RESIDUAL EFFECTS OF CALCIUM SILICATE ON THE MOVEMENT AND AVAILABILITY OF NUTRIENTS IN TROPICAL SOILS

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ABSTRACT

The residual effects of calcium silicate on plant uptake and movement of nutrients in a Gibbsihumox were studied in a series of three experiments. First, kikuyu grass and desmodium were grown in the field to determine the magnitude of response to residual Si applied several years earlier at various P and pH levels; second, the partial recovery of applied Si during five years of cropping was determined at 3 pH levels; and third, uptake of residual Si by rice grown on soil collected from the field experiment at the end of five years was studied in a growth chamber. A study of soil Al extraction methods in relation to plant Al uptake and yield was also conducted on some Hawaiian soils.

The combined yields of seven harvests of kikuyu grass and desmodium increased significantly with increasing residual P levels, but was not significantly affected by residual Si or soil pH. The relative yield differential between the three Si treatments decreased sharply with time and at the end of 56 months yield from 1660 Si was only 2.5% higher than that without Si, whereas yield from 830 Si was less than the yield without Si. The decline with time in relative yield response to P applications, on the other hand, was small indicating a continued efficiency of P applied 56 months earlier in increasing yields on a Gibbsihumox. However, it should be pointed out that two supplemental additions of P were made 21 and 27 months after the initial treatments. Although residual Si produced highly significant increases in water-extractable soil Si, the levels at the end of the experiment were low which suggests that supplemental amounts of calcium silicate may be required to maintain yield response to Si. Modified Truog-extractable P was significantly higher at 1660 Si than at zero Si five years after Si applications. Phosphorus requirements of a Gibbsihumox were decreased significantly by residual Si and P in samples collected after 5 years of cropping. However, residual P was about 7 times more effective than residual Si in reducing P requirements. Multiple regression analysis indicated that in addition to the initially applied treatments, soil P and Al and plant P, K, Mg, and possibly also Mn, Zn, Al, and Ca were important to plant growth in both species.

Plant uptake by the sugarcane plant and ratoon crops, corn, and seven harvests of kikuyu grass accounted for 12 to 21 percent of the applied Si while exhaustive extraction of profile samples taken at the end of five years with 0.1N acetic acid, adjusted to pH 3.5 and containing 50 ppm P, recovered 14 to 28 percent of the applied Si. There was no evidence that applied Si moved below 30 cm. Total recovery of applied Si ranged from 28 to 43 percent which means that 57 to 72 percent of the applied Si remained in the soil in some form not readily displaced by phosphate solution.

Rice plants extracted proportionately more native Si than did phosphate solution which resulted in comparable amounts of added Si being recovered by the two methods. Silicon uptake by rice accounted for 8 to 30 percent of applied Si and exhaustive phosphate extraction recovered 13 to 23 percent of applied Si.

The amount of Al extracted by various solutions decreased in the order of 1N ammonium acetate + 0.2N barium chloride, pH 4.8 > 1N ammonium acetate, pH 4.8 > 1N barium chloride ≥ 1N potassium chloride ≥ water ≥ 0.01M calcium chloride. Aluminum extracted from five soils was in the order: Akaka (Typic Hydrandept) > Halii (Typic Gibbsihumox) > Wahiawa (Tropeptic Eutrustox) > Lualualei (Typic Chromustert) = Kawaihae (Ustollic Camborthid) which was related to the degree of weathering and the amount of rainfall affecting the soil. Soil Al extracted with unbuffered solutions, especially 1N potassium chloride, was more closely related to plant Al whereas Al extracted with buffered solutions, especially 1N ammonium acetate, pH 4.8, was more closely related to plant yield than that extracted with other methods. However, R values for the soil Al-yield relationships were generally lower than those for soil Al-plant Al relationships suggesting that while soil Al has a strong influence on plant Al, it has considerably less effect on yield.

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INTRODUCTION

Yield of sugarcane in Hawaii has increased as a result of applying calcium silicate to highly weathered soils of Hawaii. Since silicon is not considered essential for plants, the mechanism of crop response to silicates is open to question. In addition, the residual effects of Si on plant growth as well as leaching and fixation of applied silicates have not been studied in detail.

