded together	20.4	0.151	30.8	78	0.672	136.6
P + Si banded separately	17.6	0.155	27.2	69	0.624	109.6
P mixed with 1/2 soil	17.7	0.138	24.4	77	0.237	41.9
P + Si mixed together	20.3	0.143	29.0	82	0.926	187.7
P + Si mixed separately	19.8	0.139	27.5	75	1.057	208.0
<u>Kawailoa</u>						
P banded	9.5	0.168	16.0	88	0.609	57.9
P + Si banded together	11.7	0.228	26.7	97	1.200	140.5
P + Si banded separately	10.7	0.168	18.0	89	0.938	100.3
P mixed with 1/2 soil	8.0	0.204	16.3	81	0.555	44.5
P + Si mixed together	12.2	0.228	27.8	84	1.482	180.2
P + Si mixed separately	10.1	0.180	18.2	85	1.031	104.0
<u>Wahiawa</u>						
P banded	6.7	0.180	12.0	90	0.572	38.3
P + Si banded together	9.6	0.204	19.6	93	1.163	111.6
P + Si banded separately	8.8	0.180	15.8	84	0.938	82.5
P mixed with 1/2 soil	8.0	0.180	14.6	91	0.778	63.0
P + Si mixed together	9.2	0.216	19.9	86	1.500	138.0
P + Si mixed separately	8.8	0.144	12.7	89	1.444	127.0

<sup>1/</sup> Values are means of two replicates.

Table 20. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Rice Grown on Three Hawaiian Soils<sup>1/</sup>

Placement	Yield g/pot	Phosphorus			Silicon	
		%	mg/pot	Fert. P % of Total	%	mg/pot
<u>Akaka</u>						
P banded	18.6	0.215	39.8	93	0.544	101.0
P + Si banded together	18.5	0.198	36.5	94	1.784	329.4
P + Si banded separately	19.2	0.203	39.0	91	2.115	406.2
P mixed with 1/2 soil	17.6	0.243	42.6	94	0.615	108.0
P + Si mixed together	20.1	0.192	38.4	83	2.980	599.4
P + Si mixed separately	18.8	0.210	39.4	85	3.446	647.3
<u>Kawailoa</u>						
P banded	16.7	0.264	43.8	95	0.490	81.8
P + Si banded together	21.2	0.159	33.4	89	1.174	247.9
P + Si banded separately	18.9	0.206	38.7	87	1.216	227.8
P mixed with 1/2 soil	19.0	0.225	43.1	92	0.348	66.4
P + Si mixed together	20.2	0.199	40.1	92	1.432	291.0
P + Si mixed separately	24.8	0.218	54.0	89	2.527	378.8
<u>Wahiawa</u>						
P banded	17.2	0.198	33.9	88	1.300	220.9
P + Si banded together	18.4	0.185	34.2	89	2.352	430.5
P + Si banded separately	17.0	0.228	38.6	79	2.052	350.4
P mixed with 1/2 soil	15.7	0.256	40.2	85	1.148	180.0
P + Si mixed together	18.2	0.192	35.0	87	3.362	610.0
P + Si mixed separately	16.5	0.245	40.3	77	2.937	484.4

<sup>1/</sup> Values are means of two replicates.

Table 21. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Uptake by Sugarcane Grown on Three Hawaiian Soils<sup>1/</sup>

Placement	Yield g/pot	Phosphorus mg/pot	Silicon mg/pot
<u>Akaka</u>			
P banded	256	244	693
Si banded	190	145	1350
P + Si banded together	245	323	1304
P + Si banded separately	284	245	1912
P mixed with 1/2 soil	245	232	670
Si mixed with 1/2 soil	174	199	1682
P + Si mixed together	295	316	1860
P + Si mixed separately	293	281	2160
<u>Kawailoa</u>			
P banded	197	220	478
Si banded	45	31	960
P + Si banded together	190	228	1460
P + Si banded separately	210	241	1895
P mixed with 1/2 soil	218	246	498
Si mixed with 1/2 soil	50	37	1100
P + Si mixed together	210	275	2363
P + Si mixed separately	228	261	2774
<u>Wahiawa</u>			
P banded	167	190	792
Si banded	32	21	516
P + Si banded together	183	229	1410
P + Si banded separately	186	228	1705
P mixed with 1/2 soil	198	250	903
Si mixed with 1/2 soil	34	18	457
P + Si mixed together	187	243	1630
P + Si mixed separately	180	235	1606

<sup>1/</sup> Values are means of combined harvests.

Table 22. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Sugarcane Grown on Three Hawaiian Soils at Two Months<sup>1/</sup>

Placement	Yield g/pot	Phosphorus		Silicon	
		ppm	mg/pot	%	mg/pot
<u>Akaka</u>					
P banded	40	1565	62	0.53	210
Si banded	25	1496	36	1.40	348
P + Si banded together	42	1663	69	0.90	376
P + Si banded separately	40	1452	57	1.04	412
P mixed with 1/2 soil	38	1612	63	1.00	190
Si mixed with 1/2 soil	23	1290	29	1.95	438
P + Si mixed together	34	1880	64	1.49	504
P + Si mixed separately	40	1632	63	1.65	646
<u>Kawailoa</u>					
P banded	32	1698	53	0.43	132
Si banded	7	1242	9	2.67	196
P + Si banded together	30	1670	49	1.26	375
P + Si banded separately	34	1580	53	1.27	425
P mixed with 1/2 soil	34	1710	57	0.39	137
Si mixed with 1/2 soil	14	860	12	3.31	446
P + Si mixed together	35	1535	53	1.84	634
P + Si mixed separately	41	1490	61	1.82	743
<u>Wahiawa</u>					
P banded	28	1916	54	0.82	234
Si banded	8	670	6	1.88	156
P + Si banded together	25	1916	48	1.74	439
P + Si banded separately	34	1846	63	1.26	425
P mixed with 1/2 soil	35	1740	60	0.68	236
Si mixed with 1/2 soil	8	658	5	1.90	146
P + Si mixed together	30	1870	52	1.40	377
P + Si mixed separately	27	2010	52	1.40	377

<sup>1/</sup> Values are means of two replicates.

Table 23. Effect of Phosphate and Silicate Placement in Pots on Yield, and Phosphorus and Silicon Content of Sugarcane Grown on Three Hawaiian Soils at Four Months<sup>1/</sup>

Placement	Yield g/pot	Phosphorus		Silicon	
		ppm	mg/pot	%	mg/pot
<u>Akaka</u>					
P banded	198	853	169	0.22	436
Si banded	148	670	99	0.59	876
P + Si banded together	185	1310	241	0.44	820
P + Si banded separately	225	775	174	0.60	1360
P mixed with 1/2 soil	187	833	156	0.23	426
Si mixed with 1/2 soil	135	610	80	0.77	1028
P + Si mixed together	240	985	236	0.47	1175
P + Si mixed separately	233	880	204	0.56	1298
<u>Kawailoa</u>					
P banded	150	1028	154	0.20	300
Si banded	33	650	21	2.08	675
P + Si banded together	143	1152	163	0.66	940
P + Si banded separately	159	1095	174	0.82	1302
P mixed with 1/2 soil	165	1067	176	0.19	307
Si mixed with 1/2 soil	31	664	20	1.78	547
P + Si mixed together	158	1320	209	0.98	1544
P + Si mixed separately	170	1107	189	1.06	1805
<u>Wahiawa</u>					
P banded	125	1016	125	0.39	487
Si banded	17	822	14	1.57	277
P + Si banded together	143	1170	169	0.60	855
P + Si banded separately	137	1106	151	0.84	1144
P mixed with 1/2 soil	148	1180	176	0.40	600
Si mixed with 1/2 soil	20	572	12	1.12	216
P + Si mixed together	143	1210	173	0.76	1083
P + Si mixed separately	140	1220	171	0.79	1103

<sup>1/</sup> Values are means of two replicates.

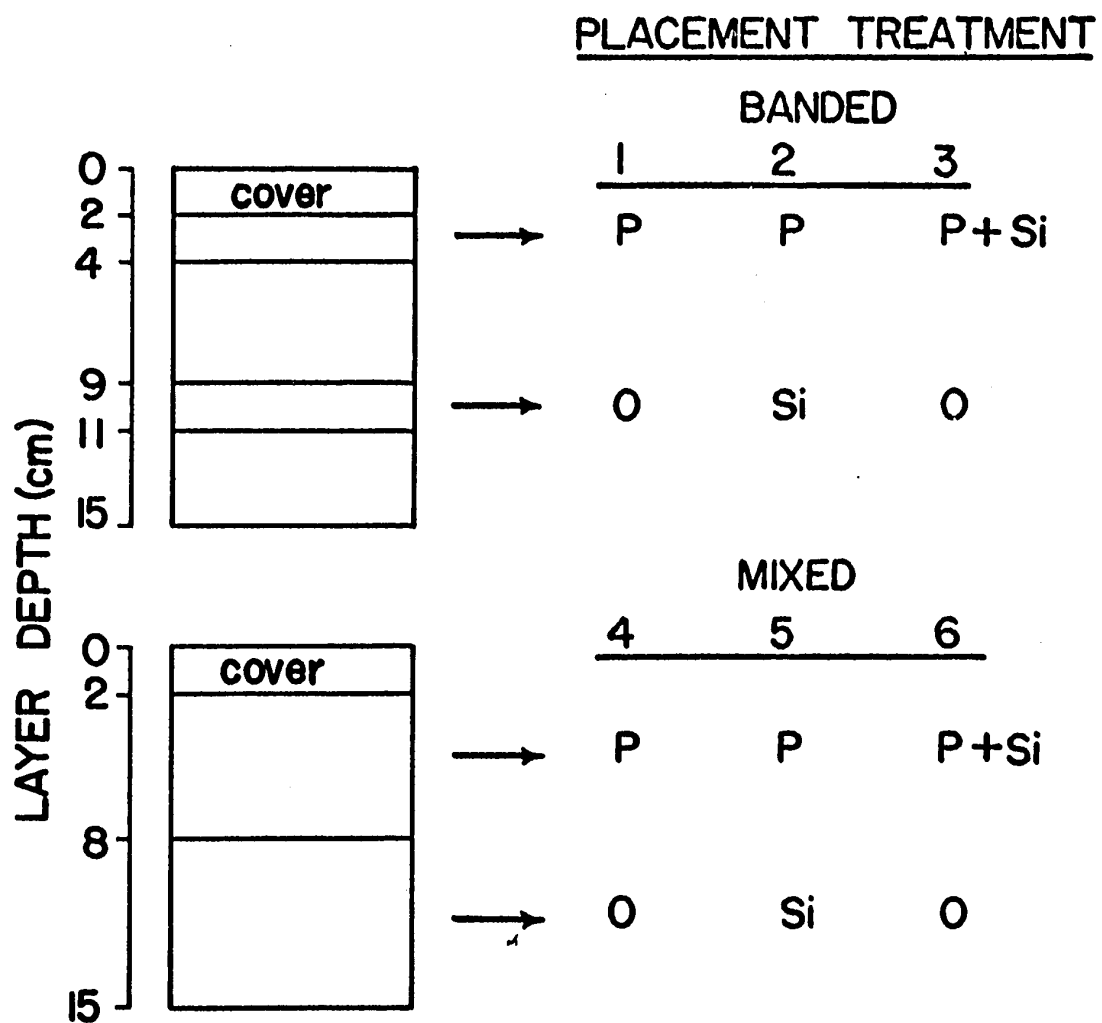


Fig. 48. Profiles of Banded and Mixed Placements Used in Greenhouse Study.

soils. Yield differences due to placements in the Akaka soil were not significant.

In general, P and Si mixed with soils were superior to band placement for yields of corn, rice and sugarcane. However, placement effects on yields varied with soils. In the Kawaihoa soil corn and rice yields were greatest when P and Si were mixed with the soils. No such trend was observed in the Wahiawa and Akaka soils. Mean placement effects on dry matter yields of rice were highly significant. Dry matter yields of rice in the Kawaihoa soil was significantly higher than those from the Wahiawa soil by Duncan's Multiple Range test.