Monteith and Sherman (1963) reported increased Sudan grass yields which followed calcium silicate applications to a Gibbsihumox were due to increased P availability. On the other hand, in a Hydrandept yield increases were believed to be due to reduced Al concentrations resulting from reaction with Ca in the calcium silicate. Suehisa et al (1963) suggested that Si enhanced availability of P by reducing P fixation capacity or by substituting for P in soil. Some of the possible mechanisms of calcium silicate effects on crop production suggested in the literature are reduction in soil Al, Fe and Mn concentrations, decreased P sorption, increased Ca capacity, increased soil pH, increased cation exchange capacity, improved internal P nutrition, correction of plant micronutrient imbalances and increased mechanical strength of plants. Ayers (1966) concluded that the high Si content of calcium silicate slag, and not other elemental constituents, was responsible for increased cane and sugar yields in Hawaii.

A field experiment was started at the Kauai Branch Station in 1966 to study the long-term effects of $CaSiO_3$, applied as TVA slag, on a Gibbsihumox adjusted to various P and pH levels. In this experiment which was designed to separate Si effects from P and pH effects, Teranishi (1968) attributed yield increase of 9-month-old sugarcane with $CaSiO_3$ to direct and indirect Si effects. Response to residual Si was measured in a sugarcane ratoon crop (Rosenau, 1969) then by a subsequent crop of field corn (Thiagalingam, 1971). Although a yield response to calcium silicate occurred in the ratoon sugarcane crop, it was not statistically significant. However, statistically significant yield increases of corn were obtained from residual $CaSiO_3$ in the same experiment.

Movement of Si in the profile has not been studied in detail. However, Roy (1969), working with the samples from the field experiment described above, reported that Si had moved to the 60 cm depth during 9-month growth period of the sugarcane plant crop. Other reports of Si movement in the soil profile were not found.

Soils in which responses to $CaSiO_3$ applications have been obtained are highly leached, have low pH and high Al activity (Plucknett and Sherman, 1963). High levels of extractable Al increase P fixation and diminish plant growth. Therefore, it is important to properly assess the level of Al activity in these soils. Most published Al extraction procedures have been developed on acid soils of the Temperate Zone. These soils differ from tropical soils in Hawaii in their mineralogical and chemical characteristics.

The main objectives of the present study are as follows:

1. To investigate effects of residual Si, P and soil pH on yield and nutrient uptake of kikuyu grass and desmodium grown on a Gibbsihumox.
2. To investigate the effects of Si, P and soil pH on availability of soil P and Si.
3. To determine Si movement in the soil profile during the 5-year cropping period.
4. To determine the fate of Si 5 years after its application.
5. To identify an extraction method for Al in tropical soil that is related to plant Al and yield.

REVIEW OF LITERATURE

Development of Tropical Soils

The development of tropical soils results from intense weathering under humid conditions with the formation of kaolinitic clay minerals, and subsequent decomposition of such minerals to form free oxides of Fe, Al, and Ti (Sherman, 1949). Rainfall plays an important role in the laterization process of Hawaiian soils. Bates (1960) reported that desilication was the dominant process of rock weathering in Hawaii with an alteration sequence of Primary silicates---> Clay minerals---> Fe and Al oxides and hydroxides in the order of increasing rainfall. Chemical weathering, and leaching under good drainage conditions, leads to the depletion of Si and bases and an accumulation of hydrated Al and Fe compounds (Mohr and Van Baren, 1954).

Cline (1955) classified Hawaiian soils into several groups including Low Humic, Humic, Humic Ferruginous, and Hydrol Humic Latosols on the basis of increasing rainfall and weathering intensity. In contrast to the crystalline layer silicates found in temperate regions, highly weathered soils of Hawaii are comprised of hydrated Al and Fe oxides, often in poorly crystalline or amorphous forms (Mahilum *et al*, 1970).

The oxidic soils of Hawaii are low in available P, Si, and Ca, are acid, and high in active Al (Cline, 1955; Younge and Plucknett, 1966; Fox, *et al*, 1967b; Plucknett, 1971).

Their electrical charge is largely pH dependent although these soils possess a net positive charge at the normal soil pH (Mahilum et al, 1970; Mekaru and Uehara, 1972; Uehara et al, 1972). Uehara et al (1972) defined these soils as variable charge minerals and presented evidence for specific ion adsorption. They proposed a model to describe the behavior of such soils.

Phosphorus Fixation in Tropical Soils

The process by which the solubility of P fertilizer added to soil is decreased, thus making it less available to plants, is known as P-Fixation. This process involves several types of reactions classified as adsorption reactions, isomorphic replacement reactions and double decomposition reactions (Bear, 1964). Their relative importance is controversial. The oxidic soils of Hawaii have a tremendous capacity to fix P and this capacity is related to soil reaction and soil mineralogical composition (Chu and Sherman, 1952; Suehisa et al, 1963; Roy, 1969; Fox, et al, 1971).

Chu and Sherman (1952) reported that Fe and Al oxides were important in P fixation under acid conditions. When 10,000 ppm P was added, as much as 90% was immobolized in 24 hours. Less than 30% of the applied P was fixed when the oxides were removed. DeDatta et al (1963) reported that three Hawaiian soils, representing a Low Humic Latosol, an Aluminous Humic Ferruginous Latosol and a Humic Latosol, immobilized 98 to 99.8% of the added P in 48 hours. Younge and Plucknett (1966) showed that removing the hydrated Fe complex from a soil reduced P fixation by 50 to 60%. Fox *et al* (1962, 1968a) studied P fixation of several Hawaiian soils and found the intensity of P retention in the order of amorphous hydrated oxides > goethite-gibbsite > kaolin > 2:1 clays. Similar results were obtained by Roy (1969).

The mechanism of P fixation by hydroxides and oxides of Fe and Al involves an exchange of phosphate of hydroxyl ions (Low and Black, 1950; Mujaldi *et al*, 1966). Hsu and Rennie (1962) reported that P will be adsorbed by aluminum hydroxide when the attraction between aluminum hydroxide and phosphate is strong enough to remove the surface hydroxyls already present. Mekaru (1969) indicated that the P adsorption capacity of soils does not depend on the amount of free iron oxide alone, but also on the reactive nature of the oxide surface. Hingston *et al* (1967, 1968) advanced the concept of specific adsorption of phosphate by ligand exchange in goethite. They defined this adsorption as an exchange reaction between the anion being adsorbed and water molecules or hydroxyl ions coordinated with the ferric ion at the goethite surface. Soil pH and cation exchange capacity changes associated with anion adsorption in Hawaiian soils reported by Mekaru (1969) support the concept of specific adsorption. He proposed a model of P adsorption by iron oxide based on the mechanism suggested by Hingston, *et al*

(1967, 1968).

The problem of phosphate fixation which results in low solution P for plant uptake, ultimately affecting crop yields, can be overcome by heavy P additions. Younge and Plucknett (1966) in Hawaii and Kamprath (1967) in North Carolina used heavy P applications to quench the soils' large capacity to sorb P. Younge and Plucknett (1966) used rates as high as 1200 pounds per acre and demonstrated that P requirements of crops can be met for extended periods of time when P equivalent to ¼ sorption maxima was initially applied. Residual effects of applied P have also been studied by Fox et al (1968a) and Roy (1969) who reported that in spite of tremendous capacity of soils to fix P, the residual effects of phosphate application were long lasting.

Other workers in Hawaii who showed P response to different crops include Clements (1965), Monteith and Sherman (1963), Ali (1966), Ibrahim (1968), Teranishi (1968), Adlan (1969), and Thiagalingam (1971). Crops included were sugarcane, Sudan grass, corn, rice, and papayas. These workers reported significant growth or yield responses to phosphate fertilization.

In recent years, phosphorus sorption curves have been used to estimate P requirements of Hawaiian soils for maximum plant growth. The approach followed is that of Beckwith (1965) who measured sorbed P against a standard supernatant concentration of 0.2 ppm as an estimate of the phosphate needs of the soils. Ozanne and Shaw (1968) used 0.3 ppm P in equilibrium solution as a standard value for P requirement for maximum plant growth. Fox and Kamprath (1970) obtained 95% maximum yield of millet when P in solution was adjusted to 0.2 ppm. Soundararajan (1971) found that an interaction existed between crops and adjusted solution concentrations required for maximum yields in different soils. However, he suggested that a value of 0.6 ppm P in solution could be used for most agricultural crops.

Silicon in Soil Solution

The reactions of Si in soil have been studied extensively by several investigators in the past (Raupach, 1957; Beckwith and Reeve, 1963; Gifford and Frugoli, 1964; Jones and Handreck, 1963, 1965, 1967; McKeague and Cline, 1963a, b; Miller, 1967). This follows the fundamental work of Alexander et al (1954) who showed that Si in solution is present in the form of monosilicic acid, $Si(OH)_4$, at pH below 9. In a saturated solution of pure amorphous Si, the solubility was between 120 to 140 ppm SiO_2. The solubility of Si was shown to be independent of pH in the range of pH 2 to 9.