Mixed placements were superior to band placements in the presence of Si for dry matter yields in sugarcane. In the absence of Si, yields were greatest from band placement in the Akaka soil, while in the Kawaihoa and Wahiawa soils mixed P was better than banded P with or without Si. Apparently, the relative merits of banding P were associated with P sorption capacities of soils. The yield of the zero P treatment, both in banded and mixed placements was more than 60 percent of the maximum yield in Akaka soil, and this was attributed to the effect of residual P.

Phosphorus Uptake: In lettuce, Mimosa, corn and sugarcane total P uptake was greatest when P and Si were placed together, while Si placed with P decreased P uptake by rice (Fig. 49). However, placement effects with respect to P uptake



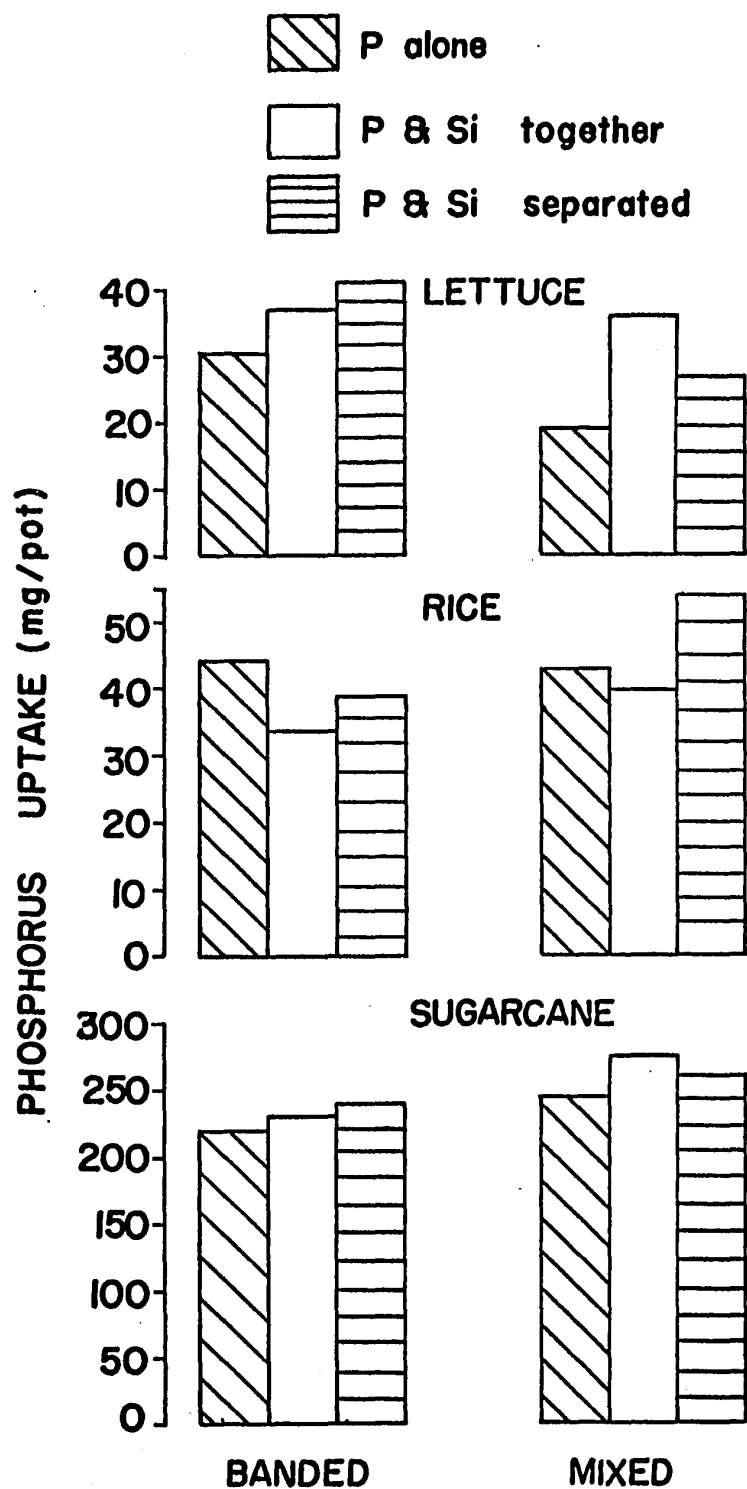


Fig. 49. Phosphorus Uptake by Three Plant Species as Influenced by Phosphate and Silicate Placement in Pots in Kawaihoa Soil.

were very different for Akaka as compared with the Wahiawa and Kawaihoa soils for growing lettuce and Mimosa. From the Akaka soil P uptake by lettuce (combined harvest) was highest when P and Si were banded together. Banding separately gave higher P uptake in the Kawaihoa and Wahiawa soils. However, P and Si mixed together were superior to the two mixed separately in the latter two soils. Both P percentage and total P uptake by Mimosa increased when P and Si were banded together and this trend was observed in the Kawaihoa and Wahiawa soils. There was no placement response in the Akaka soil. This may partially be explained by low P requirements of Mimosa and residual effects of large phosphate applications in the Akaka soil. This is evident from the high P uptake by Mimosa from the Akaka soil.

Statistical analysis of the lettuce data showed that the effect of placement on P concentrations was significant at the four weeks stage, while the placement effect on total P uptake was highly significant at both harvests. Soils affected P uptake highly significantly at both stages. There was a significant placement X soil interaction at four weeks.

For corn and sugarcane, greatest P uptake occurred when P and Si were mixed together with the soils. Separate placement was better than the zero Si treatments. Although P percentage of corn tended to remain constant in these two treatments, total P uptake was greatest in the presence of silicate

because of increased yields. Greatest P yield was from the Akaka soil and least from the Wahiawa soil. High P yields from the Akaka soil must have been associated with residual phosphate.

Sugarcane was harvested twice, at two months and at four months. No consistent trend of P uptake was noticed at two months. At four months, total P uptake was generally greater when P and Si were mixed together with the soil than when the two were banded together. Sheath P concentrations generally followed a similar trend. At two months P and Si mixed together were superior to the two banded together for sheath P, while at four months, sheath P concentrations were greatest when P and Si were banded together, except in the Akaka soil (Tables 24 and 25). This was due to a dilution effect on P concentrations in the mixed placement.

In general, P uptake by sugarcane (combined harvest) was greatest when P and Si were mixed together with the soils. However, the Akaka soil was an exception. In this soil, P and Si banded together effected most P uptake by sugarcane.

Phosphorus uptake by rice was least when P and Si were banded together with the soil. In general, P uptake by rice was greatest when P and Si were mixed separately with the soil. However, in the Akaka soil P uptake by rice was greatest when P alone was mixed with the soil. Although P percentage of rice tended to decrease in the presence of Si, total P uptake was

Table 24. Effect of Phosphate and Silicate Placement in Pots on the Phosphorus and Silicon Composition of Sugarcane Sheaths at Two Months<sup>1/</sup>

Placement	Sheath Yield g/pot	Phosphorus		Silicon	
		ppm	mg/pot	%	mg/pot
<u>Akaka</u>					
P banded	6.9	803	5.5	0.42	29
Si banded	5.2	818	4.2	1.10	55
P + Si banded together	7.8	842	6.4	0.68	59
P + Si banded separately	6.4	892	5.6	0.74	48
P mixed with 1/2 soil	7.2	880	6.2	0.42	30
Si mixed with 1/2 soil	5.7	620	3.5	1.60	93
P + Si mixed together	6.9	930	6.4	1.12	78
P + Si mixed separately	6.5	830	5.3	1.45	93
<u>Kawaihoa</u>					
P banded	4.9	710	3.5	0.34	16
Si banded	2.2	270	0.6	1.84	39
P + Si banded together	6.3	780	5.0	0.97	60
P + Si banded separately	6.8	782	5.3	1.13	76
P mixed with 1/2 soil	5.9	756	4.3	0.34	20
Si mixed with 1/2 soil	2.8	296	0.8	1.98	56
P + Si mixed together	5.6	860	4.9	1.49	83
P + Si mixed separately	6.0	710	4.2	1.62	96
<u>Wahiawa</u>					
P banded	5.6	764	4.3	0.79	43
Si banded	2.6	270	0.7	1.72	44
P + Si banded together	4.6	1090	5.0	1.07	48
P + Si banded separately	6.1	940	5.7	1.03	63
P mixed with 1/2 soil	6.3	960	6.1	0.64	40
Si mixed with 1/2 soil	2.5	265	0.7	1.54	38
P + Si mixed together	4.1	1125	4.7	1.15	46
P + Si mixed separately	4.3	970	4.0	1.35	57

<sup>1/</sup> Values are means of two replicates.

Table 25. Effect of Phosphate and Silicate Placement in Pots on the Phosphorus and Silicon Composition of Sugarcane Sheaths at Four Months<sup>1/</sup>

Placement	Sheath Yield g/pot	Phosphorus		Silicon	
		ppm	mg/pot	%	mg/pot
<u>Akaka</u>					
P banded	10.6	730	7.8	0.17	18
Si banded	11.3	480	5.4	0.62	70
P + Si banded together	10.7	640	6.8	0.47	50
P + Si banded separately	12.3	635	7.8	0.75	90
P mixed with 1/2 soil	12.0	680	8.2	0.22	26
Si mixed with 1/2 soil	11.2	475	5.3	1.12	124
P + Si mixed together	14.4	680	9.7	0.72	104
P + Si mixed separately	14.3	646	9.2	0.89	127
<u>Kawailoa</u>					
P banded	10.0	850	8.4	0.30	30
Si banded	3.2	284	0.9	1.60	50
P + Si banded together	10.3	1010	10.3	0.80	85
P + Si banded separately	11.0	840	9.2	0.82	90
P mixed with 1/2 soil	13.0	694	9.0	0.26	34
Si mixed with 1/2 soil	3.2	280	0.9	1.58	52
P + Si mixed together	11.0	610	9.0	0.93	102
P + Si mixed separately	10.5	690	7.2	1.23	130
<u>Wahiawa</u>					
P banded	8.0	900	7.2	0.34	28
Si banded	3.4	240	0.8	1.18	40
P + Si banded together	9.3	890	8.3	0.74	69
P + Si banded separately	9.2	910	8.3	0.80	74
P mixed with 1/2 soil	9.0	930	8.3	0.31	28
Si mixed with 1/2 soil	4.0	240	1.0	1.42	57
P + Si mixed together	9.8	865	8.4	0.70	68
P + Si mixed separately	9.1	896	8.2	0.76	70

<sup>1/</sup> Values are means of two replicates.

greater from separate placement of the two in the Kawaihoa soil. The placement effect on P concentrations and total P uptake by rice were highly significant.

Silicon Uptake: In general, for lettuce and Mimosa, Si uptake was greatest when P and Si were banded together with the soil, while in rice and sugarcane, highest Si uptake occurred when P and Si were mixed separately with the soil. Silicon uptake by corn was greatest when P and Si were mixed together with the soil (Fig. 50). Phosphorus and silicon banded together was the worst treatment for Si uptake by corn, rice and sugarcane.

Total Si uptake by lettuce was greatest from the Kawaihoa soil and least from the Akaka soil. Silicon uptake seems to have been related to Si solubility in these soils. Silicon concentrations in lettuce were very small and it was difficult to detect any difference due to placement. However, analysis of variance showed that placements and soils had highly significant effects both on Si concentrations in, and total Si uptake by, lettuce. This may have been due to the zero Si treatment. Since very little Si is taken up by lettuce it seems reasonable to suppose that direct benefit from silicate applications are enhanced P uptake. Silicon concentrations were also very low in Mimosa. Additions of silicate with phosphate increased Si uptake by Mimosa only slightly. Both Si percentage and total Si uptake by corn were greatest when P

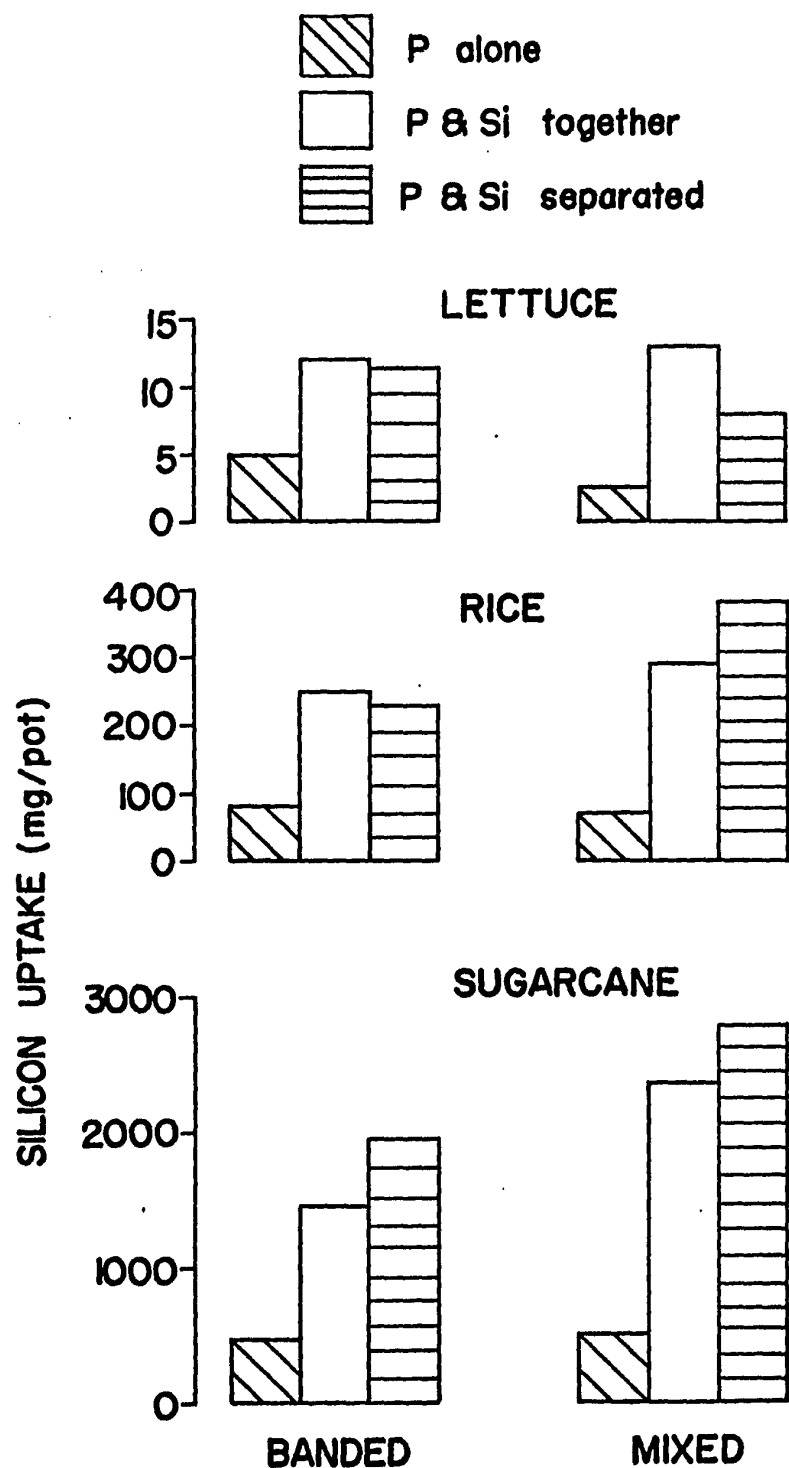


Fig. 50. Silicon Uptake by Three Plant Species as Influenced by Phosphate and Silicate Placement in Pots in Kawaihoa Soil.

and Si were mixed together with the soil, except in the Akaka soil. Increased Si uptake by these species in the presence of P may have been due to increased Si solubility in soils in the presence of P. It was indicated in an earlier section that P increases solubility of Si in soils.

In rice and sugarcane, greatest Si uptake occurred when P and Si were placed apart. Mixed placements were superior to band placements. In sugarcane, concentrations of Si were highest in the absence of added P. This was associated with very restricted cane growth in the absence of P. Sheath Si generally followed similar trends at both harvests. Total Si uptake by sugarcane was greatest from the Kawaihoa soil and least from the Wahiawa soil, while the reverse was true for rice. Comparatively greater Si uptake by sugarcane from the Akaka soil may have been associated with better cane growth in this soil. Yield responses in rice were related both to increased Si concentrations and total Si uptake by rice. Silicon concentrations of rice were usually greatest when P and Si were mixed separately with the soil. However, in the Wahiawa soil P and Si mixed together effected highest Si uptake by rice. Placement effects were highly significant both on Si concentrations and Si uptake. The soils differed significantly from each other with respect to Si status of rice.



To summarize, placement effects on P-Si interactions, as measured by P uptake, were very different for Akaka as compared with the Wahiawa and Kawaihoa soils, for growing lettuce and Mimosa. For the grasses all soils behaved similarly within a species, but there were marked species differences. For lettuce and Mimosa P and Si banded together was the best treatment for P uptake. For rice banding or mixing P and Si together were the worst treatments.

Placement effects on Si uptake varied with species and soils. Phosphorus and Si banded together were superior for plants like lettuce and Mimosa which have shallow root systems and accumulate very little Si, while P and Si mixed separately were superior for Si uptake by plants like rice and sugarcane which accumulate large amounts of Si.

These results suggest that Si interferes with P uptake by crops like rice which accumulate large amounts of Si, while in crops like lettuce and Mimosa which accumulate little Si, P uptake is enhanced by Si. Silicon increases P uptake by sugarcane and corn, although these species accumulate considerable Si. Silicon uptake is interfered by P in plants which accumulate large amounts of Si.

## SUMMARY

Phosphorus-silicon interactions in soils and plants were studied in three steps: first, laboratory equilibration; second, uptake of P and Si by plants from culture solutions; and third, uptake of P and Si by plants from soils.

Silicon status was investigated for the Wahiawa, Kawaihoa, Kapaa and Akaka soils. Silicon in soil solutions increased with time of shaking in all the soils. Concentrations of Si in soil solutions after four hours shaking ranged from 0.75 to 1.05 ppm Si. Silicon release by the soils during four hours was: Wahiawa > Kapaa > Kawaihoa = Akaka. Consistently high values for soluble Si was obtained for the Wahiawa soil.

Silicon sorption by the soils ranged from 10 to over 2200  $\mu\text{g Si/g soil}$ , at 20 ppm Si in solution. The order of sorption was: Akaka > Wahiawa > Kapaa > Kawaihoa. Sorption was greatest for soils with amorphous colloids and high sesquioxides content. Sorption was decreased considerably by leaching soils with dilute HCl. The effect of acid leaching on Si sorption by the soils was: Akaka > Wahiawa > Kapaa > Kawaihoa.

Native Si concentrations in soil solutions increased with decreasing pH of soil suspensions. Solubility was always low near pH 7. "Sorption" of added Si increased with increasing soil pH. Calcium chloride had little direct effect on Si solubility in soils.

Phosphorus sorption by all soils was high. The order of sorption was: Akaka > Kapaa > Wahiawa > Kawailoa. Phosphorus requirements of the soils were between 240 and 1400 ppm P, at 0.2 ppm P in the supernatant solution. Increasing amounts of sorbed P increased native Si solubility in soils. Silicon release as P was sorbed was in the following order: Wahiawa > Kapaa > Akaka. Kawailoa changed little as P was sorbed.

Phosphorus decreased Si sorption and Si decreased P sorption by soils but the effect of P on Si sorption was greatest. In relative terms applied Si decreased P sorption in the following order: Kawailoa > Wahiawa > Kapaa > Akaka. Phosphorus influenced Si sorption most in soils which sorbed much P. Silicon sorption as a result of P applications was decreased in the following order: Akaka > Wahiawa > Kapaa > Kawailoa.

The interaction effects of Si and P on P and Si sorption by soils were related to their solubilities in soils. Phosphorus desorption from soils increased in the presence of sorbed Si, while Si desorption decreased in the presence of sorbed P.

Phosphorus sorption by Kapaa surface soils decreased with increasing amounts of field applied phosphate and silicate. Sorption by sub-soils was much greater than sorption by surface soils. Sorption was greatest at low pH. Silicate decreased P sorption most effectively at low pH. The effect of P, on the other hand, was most pronounced at the highest pH level. The effect of

silicate on P sorption was inversely related to the amounts of residual P in the soil. Silicate applied to surface soils decreased P sorption by sub-soils. Similar effects of residual silicate on P sorption was obtained in the Akaka soil seven years after silicate applications.

Extractable soil P in the Kapaa soil increased with increasing amounts of residual silicate. Silicate was relatively most effective at low P levels. Extractable P in the sub-soil samples also increased with increasing amounts of phosphate and silicate initially applied to surface soils.

Silicon movement in soil columns was measurable in all the soils studied. Movement was fastest in the Paaloa soil. Amounts of Si leached through soil columns were related to their sorption capacities. Calcium chloride solution was more effective than water in displacing Si in Kapaa soil. This was attributed to depressed soil pH in the presence of  $\text{CaCl}_2$ .

Movement of Si in soil profiles in the field was a function of the amounts of silicate applied and soil pH. Soluble Si was highest in profiles with low soil pH. There was an inverse relationship between the rates of applied P and soluble Si content of soil profiles. Considerable Si had moved to 24 inches in the profiles of Kapaa soil during the nine months after silicate applications. Soluble Si in the profiles of Akaka soil increased with increasing amounts of TVA slag applied 5 years earlier.

Extractable soil Al in the profiles of Kapaa soil was decreased by slag applications. A further decrease was effected by superimposing  $\text{CaCO}_3$  (increased pH) over slag applications. Phosphate applications did not affect the exchangeable Al status of Kapaa soil profiles. Most exchangeable Al was concentrated in the top 12 inches of soils. Below 24 inches very little Al was detectable. Similar trends were observed in the profiles of Akaka soil.

Phosphorus and Si absorption by plants from culture solutions was a function of plant species. The presence of Si with P enhanced P absorption by lettuce, Mimosa and corn but depressed P uptake by rice and sugarcane. When P and Si were supplied from separate chambers P absorption by Mimosa, corn and rice was depressed but P absorption by lettuce was still enhanced. In all species, the presence of P with Si depressed Si uptake by plants. Silicon concentrations of lettuce, Mimosa and sugarcane were depressed most when P and Si were supplied from the same chamber. For rice and corn, greatest decrease occurred when Si and P were supplied from separate chambers.

The distribution of P and Si in sugarcane tissues was investigated. Greatest concentrations of P was in leaf No. 1 and least in mature cane tissue. Silicon concentrations were greatest in leaves 2 and 3 and least in mature cane stalks. In all plant parts, interaction effects of P and Si depressed Si and P

concentrations most when they were supplied from the same chamber.

Translocation of  $^{32}\text{P}$  from the fertilized roots to the tops was greater than to the unfertilized roots. Greatest translocation occurred in plants which accumulate considerable Si and least in plants which accumulate little Si. Lateral transport of  $^{32}\text{P}$  was very little affected by Si supply from the culture media. In the presence of P, both accumulation and lateral transport of Si was depressed.

Interaction effects of Si and P ratios in culture solutions on P and Si uptake by sugarcane were investigated. Sugarcane yields increased almost proportionately with P supply. Silicon did not increase yields significantly. Phosphorus uptake by cane was nearly proportional to P supply. Utilization of P by sugarcane sheaths indicated that Si may help more efficient use of limited amounts of P. At higher levels of P there may be an effect from Si over and above its effect on P. Silicon uptake by cane increased with increasing Si supply, but Si concentrations in plants were depressed with increasing levels of P supply. Both Si and P had stimulating effects on root growth but the effects of P were more pronounced than the effects of Si.