The solubility of monosilicic acid in soil depends mainly on soil pH and the quantity of sesquioxides present. Raupach (1957) reported that the concentration of Si in saturation extracts of some Australian soils decreased with increasing pH throughout the reaction range from pH 4 to 9. Beckwith and Reeve (1963, 1964) observed that the amount of Si decreased with increasing pH and was minimum at pH 7 to 9. Citrate ions promoted release of native Si from soils, and partially prevented the sorption of added monosilicic acid. They considered sesquioxides responsible for most of the absorption of added monosilicic acid and the reaction to be pH dependent.

McKeague and Cline (1963a) showed that dissolved Si concentration in soil solutions increased with temperature, and soil:solution ratio and decreased with increasing pH. Monomeric Si, presumably $Si(OH)_4$, was the dissolved form of Si in all extracts studied. Studying the adsorption of Si, the same authors (1963b) found freshly precipitated hydroxides of polyvalent metal ions most effective, iron oxide minerals moderately effective, and alkaline earth carbonates ineffective in adsorbing Si.

Jones and Handreck (1963, 1965) established that Si in soil solutions is entirely of the form of monosilicic acid and ranges from 30 to 40 ppm SiO_2. They observed different concentrations of monosilicic acid among soils of the same pH; but the highest reported were below that of a saturated solution of monosilicic acid. They also found that aluminum oxides were more effective in adsorbing monosilicic acid than were iron oxides.

From the foregoing, it can be concluded that the concentration of monosilicic acid in soil solution is largely controlled by an adsorption reaction dependent on pH. An adsorption maximum occurs around pH 9 with decreased adsorption at either higher or lower pH values. Sesquioxides, especially aluminum oxides, play a dominant role in Si adsorption.

Jones and Handreck (1967) proposed a mechanism by which Si is adsorbed on the sesquioxides such that monosilicic acid is formed through a hydrogen bond to an oxygen atom that bridges two iron (or aluminum) atoms as follows:

$$(OH)_3Si - O - H --- O(Fe_2O_4H_4)$$

Since monosilicic acid here is acting as an acid, it is repelled by increasing acidity. These investigators disagreed with the earlier work of Beckwith and Reeve (1963) where this phenomenon is explained through the formation of a salt.

Tran Vinh An and Herbillion (1966) studied the adsorption of Si by ferric oxides and concluded that Si chemically bound to a ferric hydroxide gel stabilizes the amorphous and depolymerized state of the ferric particles. They suggested that the reaction between Si and ferric oxides was mainly a chemisorption process made easier by the large surface areas of the amorphous ferric hydroxides. This is supported by the work of Hingston et al (1967, 1968) who proposed a theory of anion specific adsorption by ligand exchange. This is defined as an exchange reaction between the ion that is adsorbed and water molecules or hydrated ions coordinated with the ferric ion in the goethite surface. The characteristics of such an exchange are that it renders the surface less positive or more negative, and it can occur only when both the ion and its undissociated acid is present.

Herbillon and Tran Van An (1969) employed x-ray diffraction, infra-red spectroscopy and surface area measurements to study the nature of silicon-iron mixed hydroxide and found that compounds with molecular ratios (MR) of SiO_2/Fe_2O_3 that range from 0.01 to 1.17 were essentially amorphous. They identified two ranges of Si contents that existed in the mixed hydroxides. In the first range, $MR < 0.01$, Si is directly chemisorbed on the absorbent. In the $MR > 0.1$ range, Si polymerizes as a separate phase grown upon the "ferrosic" of "ferric" phase. They agreed with Gifford and Frugoli (1964) that the immediate source of SiO_2 in the soil was the "solid" silicic acid and that such a form of Si is chemisorbed on ferric or ferrosic hydroxides.

Obihara and Russell (1972) studied the specific adsorption phenomenon of silicate and phosphate, and showed that when phosphate displaced silicate, or vice-versa, more moles of the displacing acid are adsorbed than moles of the displaced acid released. Maximum adsorption of Si from pure solution occurred at pH 9.2. These results are in conformity with the work of Hingston et al (1967).