Pot experiments were conducted to evaluate placement effects in soils on P and Si uptake by plants. Placement effects varied with species. Placement effects with respect to P uptake was

very different for Akaka as compared with the Wahiawa and Kawaihoa soils for growing lettuce and Mimosa. For the grasses all soils behaved similarly within a species but there were marked species differences. For lettuce, Mimosa and corn, P uptake was enhanced by placing P and Si together in the soil, while for rice, which accumulates the largest amounts of Si, the presence of Si depressed P uptake. For lettuce and Mimosa, banding P and Si together was superior for P uptake, while in corn and sugarcane, P and Si mixed together was best. The merits of banding or mixing P and Si with soils were associated with the nature of root systems (shallow or deep). In rice, phosphorus and Si mixed together or banded together were the worst treatments for P uptake. This suggests ion competition for absorption in plants which accumulate large amounts of Si.

Placement effects of P and Si on Si uptake varied with species. In shallow rooted crops (lettuce and Mimosa), Si uptake was greatest when P and Si were banded together, while in rice, and sugarcane, Si uptake was greatest when P and Si were mixed separately with the soil. In corn, P and Si mixed together effected the highest Si uptake.

## LITERATURE CITED

- Acquaye, D. and J. Tinsley. 1964. Soluble silica in soils. Proc. 11th Easter School in Agril. Sci., Univ. of Nottingham. (Experimental Pedology, 1965, Butterworths, London.):126-148.
- Akhromeiko, A. I. 1934. Influence of silicic acid upon the utilization by plants of  $P_2O_5$  from various sources. Z. Pflanzenernahr, Dung. Bodenk. 34(A):430-459. (Chem. Abstr. 29:874.)
- Alexander, G. B., W. M. Heston and R. K. Iler. 1954. The solubility of amorphous silica in water. J. Phys. Chem. 58:453-455.
- \_\_\_\_\_. 1967. Silica and Me. Doubleday and Company, Inc., New York.
- Alexander, A. G. 1968. Effects of foliar combinations of gibberellic acid and silicon on sucrose production by sugar cane. J. Agr. Univ. P. R. Vol. 52(3):218-226.
- Ali, M. Y. 1966. Effects of phosphorus, silicon and zinc applications on the yield and mineral composition of sugarcane. M. S. Thesis, Univ. of Hawaii.
- Andrew, C. S. 1962. C.S.I.R.O., Australia, Division of Tropical Pastures, Ann. Report 1961-1962. (Cited by R. S. Beckwith, 1965.)
- Ayres, A. S. 1934. Phosphate fixation in Hawaiian soils. Haw. Planter's Rec. 38:131-145.
- \_\_\_\_\_. 1966. Calcium silicate slag as a growth stimulant for sugarcane on low-silicon soils. Soil Sci. 101:216-227.
- Barber, D. A. and M. G. T. Shone. 1966. The absorption of silicon from aqueous solutions by plants. J. Exp. Bot. 17:569-578.
- Barnette, M. R. 1924. Synthetic calcium silicate as a source of agricultural lime: A comparison of the influence of synthetic calcium silicate with other forms of lime as affecting plant growth. Soil Sci. 18:479-491.



- Bastisse, E. M. 1950. Investigation of the theoretical and practical conditions allowing the maintenance of availability of phosphoric acid in lateritic soils. *Ann. Agron.* 1:748-761.
- Bates, T. F. 1960. Rock weathering and clay formation in Hawaii. *Miner. Industries, Penn. State Univ.* 29:1-6.
- Bear, F. E. 1958. *Chemistry of the Soil.* Reinhold Publishing Corporation, 430 Park Avenue, New York.
- Beckwith, R. S. 1965. Sorbed phosphorus at a standard supernatant concentration as an estimate of the phosphate needs of soils. *Austr. J. Exp. Agric. and Animal Husb.* 5:52-58.
- \_\_\_\_\_ and R. Reeve. 1964. Studies of soluble silica in soils-I. *Austr. J. Soil Res.* 1:157-168.
- Behrman, A. S. and H. Gustafson. 1940. Removal of silica from water. *Ind. Eng. Chem.* 32:468-472.
- Betz, L. D., C. A. Noll and J. J. Maguire. 1941. Adsorption of soluble silica from water. *Ind. Eng. Chem.* 33:814-820.
- Birch, H. F. 1953. The relationships between phosphate response and base saturation, pH, and silica content of acid soils. *E. Afri. Agril. J.* 19:48-49.
- Black, C. A. 1942. Phosphate fixation by kaolinite and other clays as affected by pH, phosphate concentration and time of contact. *Soil Sci. Soc. Amer. Proc.* 7:123-133.
- Bradfield, R. 1963. The soil chemist and food for peace. *Amer. Soc. Agron. Special Pub. No.* 1:42-51.
- Brenchely, W. E., E. J. Maskell and K. Warrington. 1927. The interrelation between silicon and other elements in plant nutrition. *Ann. Appl. Biol.* 14(1):45-82.
- Chapman, H. D. and P. F. Pratt. 1961. *Methods of analysis for soils, plants, and waters.* Div. of Agric. Sci., Univ. of California.
- Chu, A. C. and G. D. Sherman. 1952. Differential fixation of phosphate by typical soils of Hawaiian great soil group. *Tech. Bull. of Univ. of Hawaii Agric. Exp. Sta.* No. 16.

- Clements, H. F. 1965. The roles of calcium silicate slags in sugarcane growth. 1965 Reports, Haw. Sugar Tech. pp. 103-126.
- Cline, M. G. et al. 1965. Soil survey of the territory of Hawaii. U. S. Dept. Agr. Series, 1939. No. 25. pp. 71-79 and 111-116.
- Coleman, R. 1944. The mechanism of phosphate fixation by kaolinitic and montmorillonitic clays. Soil Sci. Soc. Amer. Proc. 7:134-138.
- Cooke, G. W. 1956. The effect of some silicate slags on the utilization of soil and fertilizer phosphorus. J. Sci. of Food and Agric., 7 Jan. pp. 56-60.
- Dainty, J. 1962. Ion transport and electrical potentials in plant cells. Ann. Rev. Plant Physiol. 13:379-402.
- Dean, L. A. and E. J. Rubins. 1947. Anion exchange in soils. Soil Sci. 63:389-397.
- De Datta, S. K. 1958. Soil and fertilizer phosphorus used by legumes. Effect of organic matter, silicates and chelates and study of their residual effects. Indian Agr. Res. Inst., Div. of Soil Sci. and Agr. Chem., New Delhi, India. pp. 22-28. (Unpublished data.)
- Deshpande, T. L., D. J. Greenland and J. P. Quirk. 1968. Changes in soil properties associated with the removal of iron and aluminum oxides. J. Soil Sci. 19(1):108-122.
- Dewan, M. and A. S. Hunter. 1949. Absorption of phosphorus by soybean and Sudan grass. II. Effect of silicates. Soil Sci. 68:479-482.
- Dias, I. P. 1965. Effect of the use of lime and other soil amendments on amorphous and differentially crystallized sub-soil of the Akaka series. Ph.D. Thesis, Univ. of Hawaii.
- Eitel, W. 1965. Silicate Science. Volumes I to IV. Academic Press, New York and London.
- Engel, W. A. 1953. The compounds that contain silica in the straw of oats. Planta. 41:358-390.

- Fisher, R. A. 1929. Preliminary note on the effects of sodium silicate in increasing the yield of barley. *J. Agric. Sci.* 19: 132-139.
- Fletcher, H. F. and L. T. Kurtz. 1964. Differential effects of phosphorus fertilizer on soybean varieties. *Soil Sci. Soc. Amer. Proc.* 28:225-228.
- Fox, R. L., S. K. De Datta and G. D. Sherman. 1962. Phosphorus solubility and availability to plants and the aluminum status of Hawaiian soils as influenced by liming. *Int'l. Soil Conference, New Zealand.* pp. 3-12.
- \_\_\_\_\_, J. A. Silva, O. R. Younge, D. L. Plucknett and G. D. Sherman. 1967. Soil and plant silicon and silicate response by sugarcane. *Soil Sci. Soc. Amer. Proc.* 31: 775-779.
- \_\_\_\_\_, D. L. Plucknett and A. S. Whitney. 1968. Phosphate requirements of Hawaiian Latosols and residual effects of fertilizer requirements. *Trans. 9th Int'l. Congr. Soil Sci., Adelaide, Australia.* Vol. 2:301-310.
- \_\_\_\_\_, J. A. Silva, D. L. Plucknett and D. Y. Teranishi. 1969. Soluble and total silicon in sugarcane. *Plant and Soil* 30(1):81-92.
- \_\_\_\_\_. (Personal communication.)
- Fried, M. and R. E. Shapiro. 1956. Phosphate supply pattern of various soils. *Soil Sci. Soc. Amer. Proc.* 20:471-475.
- Ganssmann, W. 1962. *Phosphorsaeure* 22:223-241. (Cited by L. H. P. Jones and K. A. Handreck, 1967. *In* Silica in soils, plants and animals. *Advances in Agron.* Vol. XIX: 107-149.)
- Germer, B. 1934. Some functions of silicic acid with special reference to resistance to mildew. *Z. Pflanzenernahr. Duang. Bodenk. Ser.* A35:102-115. (Cited by A. Okuda and E. Takahashi, 1964.)
- Germer, L. H. and K. H. Storks. 1939. Identification of aluminum hydrate films of importance in silicosis prevention. *Ind. Eng. Chem. Anal.* 11:583-592.

- Gifford, R. O. and D. M. Frugoli. 1964. Silica source in soil solution. *Science* 145:386-388.
- Gile, P. L. and J. G. Smith. 1929. Colloidal silica and the efficiency of phosphates. *J. Agril. Res.* 31:247-260.
- Gunary, D. and C. D. Sutton. 1967. Soil factors affecting plant uptake of phosphate. *J. Soil Sci.* 18:167-173.
- Hall, A. D. and C. G. T. Morrison. 1906. On the function of silica in the nutrition of cereals. I. *Proc. Roy. Bot. Soc.* 77:455-477.
- Hemwall, J. B. 1957. The role of soil clay minerals in phosphorus-fixation. *Soil Sci.* 83:101.
- Hunter, A. S. 1965. Effects of silicates on uptake of phosphorus from soils by four crops. *Soil Sci.* 100:391-396.
- Ibrahim, A. A. B. 1968. Effect of nitrogen and silicon on growth of rice. M.S. Thesis, Univ. of Hawaii.
- Ikawa, H. 1956. The role of soluble silicate on the fixation and release of phosphorus of tropical soils. M.S. Thesis, Univ. of Hawaii.
- Iler, R. K. 1955. *The Colloid Chemistry of Silica and Silicates.* Cornell Univ. Press, Ithaca, N. Y.
- Islam, M. A. and Hafizur Rahman. 1959. Degree of phosphate saturation as a measure of phosphate availability to plants. *Soil Sci.* 88:172-178.
- Jones, R. C. (Personal communication.)
- Jones, L. H. P. 1965. Studies of soluble silica in the oat plant. III. Uptake of silica from soils by the plants. *Plant and Soil* 23:79-96.
- Khan, D. H. 1960. A study of the effects of colloidal silica in peptizing iron oxide with reference to red brown soil formation on lime stone. *J. Sci. Food and Agric.* 11:133-136.
- \_\_\_\_\_ and A. C. Roy. 1964. Study on the phosphate retention and release in some East Pakistan soils. *Plant and Soil* 21:365-376.

- Khan, D. H. and A. C. Roy. 1964. Growth, P uptake and fibre cell dimensions of jute plant as affected by silicate treatment. *Plant and Soil* 20:331-336.
- Kilmer, V. J. 1965. Silicon. In C. A. Black (ed.) *Methods of soil analysis. Agron. Monograph, Part II.* pp. 959-962.
- Kitson, R. E. and M. G. Mellon. 1944. Colorimetric determination of phosphorus as molybdi-vanado-phosphoric acid. *Ind. Eng. Chem. Anal.* 16:379-383.
- Kittrick, J. E. and M. L. Jackson. 1955. Rate of phosphate reaction with soil minerals and electron microscope observations on the reaction mechanism. *Soil Sci. Soc. Amer. Proc.* 19:292-295.
- Laws, W. D. 1950. Water-soluble silicate application to a calcareous clay soil and effect on soil properties. *Soil Sci. Soc. Amer. Proc.* 15:89-92.
- Lipman, C. B. 1939. Importance of silicon, aluminum and chlorine for higher plants. *Soil Sci.* 45:189-198.
- Low, P. F. and C. A. Black. 1947. Phosphate induced decomposition of kaolinite. *Soil Sci. Soc. Amer. Proc.* 12:180-184.
- Mahilum, B. C. 1965. Effects of silicates and carbonates on the status of mineral nutrients in a Hydrol Humic Latosol. M.S. Thesis, Univ. of Hawaii.
- Manuelpillai, R. G. 1967. Influence of silicon and phosphorus and their interaction on yield and chemical composition of plants. M.S. Thesis, Univ. of Hawaii.
- Mattson, S. 1931. The laws of soil chemical behavior. V. Ion adsorption and exchange. *Soil Sci.* 31:311-331.
- McGeorge, W. T. 1924. Iron, aluminum, and manganese in the soil solution of Hawaiian soils. *Soil Sci.* 18:1-11.
- \_\_\_\_\_ and J. F. Breazeale. 1924. The influence of silicon, lime and soil reaction upon the availability of phosphorus in highly ferruginous soils. *Soil Sci.* 17:463-468.

- McKeague, J. A. and M. G. Cline. 1963. Silica in soil solutions. I. Form and concentration of dissolved silica in aqueous extracts of some soils. *Can. J. Soil Sci.* 43:70-82.
- \_\_\_\_\_. 1963. Silica in soil solutions. II. The adsorption of monosilicic acid by soil and by other substances. *Can. J. Soil Sci.* 43:83-96.
- Midgley, A. R. and J. B. Kelly. 1943. Phosphate fixation and exchange of phosphate and hydroxyl ions. *Soil Sci.* 55:167-176.
- Miller, R. W. 1967. Soluble silica in soil. *Soil Sci. Soc. Amer. Proc.* 31:46-49.
- Mitsui, S. and H. Takatoh. 1963. Nutritional study of silicon in gramminaceous crops. Parts I and II. *Soil and Plant Nutr.* (Tokyo). 9(2):7-16.
- Mohr, E. C. J. and F. A. Van Baren. 1954. *Tropical Soil.* pp. 498. New York.
- Monteith, N. H. and G. D. Sherman. 1963. 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. *Hawaii Agric. Expt. Sta. Tech. Bull.* No. 53.
- Nelson, W. C., B. A. Krantz, C. D. Welch and N. W. Hall. 1949. Utilization of phosphorus as affected by placement: II. Cotton and corn in North Carolina. *Soil Sci.* 68:137-144.
- Nielsen, D. R. and J. W. Biggar. 1962. Miscible displacement: III. Theoretical considerations. *Soil Sci. Soc. Amer. Proc.* 26:216-221.
- Noda, M. and K. Saito. 1952. Studies on the phosphate fixing capacity of Fe and Al in soil. II. Complex-forming action of silicic acid and humic acids with Fe and Al phosphates. *J. Sci. Soil* (Tokyo). 22:273.
- Okuda, A. and E. Takahashi. 1962. The physiological role of silicon in crop plants. Parts V to VII. *J. Sci. Soil and Manure* (Tokyo).

Pt. V: Effect of silicon supply on injuries due to excessive amount of  $\text{Fe}^{++}$ ,  $\text{Mn}^{++}$ ,  $\text{Cu}^{++}$ ,  $\text{AsO}_3^{---}$ ,  $\text{Al}^{+++}$ , and  $\text{Co}^{++}$  in barley and rice plants 33:1-8.

Pt. VI: Effect of silicon supply on the iron uptake by rice plants from ferrous sulphate solution and the oxidizing power of the root. 33:59-64.

Pt. VII: Effect of silicon supply on the growth of rice plants under various phosphorus supply levels. 33:65-69.

Olsen, S. R., F. S. Watanabe and R. E. Danielson. 1961. Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. *Soil Sci. Soc. Amer. Proc.* 25:289-294.

Ozaki, K. and H. Higashiro. 1957. Effect of silicon on the nitrogen metabolism of rice plants. (Cited by Okuda et al., 1965.)

Ozanne, P. G. and T. C. Shaw. 1967. Phosphate sorption by soils as a measure of the phosphate requirement for pasture growth. *Austr. J. Agric. Res.* 18:601-612.

Raleigh, G. J. 1939. Evidence for the essentiality of silicon for the growth of the beet plant. *Plant Physiol.* 14:823-829.

\_\_\_\_\_. 1953. Some effects of various silicates, lime and gypsum on growth of tomato plants in Western and Eastern soils of low levels of phosphorus nutrition. *Cornell Agric. Exp. Sta. Memo.* 326. pp. 78.

Raupach, M. 1957. Investigations into the nature of soil pH. C.S.I.R.O. (Australia) Soil Pub. No. 9. (From: Raupach and Piper, 1959.)

\_\_\_\_\_ and C. S. Piper. 1959. Interactions of silicate and phosphate in a lateritic soil. *Austr. J. Agric. Res.* 10(6): 818-831.

Ravikovitch, S. 1934. Anion exchange. I. Adsorption of phosphoric acid by soils. *Soil Sci.* 38:219-239.

Rhoads, W. A., A. Wallace and E. M. Romney. 1956. A slowly source of micronutrients. *Soil Sci.* 81:359-369.

- Robertson, W. K., P. M. Smith, A. J. Ohlrogge and D. M. Kinch. 1954. Phosphorus utilization by corn as affected by placement and nitrogen and potassium fertilisation. *Soil Sci.* 77:219-226.
- Rothbuhr, L. and F. Scott. 1957. A study of the uptake of silicon and phosphorus by wheat plants with radio chemical methods. *Biochem. J.* 65:241-245.
- Russell, G. C. and P. F. Low. 1954. Reactions of phosphate with kaolinite in dilute solutions. *Soil Sci. Soc. Amer. Proc.* 18:22-25.
- Sasamoto, K. 1957. Studies on the relation between the silica content in the rice plant and insect pests. V. *Botyukagaku. Inst. of Insect Control, Japan.* 22:159-164.
- Scarseth, G. D. 1935. The mechanism of phosphate retention by natural aluminosilicate colloids. *J. Amer. Soc. Agron.* 27:596-616.
- Schollenberger, C. J. 1922. Silica and silicates in relation to plant growth and composition. *Soil Sci.* 14:347-362.
- Sherman, G. D. 1949. Factors influencing the development of laterite and lateritic soils in the Hawaiian islands. *Pacific Sci.* 3:307-314.
- \_\_\_\_\_. 1958. Gibbsite-rich soils of the Hawaiian islands. *Haw. Agri. Expt. Sta. Bul. No.* 116.
- \_\_\_\_\_. (Personal communication.)
- \_\_\_\_\_, A. C. Chu and C. M. Sakamoto. 1955. The influence of application of soluble silicates on phosphorus availability in certain Hawaiian soils. *Proc. Haw. Acad. Sci.* 30th Ann. Meeting, Honolulu. p. 16.
- Sieling, D. H. 1947. Role of kaolin in anion sorption and exchange. *Soil Sci. Soc. Amer. Proc.* 11:161-170.
- Sreenivasan, A. 1935. The role of silicon in plant nutrition. *Current Sci.* 3:193-197 (Chem. Abst. 29:2205).
- Stout, P. R. 1939. Alteration in the crystal structure of clay minerals as a result of phosphate fixation. *Soil Sci. Soc. Amer. Proc.* 4:177-182.



- Suehisa, R. H., O. R. Younge and G. D. Sherman. 1963. Effects of silicates on phosphorus availability to Sudan grass grown on Hawaiian soils. Haw. Agric. Exp. Sta. Tech. Bull. No. 51.
- Suhr, N. H. and C. O. Ingamells. 1966. Solution technique for analysis of silicates. Anal. Chem. 38:730-734.
- Tanaka, A. and Y. D. Park. 1966. Significance of the absorption and distribution of silica in the growth of rice plant. Soil Sci. and Plant Nutr. 12:191-196.
- Taranovskya, V. G. 1941. The effectiveness of lime and silicate applications on red loam. Chem. Soc. Agric. USSR. 10:37-42 (Chem. Abst. 37:111).
- Teakle, L. J. H. 1928. Phosphate in the soil solution as affected by reaction and cation concentrations. Soil Sci. 25: 143-162.
- Teranishi, D. Y. 1968. The effects of silicon, phosphorus, and soil pH and their interactions on yield and nutrient uptake by sugarcane. M.S. Thesis, Univ. of Hawaii.
- Tiulin, A. T. 1936. Availability of soil phosphorus for the plant from the viewpoint of colloid chemistry. Soil Sci. 42:291-299.
- Toth, S. J. 1939. The stimulating effects of silicate on plant yields in relation to anion displacement. Soil Sci. 47:122-139.
- Truog, E. 1938. Phosphate fixation. Soil Sci. 38:263-271.
- Vlamiš, J. and D. E. Williams. 1967. Manganese and silicon interaction in the gramineae. Plant and Soil 27(1):131-139.
- Volk, R. J., R. P. Kahn, and R. L. Weintraub. 1957. Silicon content of the rice plant as a factor influencing its resistance to infection by *Piricularia oryzae*. Abs. in Phytopathology. 47:35.
- Welch, L. F., D. L. Mulvany, L. V. Boone. 1966. Relative efficiency of broadcast versus banded phosphorus for corn. Agron. J. 58:283-287.

- Werkhoven, C. H. E. and M. H. Miller. 1960. Absorption of fertilizer phosphorus by sugarbeets as influenced by placement of phosphorus and nitrogen. *Can. J. Soil Sci.* 40:49-58.
- \_\_\_\_\_ and F. Massantini. 1967. Effect of phosphorus and nitrogen placement on safflower growth and phosphorus absorption. *Agron. J.* 59(2):169-171.
- Whittenberger, R. 1945. Silicon absorption by rye and sunflower. *Ann. J. Bot.* 32:539-549.
- Williams, D. E. and J. Vlamis. 1957. The effect of silicon on yield and  $Mn^{54}$  uptake and distribution in the leaves of barley plants grown in culture solution. *Plant Phys.* 32:404-409.
- Woodruff, C. M. 1954. The solubility of silica in hydrogen beidelite. *Proc. 2nd Nat'l. Conf. on Clays and Clay Minerals. Nat'l. Acad. Sci. Nat'l Res. Council Pub. 1*, 327:120-123.
- Woodruff, J. R. and E. J. Kamprath. 1965. Phosphorus absorption maximum as measured by the Langmuir isotherm and its relationship to phosphorus availability. *Soil Sci. Soc. Amer. Proc.* 29:148-150.
- Yoshida, S., Y. Ohrishi, and K. Kitagashi. 1962a. Histochemistry of silicon in rice plants. *Soil and Plant Nutr. (Tokyo)* 8(1):30-41.
- \_\_\_\_\_, \_\_\_\_\_ and \_\_\_\_\_. 1962. Chemical form, mobility and deposition of silica in rice plant. *Soil Sci. and Plant Nutr.* 8:107-113.
- Younge, O. R. and D. L. Plucknett. 1965. Beef production with heavy phosphorus fertilization in infertile wetlands of Hawaii. *Proc. IX Int'l. Grassland Congr., Sao Paulo.*
- \_\_\_\_\_ and \_\_\_\_\_. 1966. Quenching the high phosphorus fixation of Hawaiian Latosols. *Soil Sci. Soc. Amer. Proc.* 5:653-655.

## A P P E N D I X

Table 26. Effect of Time of Equilibration on Phosphorus Solubility in Four Hawaiian Soils<sup>1/</sup>  
(Results in ppm P in a 1:10 soil extract)

Soil	Time (Hours)				
	12	24	48	96	144
Akaka	0.96	0.26	0.19	0.16	0.12
Kapaa	4.2	1.4	0.42	0.26	0.21
Kawailoa	4.8	2.1	1.2	0.74	0.71
Wahiawa	1.6	0.48	0.32	0.22	0.20

<sup>1/</sup> Kawailoa and Wahiawa received 50 ppm P, while Akaka and Kapaa received 100 ppm P solutions.