Kittrick (1971) showed by thermodynamic calculations that equilibrium between kaolinite and montmorillonite would maintain approximately 10^{-3} M $Si(OH)_4$ in solution (28 ppm Si). He pointed out that equilibrium was not readily obtained in the complex aluminosilicate systems. Elgawhary and Lindsay (1972) constructed solubility diagrams of various ionic and molecular species of Si in equilibrium with amorphous Si as a function of pH and found that below pH 8.2, only uncharged $Si(OH)_4$ contributed significantly to total soluble Si. Above this pH, other ionic forms became more important. The same authors also measured the equilibrium Si concentrations in two soils over a period of 50 days. The acid soil supported about 19 ppm Si in solution, while the calcarious soil supported 25 ppm. They concluded that the solid phase Si which is less soluble than amorphous Si (51 ppm Si) and more soluble than quartz (2.8 ppm Si), lies very near the level predicted by Kittrick (1971) and controls Si solubility.

The effect of Si solubility in controlling the intensity factor (equilibrium concentration) and capacity factor (supplying power) has been considered by several other workers. In a study of finely ground Si, Dempster and Ritchie (1952) found that siliceous dust consists of two parts; an outer layer of high solubility and a less soluble inner core. The separation of the two parts is not sharply demarcated, but slightly blended at the interfacial joint.

Miller (1967) stated that the concentration of Si in a soil solution is determined by a soil's properties, and is both pH- and temperature-sensitive. The results show that if the soil has a low Si concentration, then large quantities of added Si will not remain in solution for a long time. Miller suggested that the disorganized form of Si that is formed from the extra material added will be adsorbed on the surface of various silicate materials. Roy (1969) reported that native Si concentration in the soil solution increased with decreasing pH of the soil suspension. Sorption of added Si increased with increasing soil pH, and was greatest for soils with amorphous colloids and high sesquioxide contents.

Effects of Si on the Growth and Yield of Plants

Beneficial effects of silicate applications on plant growth in tropical soils have been reported by several investigators (Sherman *et al*, 1955; Ikawa, 1956; Monteith and Sherman, 1963; Suehisa *et al*, 1963; Clements, 1965; Ayers, 1966; Fox *et al*, 1967b; Teranishi, 1968; Rosenau, 1969; Thiagalingam, 1971; Tamimi and Matsuyama, 1972). The function of Si, as well as reasons for these responses have been extensively reviewed by Plucknett (1971) and Silva (1971).

Yield response to soluble silicate additions in Hawaii was first demonstrated in a Humic Latosol by Sherman and associates in 1955, using Sudan grass as a test crop. In another pot experiment, plant growth and dry matter yield increases of corn were associated with sodium silicate applications in a similar soil (Ikawa, 1956). Later, Monteith and Sherman (1963) reported increased yield of Sudan grass both with $CaCO_3$ and $CaSiO_3$ in a Hydrol Humic Latosol when the pH was below 6.8. In a Humic Ferruginous Latosol, however, $CaCO_3$ application depressed yield at high pH values while silicate response continued. The response in the Hydrol Humic Latosol was believed to be due to reduced Al toxicity, whereas increased P availability was a factor in the Humic Ferruginous Latosol.

The first field response to soluble silicate was reported by Suehisa and co-workers (1963). Sudan grass yields increased significantly, due to silicates in a Humic Latosol, while no beneficial effects were observed in a Low Humic and Humic Ferruginous Latosol.

Following the greenhouse and field responses to silicates by Sudan grass, the material was tried on sugarcane at different locations in the Hawaiian islands. A yield increase of 5.1 tons of raw sugar in the combined plant and ratoon crop was obtained with 5,000 pounds of calcium silicate per acre at Grove Farm on Kauai (Sherman _et al_, 1964). Lime applied at 4,000 pounds per acre, on the other hand, produced a slight depression in yield. In another experiment that involved phosphate, coral stone, and sodium silicate installed on the Kilauea Plantation, Kauai, a significant gain of 0.6 tons of sugar per acre was obtained, with 1,000 pounds per acre of silicate addition (Clements, 1965). Ayers (1966) reported highly significant gains in yield of cane and sugar with silicate applied to an Aluminous Ferruginous Latosol. He concluded from this study that Si, directly or indirectly, was beneficial to the growth and development of sugarcane. Fox et al (1967b) reported a sugar increase of 12 tons/ha, upon addition of 4.5 tons of TVA slag to a Gibbsihumox soil on Kauai where the phosphate-extractable soil Si level was 20 ppm. They suggested critical levels of soil and plant Si in relation to sugarcane growth in the highly weathered soils of Hawaii.