Table 27. Effect of Time of Equilibration on the Solubility of Silicon in Four Hawaiian Soils<sup>1/</sup>

Soil	Time (Hours)					
	1	4	12	24	72	144
<u>No Si Added</u>						
Akaka	0.69	0.75	0.76	0.83	0.93	1.18
Kapaa	0.72	0.80	0.89	1.06	1.14	1.45
Kawailoa	0.56	0.75	1.19	1.42	1.86	2.25
Wahiawa	1.02	1.05	1.18	1.22	1.34	1.43
<u>500 <math>\mu</math>g/g Si Added</u>						
Akaka	25.4	23.2	23.0	20.4	18.7	18.9
Kapaa	35.1	33.7	33.0	29.2	24.5	24.9
Kawailoa	45.0	43.7	43.7	42.0	39.0	39.5
Wahiawa	16.2	14.5	12.6	8.1	6.2	5.3

<sup>1/</sup> Values are ppm Si in a 1:10 soil extract.

Table 28. Silicon Sorption by Four Hawaiian

Si Added ( $\mu\text{g/g}$ )	Soil							
	Akaka			Kapaa			Kaw	
	Soln. pH	Si in Soln. (ppm)	Si Sorbed <sup>1/</sup> ( $\mu\text{g/g}$ )	Soln. pH	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )	Soln. pH	Si Sol (ppm)
						<u>Untreated</u>		
0	5.2	1.0	-	5.2	1.0	-	5.5	0
200	5.3	4.4	458.0	5.4	13.3	65.3	5.6	17
400	5.5	9.6	884.2	5.5	26.2	132.7	5.7	35
600	5.7	14.5	1330.0	5.6	38.8	204.0	5.8	53
800	5.7	20.7	1710.0	5.6	50.8	273.1	5.9	69
1000	5.8	23.9	2260.0	6.0	61.3	385.2	5.9	84
						<u>Acid Leached</u>		
0	3.2	9.1	-	3.8	1.1	-		
200	3.3	14.8	130.1	4.1	14.7	53.1	3.5	1
400	3.4	29.1	274.0	4.2	29.2	107.9	3.6	19
600	3.4	42.0	450.2	4.3	44.2	158.4	3.7	37
800	3.5	55.3	616.4	4.4	60.2	198.3	3.8	56
1000	3.5	71.0	725.5	4.5	74.9	251.5	3.8	74
							3.9	95

<sup>1/</sup> Silicon sorbed calculated on O.D. soil basis but the experiment was conducted

## 28. Silicon Sorption by Four Hawaiian Soils

Soil								
Kapaa			Kawailoa			Wahiawa		
Soln. pH	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )	Soln. pH	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )	Soln. pH	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )
<u>Untreated</u>								
5.2	1.0	-	5.5	0.9	-	6.3	1.1	-
5.4	13.3	65.3	5.6	17.9	20.7	6.4	4.7	152.7
5.5	26.2	132.7	5.7	35.6	43.9	6.5	9.8	302.1
5.6	38.8	204.0	5.8	53.0	70.0	6.6	15.1	449.2
5.6	50.8	273.1	5.9	69.5	105.0	6.8	19.2	608.3
6.0	61.3	385.2	5.9	84.3	150.4	6.9	23.9	761.4
<u>Acid Leached</u>								
3.8	1.1	-				3.4	2.7	-
4.1	14.7	53.1	3.5	1.2	-	3.5	9.3	107.0
4.2	29.2	107.9	3.6	19.1	8.7	3.6	19.8	201.7
4.3	44.2	158.4	3.7	37.8	22.0	3.8	31.7	283.0
4.4	60.2	198.3	3.8	56.9	31.0	3.9	42.5	375.0
4.5	74.9	251.5	3.8	74.8	42.5	4.0	55.4	446.4
			3.9	95.5	45.1			

oil basis but the experiment was conducted on a 40 percent dry matter basis.

Table 29. Effect of pH on the Solubility  
of Native Silicon in Four Hawaiian Soils<sup>1/</sup>

Soil							
Akaka		Kapaa		Kawailoa		Wahiawa	
Soln. pH	Si in Soln.	Soln. pH	Si in Soln.	Soln. pH	Si in Soln.	Soln. pH	Si in Soln.
2.5	3.5	2.5	2.4	2.3	2.4	2.3	10.5
3.0	2.1	3.0	1.9	2.7	1.8	2.8	8.1
3.2	1.7	3.1	1.7	2.8	1.7	3.0	7.0
3.3	1.5	3.3	1.6	3.0	1.7	3.4	5.7
3.5	1.3	3.4	1.4	3.2	1.5	4.0	4.2
3.8	1.1	3.5	1.2	3.6	1.2	4.7	2.5
4.6	1.0	4.8	0.98	4.8	0.9	6.0	1.1
5.9	0.54	6.7	0.59	5.3	0.81	5.2	0.9
6.2	0.43	5.6	0.68	5.5	0.9	6.8	0.32
6.3	0.34	6.1	0.54	5.8	0.91	7.0	0.18
6.5	0.27	6.2	0.46	6.0	0.93	7.1	1.10
6.7	0.19	6.4	0.42	6.4	0.96	7.3	0.11
6.9	0.07	7.0	0.18	6.4	0.96	7.6	0.10

<sup>1/</sup> Values are ppm Si in a 1:10 water extract.

Table 30. Effect of pH on Silicon "Sorption" by Four Hawaiian Soils<sup>1/</sup>

Soil											
Akaka			Kapaa			Kawailoa			Wahiawa		
Soln. pH	Si in Soln. (ppm)	Si Sorbed <sup>2/</sup> (μg/g)	Soln. pH	Si in Soln. (ppm)	Si Sorbed (μg/g)	Soln. pH	Si in Soln. (ppm)	Si Sorbed (μg/g)	Soln. pH	Si in Soln. (ppm)	Si Sorbed (μg/g)
2.5	33.4	248	3.1	37.8	50	2.3	39.9	21	2.3	33.7	96
3.2	32.6	354	3.2	37.8	84	2.8	43.9	17	3.3	34.2	124
3.4	31.9	388	3.3	37.9	90	2.9	44.0	25	3.7	31.2	169
3.6	31.7	410	3.5	38.1	96	3.0	45.3	19	4.3	28.1	208
3.8	31.1	440	3.8	38.3	102	3.5	46.8	13	5.3	22.8	267
4.2	29.0	510	4.3	37.4	119	4.1	46.9	21	6.7	6.5	434
5.8	14.9	870	5.5	31.2	197	5.2	42.3	69	6.9	4.0	458
6.3	11.6	950	5.9	25.9	243	5.4	39.8	86	7.1	2.5	473
6.5	8.0	1040	6.3	20.5	294	5.6	36.9	109	7.2	2.1	477
6.7	5.6	1100	6.8	15.0	347	5.8	31.5	160	7.4	1.3	485
6.8	4.9	1115	6.9	11.8	378	6.0	25.7	217	8.5	0.7	485
6.9	1.1	1215	7.2	9.3	402	6.4	11.0	368			

<sup>1/</sup> The soils received a 50 ppm Si solution at a soil:solution ratio of 1:10.

<sup>2/</sup> Silicon sorbed calculated on O.D. soil basis but the experiment was conducted on a 40 percent dry matter basis.



Table 31. Phosphorus Sorption and Native Silicon Release by Four Hawaiian Soils  
(Calcium Phosphate + 0.01 M Calcium Chloride)

P Added ( $\mu\text{g/g}$ )	Soil								
	Kapaa			Kawailoa			Wahiawa		
	P in Soln. (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Soln. (ppm)	P in Soln. (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Soln. (ppm)	P in Soln. (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Soln. (ppm)
<u>Equilibration Time 24 Hours</u>									
0	0.008	-	1.20	0.035	-	1.96	0.032	-	1.33
250	0.058	249.4	1.80	0.596	244.0	1.99	0.176	248.2	3.12
500	0.132	498.8	2.13	2.560	474.4	1.99	0.800	492.0	4.98
750	0.250	743.9	2.33	5.310	696.9	1.96	2.030	729.7	7.00
1000	0.640	993.6	3.02	10.560	894.4	1.99	5.000	950.0	9.00
<u>Equilibration Time 6 Days</u>									
0	0.012	-	1.49	0.035	-	2.82	0.022	-	1.25
250	0.026	249.7	2.29	0.154	248.5	3.03	0.088	249.6	2.95
500	0.064	499.4	2.89	0.720	492.8	2.95	0.358	498.0	4.81
750	0.096	749.0	3.39	2.02	729.8	2.86	0.870	741.3	6.69
1000	0.218	997.8	4.07	4.70	953.0	3.04	1.980	972.0	8.80

Table 31. Phosphorus Sorption and Native Silicon Release by Four Hawaiian Soils  
(Calcium Phosphate + 0.01 M Calcium Chloride) (Continued)

P Added ( $\mu\text{g/g}$ )	Akaka Soil		
	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Solution (ppm)
<u>Equilibration Time 24 Hours</u>			
0	0.006	-	0.96
500	0.580	499.6	1.58
750	0.112	748.9	1.74
1000	0.202	997.9	1.96
2000	1.510	1985.0	2.82
<u>Equilibration Time 6 Days</u>			
0	0.010	-	1.13
500	0.040	499.6	1.69
750	0.061	749.5	2.13
1000	0.102	999.0	2.29
2000	0.429	1992.7	3.49

Table 32. Phosphorus-Silicon Interaction Effects on  
Silicon and Phosphorus Sorption by Four Hawaiian Soils<sup>1/</sup>

P Added ( $\mu\text{g/g}$ )	Si Added ( $\mu\text{g/g}$ )	Soln. pH	P in Soln. (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )
<u>Akaka</u>						
0	0	4.7	0.015	-	0.90	-
	250	5.3	0.018	-	5.6	575
	500	5.5	0.021	-	11.0	1000
1000	0	4.5	0.147	998.5	2.3	-
	250	5.0	0.176	998.2	18.1	228.8
	500	5.8	0.176	998.2	32.0	575.0
2000	0	4.8	1.54	1984.6	3.0	-
	250	5.0	1.67	1983.3	20.7	182.0
	500	5.5	1.60	1984.0	39.5	338.0
<u>Kapaa</u>						
0	0	4.5	0.013	-	1.3	-
	250	5.0	0.020	-	15.7	106.4
	500	5.2	0.024	-	29.1	222.0
500	0	4.1	0.123	498.8	2.50	-
	250	4.3	0.146	498.5	19.8	76.6
	500	4.5	0.176	498.2	35.9	165.6
1000	0	4.1	0.406	995.9	3.6	-
	250	4.4	0.747	992.5	22.3	63.0
	500	4.5	0.744	992.5	39.4	142.0

<sup>1/</sup> Values are means of two replicates.

Table 32. Phosphorus-Silicon Interaction Effects  
on Silicon and Phosphorus Sorption  
by Four Hawaiian Soils<sup>1/</sup> (Continued)

P Added ( $\mu\text{g/g}$ )	Si Added ( $\mu\text{g/g}$ )	Soln. pH	P in Soln. (ppm)	P Sorbed ( $\mu\text{g/g}$ )	Si in Soln. (ppm)	Si Sorbed ( $\mu\text{g/g}$ )
<u>Kawailoa</u>						
0	0	4.8	0.064	-	2.1	-
	250	5.0	0.085	-	23.3	37.6
	500	5.2	0.096	-	44.9	71.0
500	0	3.9	0.145	498.6	2.4	-
	250	4.0	2.88	471.2	24.6	27.6
	500	4.2	3.52	465.8	47.4	50.0
1000	0	3.8	9.12	908.8	2.5	-
	250	4.0	14.21	857.9	25.0	24.7
	500	4.2	18.4	816.0	47.1	54.3
<u>Wahiawa</u>						
0	0	6.2	0.026	-	1.4	-
	250	6.4	0.029	-	6.4	200.0
	500	6.6	0.040	-	11.5	399.1
500	0	5.8	0.269	497.3	5.3	-
	250	6.1	0.466	495.3	13.2	170.0
	500	6.5	1.104	489.0	22.3	330.0
1000	0	5.5	4.05	960.0	9.2	-
	250	6.1	4.89	951.1	20.3	140.0
	500	6.2	8.67	913.1	29.5	297.6

<sup>1/</sup> Values are means of two replicates.

Table 33. Phosphorus-Silicon Interaction Effects on Desorption of Silicon and Phosphorus from Four Hawaiian Soils<sup>1/</sup>

P Added ( $\mu\text{g/g}$ )	Si Added ( $\mu\text{g/g}$ )	Solution pH	Phosphorus in Solution (ppm)	Silicon in Solution (ppm)
<u>Kapaa</u>				
0	0	5.2	0.029	0.42
	250	5.1	0.037	2.85
	500	5.4	0.055	4.86
500	0	4.5	0.091	0.55
	250	4.7	0.130	2.53
	500	4.9	0.138	4.15
1000	0	4.5	0.458	0.59
	250	4.8	0.548	2.17
	500	4.9	0.556	3.42
<u>Akaka</u>				
0	0	4.7	0.020	0.48
	250	5.2	0.022	4.27
	500	5.5	0.025	7.55
1000	0	4.7	0.151	0.54
	250	5.3	0.150	3.51
	500	4.8	0.161	5.29
2000	0	5.3	1.27	0.52
	250	5.3	1.22	2.78
	500	5.7	1.30	5.15

<sup>1/</sup> Values are means of two replicates.

Table 33. Phosphorus-Silicon Interaction Effects  
on Desorption of Silicon and Phosphorus  
from Four Hawaiian Soils<sup>1/</sup> (Continued)

P Added ( $\mu\text{g/g}$ )	Si Added ( $\mu\text{g/g}$ )	Solution pH	Phosphorus in Solution (ppm)	Silicon in Solution (ppm)
<u>Kawailoa</u>				
0	0	5.1	0.065	0.36
	250	5.1	0.075	1.12
	500	5.2	0.050	1.79
500	0	4.3	1.24	0.21
	250	4.5	1.58	0.65
	500	4.7	1.52	1.06
1000	0	4.3	5.35	0.17
	250	4.4	5.91	0.49
	500	4.6	6.13	0.96
<u>Wahiawa</u>				
0	0	6.2	0.022	0.85
	250	6.4	0.023	2.50
	500	6.5	0.025	4.79
500	0	6.0	0.293	1.52
	250	6.3	0.580	4.34
	500	6.3	0.650	5.86
1000	0	5.9	3.36	2.17
	250	6.1	4.79	4.56
	500	6.3	4.64	5.71

<sup>1/</sup> Values are means of two replicates.

Table 34. Effect of Phosphorus-Silicon Interactions on the Desorption of Previously Applied Phosphorus and Silicon from Kapaa Soil During Successive Extractions<sup>1/</sup>

P Added ( $\mu\text{g/g}$ )	Si Added ( $\mu\text{g/g}$ )	Extraction Number			
		1	2	3	4
<u>Phosphorus<sup>2/</sup></u>					
500	0	0.079	0.110	0.090	0.078
	500	0.123	0.141	0.111	0.119
750	0	0.183	0.225	0.202	0.193
	500	0.214	0.283	0.227	0.241
1000	0	0.415	0.422	0.352	0.344
	500	0.604	0.593	0.482	0.439
2000	0	3.14	2.32	1.75	1.53
	500	3.32	2.37	1.80	1.58
<u>Silicon<sup>3/</sup></u>					
500	0	0.21	0.12	0.15	0.07
	500	1.47	0.61	0.44	0.32
750	0	0.23	0.17	0.11	0.07
	500	1.29	0.53	0.40	0.28
1000	0	0.23	0.17	0.11	0.07
	500	1.36	0.49	0.36	0.26
2000	0	0.22	0.17	0.12	0.07
	500	0.83	0.29	0.34	0.22

<sup>1/</sup> Values are means of two replicates.

<sup>2/</sup> Values are ppm P in a 1:30 water extract.

<sup>3/</sup> Values are ppm Si in a 1:30 water extract.

Table 35. Effect of Phosphorus-Silicon Interactions on the Desorption of Previously Applied Phosphorus and Silicon from Akaka Soil During Successive Extractions<sup>1/</sup>

P Added (μg/g)	Si Added (μg/g)	Extraction Number			
		1	2	3	4
<u>Phsophorus<sup>2/</sup></u>					
500	0	0.057	0.041	0.041	0.037
	500	0.057	0.047	0.041	0.034
750	0	0.119	0.080	0.084	0.073
	500	0.151	0.126	0.100	0.093
1000	0	0.646	0.516	0.435	0.371
	500	0.725	0.576	0.472	0.414
2000	0	1.72	1.52	1.21	1.07
	500	1.87	1.63	1.32	1.21
<u>Silicon<sup>3/</sup></u>					
500	0	0.28	0.13	0.08	0.07
	500	2.13	0.83	0.55	0.39
750	0	0.27	0.15	0.08	0.06
	500	1.97	0.67	0.44	0.24
1000	0	0.24	0.10	0.08	0.05
	500	1.38	0.46	0.31	0.28
2000	0	0.24	0.13	0.08	0.06
	500	1.19	0.35	0.27	0.28

<sup>1/</sup> Values are means of two replicates.

<sup>2/</sup> Values are ppm P in a 1:30 water extract.

<sup>3/</sup> Values are ppm Si in a 1:30 water extract.



Table 36. Effects of Phosphate, Silicate and pH on Phosphorus Sorption by Kapaa Soil  
Nine Months After Fertilizer Applications<sup>1/</sup>

P Added ( $\mu\text{g/g}$ )	Initial Phosphate Application (lbs. P/A)							
	100				1000			
	No Slag		4 T Slag/A		No Slag		4 T Slag/A	
	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )
<u>Surface Soil (pH 5.5)</u>								
500	0.020	499.7	0.029	497.1	0.035	496.5	0.035	496.5
750	0.044	749.7	0.064	749.4	0.051	749.6	0.080	749.2
1000	0.092	999.6	0.163	998.3	0.099	999.0	0.142	998.1
1500	0.228	1499.6	0.488	1497.1	0.249	1497.8	0.362	1496.4
2000	0.480	1995.2	0.918	1990.8	0.602	1993.8	0.952	1990.4
<u>Surface Soil (pH 6.2)</u>								
500	0.040	499.3	0.029	499.5	0.032	499.7	0.051	499.5
750	0.076	749.2	0.048	749.5	0.062	749.7	0.109	749.5
1000	0.131	998.7	0.105	998.5	0.105	998.5	0.157	998.5
1500	0.321	1497.9	0.211	1497.9	0.204	1498.0	0.409	1495.9
2000	0.563	1996.9	0.445	1993.4	0.544	1994.0	0.762	1992.4
<u>Sub-Soil (Surface Soil pH 5.5)</u>								
500	0.020	499.7	0.029	497.1	0.035	499.6	0.035	499.7
750	0.044	749.7	0.064	749.4	0.051	749.6	0.080	749.7
1000	0.092	99.6	0.163	998.3	0.099	999.0	0.142	998.1
1500	0.228	1499.6	0.488	1497.1	0.249	1497.8	0.362	1496.4
2000	0.480	1995.2	0.918	1990.8	0.602	1993.8	0.952	1990.4

<sup>1/</sup> Samples for three replicates were composited.

Table 36. Effects of Phosphate, Silicate and pH on Phosphorus Sorption by Kapaa Soil  
Nine Months After Fertilizer Applications<sup>1/</sup> (Continued)

P Added ( $\mu\text{g/g}$ )	Initial Phosphate Application (lbs. P/A)							
	100				1000			
	No Slag		4 T Slag/A		No Slag		4 T Slag/A	
	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )
Sub-Soil (Surface Soil pH 6.2)								
500	0.040	499.3	0.029	499.5	0.032	499.7	0.051	499.5
750	0.076	749.2	0.048	749.5	0.062	749.7	0.109	749.6
1000	0.131	998.7	0.105	998.5	0.105	998.5	0.157	998.5
1500	0.321	1497.9	0.211	1497.9	0.204	1498.0	0.409	1495.9
2000	0.563	1996.9	0.445	1993.4	0.544	1994.0	0.762	1992.4

<sup>1/</sup> Samples for three replicates were composited.

Table 37. Effects of Silicate on Phosphorus Sorption by Akaka Soil  
Five Years After Slag Applications<sup>1/</sup>

P Added ( $\mu\text{g/g}$ )	Surface Soil (0-6")				Sub-Soil (12-18")			
	Silicate Applied				Silicate Applied			
	None		Slag (8 T/A)		None		Slag (8 T/A)	
	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )	P in Solution (ppm)	P Sorbed ( $\mu\text{g/g}$ )
500	0.026	499.7	0.034	499.7	0.038	499.6	0.050	499.5
1000	0.125	998.6	0.147	998.5	0.099	999.0	0.146	998.5
1500	0.289	1497.0	0.350	1496.5	0.207	1497.9	0.323	1496.8
2000	0.467	1995.0	0.538	1994.6	0.378	1996.2	0.608	1993.8
3000	1.257	2987.4	1.378	2988.2	0.874	2991.2	1.142	2988.6

<sup>1/</sup> Samples for four replicates were composited.

Table 38. Influence of Applied Phosphate, Silicate and Soil pH  
on Extractable Soil Phosphorus in Kapaa Soil<sup>1/</sup>

Slag (T/A)	pH 5.5			pH 5.8			pH 6.2		
	Phosphorus (lbs./A)			Phosphorus (lbs./A)			Phosphorus (lbs./A)		
	100	250	1000	100	250	1000	100	250	1000
	<u>Surface Soil (0-6")</u>								
0	11.0 <sup>2/</sup>	13.8	46.4	8.6	14.1	119.0	17.0	17.0	118.4
2	19.5	17.0	64.6	14.1	28.8	133.8	28.2	37.8	125.4
4	24.6	31.4	68.5	30.4	58.9	159.0	38.4	37.8	207.0
	<u>Sub-Soil (6-12")</u>								
0	2.9	4.5	4.5	4.5	4.5	10.6	6.4	7.0	10.2
2	5.4	6.1	6.4	7.0	5.4	13.4	7.7	9.9	12.8
4	7.0	7.0	15.7	7.4	5.8	19.2	8.6	10.2	16.0

<sup>1/</sup> Three replicates were composited for analyses.

<sup>2/</sup> Values are ppm P extracted on O.D. soil basis.

Table 39. Distribution of Silicon in Soil Columns After Leaching the Columns with Seventy Centimeters of Water (320 mg Si Added)

Depth in Inches	Soil					
	Kapaa		Lahaina		Paaloa	
	Water Soluble <sup>1/</sup>	Phosphate Extractable <sup>2/</sup>	Water Soluble	Phosphate Extractable	Water Soluble	Phosphate Extractable
0 - 1	13.7	386	26.8	322	14.7	174
1 - 2	4.4	128	81.0	130	4.5	50
2 - 3	3.7	120	72.0	108	3.2	46
3 - 4	3.4	110	66.0	114	2.0	40

<sup>1/</sup>Values are ppm Si in a 1:10 water extract.

<sup>2/</sup>Values are ppm Si on O.D. soil basis.

Table 40. Silicon Distribution in Kapaa Soil Profiles as Influenced by Silicate Applications<sup>1/</sup>

Depth in Inches	Slag Applied (T/A)					
	0		2		4	
	Water Soluble <sup>2/</sup>	Phosphate Extractable <sup>3/</sup>	Water Soluble	Phosphate Extractable	Water Soluble	Phosphate Extractable
0 - 6	0.47	23.4	1.05	48.1	1.71	81.0
6 - 12	0.28	19.5	0.39	26.2	0.45	27.2
12 - 24	0.11	18.3	0.14	19.3	0.13	21.0
24 - 36	0.09	20.2	0.10	26.5	0.09	22.4
36 - 48	-	-	0.10	24.0	0.09	27.0

<sup>1/</sup>Values are means of 3 phosphate and 3 pH levels.

<sup>2/</sup>Values are ppm Si in a 1:10 water extract.

<sup>3/</sup>Values are ppm Si on O.D. soil basis.

Table 41. Effect of pH on the Distribution of Soluble Silicon in Kapaa Soil Profiles at 1,000 Pounds Phosphorus Per Acre

Depth in Inches	pH 5.5			pH 5.8			pH 6.2		
	Slag Applied (T/A)			Slag Applied (T/A)			Slag Applied (T/A)		
	0	2	4	0	2	4	0	2	4
<u>Water Soluble<sup>1/</sup></u>									
0 - 6	0.46	1.00	1.78	0.76	1.80	1.96	0.44	0.76	0.94
6 - 12	0.22	0.39	0.42	0.31	0.38	0.52	0.30	0.32	0.48
12 - 24	0.11	0.11	0.10	0.14	0.36	0.22	0.10	0.08	0.09
24 - 36	0.08	0.08	0.09	0.08	0.16	0.10	0.12	0.08	0.08
36 - 48	-	0.10	-	-	0.08	-	0.08	0.06	
<u>Phosphate Extractable<sup>2/</sup></u>									
0 - 6	27	49	52	25	44	78	22	45	49
6 - 12	15	28	32	21	20	27	29	24	27
12 - 24	18	16	25	16	16	17	18	19	20
24 - 36	19	23	18	21	38	18	24	32	23
36 - 48	-	26	19	-	-	26	-	28	24

<sup>1/</sup> Values are ppm Si in a 1:10 water extract.

<sup>2/</sup> Values are ppm Si on O.D. soil basis.

Table 42. Effect of Phosphate Fertilization on the Distribution of Soluble Silicon in Kapaa Soil Profiles at Four Tons of Slag Per Acre

Depth in Inches	pH 5.5			pH 5.8			pH 6.2		
	Phosphate Applied (lbs. P/A)			Phosphate Applied (lbs. P/A)			Phosphate Applied (lbs. P/A)		
	100	250	1,000	100	250	1,000	100	250	1,000
	<u>Water Soluble<sup>1/</sup></u>								
0 - 6	2.24	1.33	1.78	2.28	1.38	1.96	1.64	1.90	0.94
6 - 12	0.52	0.37	0.42	0.42	0.32	0.52	0.63	0.38	0.48
12 - 24	0.12	0.15	0.10	0.08	0.08	0.22	0.14	0.18	0.09
24 - 36	0.10	0.08	0.09	0.13	0.07	0.10	0.12	0.08	0.08
36 - 48	0.12	0.08	0.10	0.09	0.06	0.08	0.11	0.11	0.06
	<u>Phosphate Extractable<sup>2/</sup></u>								
0 - 6	106	18	52	142	52	78	110	122	49
6 - 12	32	14	32	32	22	27	30	30	27
12 - 24	23	18	25	20	15	17	25	26	20
24 - 36	26	15	18	25	19	18	30	28	23
36 - 48	33	26	19	26	23	26	28	38	24

<sup>1/</sup> Values are ppm Si in a 1:10 water extract.

<sup>2/</sup> Values are ppm Si on O.D. soil basis.



Table 43. Phosphate, Silicate and pH Interaction Effects on the Distribution of Soluble Silicon in Kapaa Soil Profiles Nine Months After Slag Applications<sup>1/</sup>

Slag Applied (T/A)	Depth Increments (Inches)	pH 5.5			pH 5.8			pH 6.2		
		Phosphate (lbs. P/A)			Phosphate (lbs. P/A)			Phosphate (lbs. P/A)		
		100	250	1000	100	250	1000	100	250	1000
		Water Soluble <sup>2/</sup>								
0	0 - 6	0.45	0.50	0.46	0.36	0.46	0.76	0.46	0.36	0.44
	6 - 12	0.06	0.34	0.22	0.10	0.22	0.32	0.36	0.34	0.30
	12 - 24	0.08	0.06	0.11	0.12	0.07	0.14	0.12	0.20	0.10
	24 - 36	0.08	0.06	0.08	0.07	0.08	0.08	0.12	0.12	0.12
	36 - 48	-	-	-	-	-	-	-	-	-
2	0 - 6	1.14	0.79	1.00	1.07	0.89	1.80	0.80	1.20	0.76
	6 - 12	0.31	0.30	0.39	0.43	0.42	0.38	0.60	0.40	0.32
	12 - 24	0.08	0.06	0.11	0.15	0.12	0.36	0.20	0.12	0.08
	24 - 36	0.06	0.07	0.08	0.15	0.12	0.36	0.20	0.12	0.08
	36 - 48	0.08	0.08	0.10	0.09	0.09	-	0.16	0.11	0.08
4	0 - 6	2.24	1.33	1.78	2.28	1.38	1.96	1.64	1.90	0.94
	6 - 12	0.52	0.37	0.42	0.42	0.32	0.53	0.63	0.38	0.48
	12 - 24	0.12	0.15	0.10	0.08	0.08	0.22	0.14	0.18	0.09
	24 - 36	0.10	0.08	0.09	0.13	0.07	0.10	0.12	0.08	0.08
	36 - 48	0.12	0.08	0.10	0.09	0.07	0.08	0.11	0.11	0.06

<sup>1/</sup> Three replicates were composited for analyses.

<sup>2/</sup> Values are ppm Si in a 1:10 water extract.

Table 43. Phosphate, Silicate and pH Interaction Effects on the Distribution of Soluble Silicon in Kapaa Soil Profiles Nine Months After Slag Applications<sup>1/</sup> (Continued)

Slag Applied (T/A)	Depth Increments (Inches)	pH 5.5			pH 5.8			pH 6.2		
		Phosphate (lbs. P/A)			Phosphate (lbs. P/A)			Phosphate (lbs. P/A)		
		100	250	1000	100	250	1000	100	250	1000
		Phosphate Extractable <sup>3/</sup>								
0	0 - 6	21	24	27	17	22	25	26	28	22
	6 - 12	19	20	15	18	20	21	22	22	20
	12 - 24	19	24	18	18	15	16	16	21	18
	24 - 36	16	18	19	16	18	21	19	30	24
	36 - 48	-	-	-	-	-	-	-	-	-
2	0 - 6	46	38	49	58	46	44	42	65	45
	6 - 12	20	20	27	27	31	20	25	41	24
	12 - 24	18	18	16	18	22	16	22	24	19
	24 - 36	18	22	23	20	24	38	32	31	32
	36 - 48	26	22	26	20	34	-	33	30	28
4	0 - 6	106	18	52	142	52	78	110	122	49
	6 - 12	32	14	32	32	22	27	30	30	27
	12 - 24	23	18	25	20	15	17	25	26	20
	24 - 36	26	15	18	25	19	18	30	28	23
	36 - 48	33	26	19	26	23	26	28	38	24

<sup>1/</sup> Three replicates were composited for analyses.

<sup>2/</sup> Values are ppm Si in a 1:10 water extract.

<sup>3/</sup> Values are ppm Si on O.D. soil basis.

Table 44. Distribution of Soluble Silicon in Akaka Soil Profiles  
Five Years After Slag Applications<sup>1/</sup>

Depth in Inches	Slag Applied (T/A)				
	0	2	4	6	8
	<u>Water Soluble<sup>2/</sup></u>				
0 - 6	0.80	1.60	1.90	2.20	2.50
6 - 12	0.60	0.80	1.00	1.20	1.50
12 - 18	0.30	0.40	0.50	0.70	0.80
18 - 24	0.40	0.30	0.40	0.40	0.40
24 - 36	0.25	0.15	0.13	0.22	0.18
36 - 48	0.19	0.18	0.16	0.18	0.19
	<u>Phosphate Extractable<sup>3/</sup></u>				
0 - 6	74	132	179	200	211
6 - 12	65	89	112	117	146
12 - 18	45	61	78	75	79
18 - 24	34	39	58	54	58
24 - 36	29	27	33	41	41
36 - 48	28	34	30	33	33

<sup>1/</sup> Values are means of four replicates.

<sup>2/</sup> Values are ppm Si in a 1:10 water extract.

<sup>3/</sup> Values are ppm Si on O.D. soil basis.

Table 45. Analysis of Variance of Dry Matter Yield and Chemical Composition of Plants as Influenced by Phosphate and Silicate Placement in Pots

Source of Variation	d.f.	D.M. Yield	P Conc.	P Uptake	Si Conc.	Si Uptake
<u>Mean Squares</u>						
<u>Lettuce - Harvest 1</u>						
Replications	1	0.04	32	1.7	374	0.08
Placements	5	0.46**	474569*	7.9**	57137**	0.74**
Soils	2	5.73**	681518*	95**	622306**	10.3**
Pl. X Soils	10	0.20*	390298*	5.2*	16094**	0.15*
Error	17	0.06	122600	1.6	4554	0.05
<u>Lettuce - Harvest 2</u>						
Replications	1	0.38	824161	60.8	3885	0.04
Placements	5	3.87**	223811	70.4**	270638**	20.6**
Soils	2	8.90**	70172	120.6**	1602534**	108.8**
Pl. X Soils	10	2.2**	105255	18.7	28264	6.1**
Error	17	0.57	210300	11.2	12707	1.1
<u>Rice</u>						
Replications	1	9.6**	1122	40	783225	407
Placements	5	6.4**	298789**	70*	423167802**	169568**
Soils	2	24.2	16681**	79*	441218702**	991**
Pl. X Soils	10	5.6**	90572	25	31936669**	11011**
Error	17	0.95	54053	19	1200940	672

\*Significant at 5% level.

\*\*Significant at 1% level.

Table 46. Analysis of Variance of Dry Matter Yield and Chemical Composition of Sugarcane as Influenced by Ratios of Phosphorus and Silicon in Culture Solutions

Source of Variation	d.f.	D.M. Yield	P Conc.	P Uptake	Si Conc.	Si Uptake
Mean Squares						
Replications	1	18	4	1	3010225*	0.8
Phosphorus	3	10119	82993**	2465**	18262145**	880**
Silicon	3	31	6265*	9	71069904**	53105**
P X Si	9	37	4825*	10	4494319**	226**
Harvest	1	25913**	615048*	1753**	1802306	28852**
H X P	3	3363**	3848	343**	3929835**	133
H X Si	3	40	1404	7	2187010*	7297**
H X P X Si	9	60	832	12	1656300	48
Error	31	41	1635	8	625500	51

\*Significant at 5% level.

\*\*Significant at 1% level.

Table 47. Analysis of Variance of Phosphorus and Silicon Composition of Plants  
as Influenced by Phosphorus and Silicon Interactions in Solution Culture  
(Split-Root Technique)

Source of Variation	d.f.	P Conc.	P Uptake	Si Conc.	Si Uptake
Mean Squares					
<u>Lettuce</u>					
Replications	2	39600	5.7	266	0.12
Treatments	4	776136**	23.9	3024**	0.03
Error	8	99146	7.8	139	0.009
<u>Corn</u>					
Replications	2	10	0.001	360240	0.06
Treatments	4	3490*	0.185*	1699951*	7.0**
Error	4	235	0.023	297815	0.136
<u>Mimosa</u>					
Replications	2	445771*	3.2	9	0.008*
Treatments	4	1221120**	44.5*	1551**	0.060**
Error	8	56596	1.6	36	0.001
<u>Rice</u>					
Replications	2	10709	0.16	419285	9.5
Treatments	4	1410658**	20.60**	38492701**	763**
Error	8	24505	0.55	289168	2.5

\*Significant at 5% level.

\*\*Significant at 1% level.

Table 47. Analysis of Variance of Phosphorus and Silicon Composition of Plants  
as Influenced by Phosphorus and Silicon Interactions in Solution Culture  
(Split-Root Technique) (Continued)

Source of Variation	d.f.	P Conc.	P Uptake	Si Conc.	Si Uptake
Mean Squares					
			<u>Sugarcane</u>		
Replications	2	125767*	7	202142	31
Treatments	4	7508866**	365**	53501737**	2718**
Tissue	5	6114255**	239**	13126276**	1945**
Pl. X Tissue	20	445864**	17**	2811247**	347**
Error	58	31727	3.8	110565	26

\*Significant at 5% level.

\*\*Significant at 1% level.