Residual effects of silicate applications on plant growth have been investigated in Hawaii and elsewhere. Clements et al (1967) reported that application of 8 tons Si slag per acre resulted in 34 per cent more sugar in the plant crop, and 40 per cent more sugar in the first ratoon crop at Kilauea Sugar Plantation, Kauai. Hagihara (1971) reported that the sugarcane ratoon crop responded to residual silicate, with gains similar to plant crops, where 4 to 8 tons slag per acre were added.

A field experiment was installed on a Gibbsihumox to study the continued effects of $CaSiO_3$ and $CaCO_3$. A nine-month plant crop of sugarcane was followed by a nine-month ratoon crop and then by a crop of corn. A highly significant effect of Si on cane yield was observed in the plant cane crop (Teranishi, 1968). In the ratoon crop, yields probably increased with residual Si, although the response was not statistically significant (Rosenau, 1969). In the corn crop residual Si increased significantly (Thiagalingam, 1971). The effect of Si on ear corn yield at higher P levels was apparent but not significant.

In Mauritius, calcium silicate applied to a sugarcane plant crop produced high yield increases in the plant crop and first and second ratoons (Wong and Halais, 1969; Wong, 1970, 1971). The effect of coral stone on cane growth as well as sugar yield vanished after the plant crop (Wong, 1971). In addition to the yield response, the beneficial effects of calcium silicate over $CaCO_3$ include better tillering, larger stalk girth, heavier leaves and sheaths and an absence of freckling.

In a nutrient solution experiment, Wong et al (1973) obtained a significant increase in cane yield with silicic acid in two sugarcane varieties. Sucrose production of one variety was also increased. The researchers reported leaf freckling in minus Si plots.

Based on the earlier research on sugarcane nutrition, Plucknett (1971) has summarized the effects of Si as follows: 1) correction of the freckling disease; 2) larger growth index, expressed as green weight of leaf sheaths 3 to 6; 3) gain in stalk size and elongation; 4) larger stalks and larger suckers during growth; 5) increased numbers of green and functioning leaves; 6) a greater yield of cane and a greater dry matter yield; and finally, 7) an increased yield of sugar.

Response to Si applications has also been observed in various other crops. Ganssmann (1962) showed that the growth and yield of oats and beans increased in sand cultures, due to colloidal Si additions that improved the moisture holding capacity of the medium. Silicon also appears to play an important role in rice production. Mitsui and Takatoh (1963) reported that 100 ppm Si added to a culture solution increased the production of new roots and tillers of rice plants, advanced the time of head sprouting, and suppressed Si deficiency symptoms. Reduced infection by fungi and an increased number of seeds produced were also observed. When the Si level was 0.5 per cent or less of total dry matter, plants showed retarded growth in both the vegetative and reproductive stages. Similar observations were made by Okuda and Takahashi (1964). Increased yields of barley, oats, wheat, rye grass (Williams and Vlamis, 1957; Vlamis and Williams, 1967) and sorghum (Tamimi and Matsuyama, 1972) have been reported from Si application.

Thiagalingam (1971) studied the response of calcium silicate applications to 22 plant species including legumes, grasses, grain crops and vegetable and fruits and reported that yields of most of the species were higher with calcium silicate than without. Yield at 2.2 T Si/ha were 85% or more in 17 out of 22 species grown on Kapaa soil; and he suggested this rate to be more economical over 8.8 T Si/ha. High rates of calcium silicate depressed yields in some species suggesting these levels to be toxic.

The Mechanism of Crop Response to Si Application

Fox *et al* (1967a) suggested the following as possible ways in which calcium silicate can benefit crops:

1) Make soil P (and perhaps sulphur) more available.
2) Decrease fertilizer P fixation.
3) Correct Ca and Mg deficiency.
4) Increase soil pH.
5) Decrease the requirements for P within the plant.
6) Prevent the accumulation of toxic concentrations of Mn (or other elements) in the plant.
7) Enhance efficient use of water by plants.
8) Guard plant tissues against damage by insects and fungal diseases.
9) Strengthen tissues, decrease lodging, and promote more efficient use of sunlight.
10) Benefit plants in some, as yet unknown, "essential" role.

Clements *et al* (1967, 1971) considered the elimination, through precipitation, of certain soil solutes, notably Al, Mn, and Fe, which are injurious to plant growth, as the primary function of calcium silicate. They attributed leaf freckling in sugarcane to a nutrient imbalance in the plant and concluded that it could be effectively ameliorated with calcium silicate which improves growth.

Silva (1971) reviewed earlier work on the possible mechanisms of crop response to calcium silicate applications and identified soil and plant effects separately. The effects in the soil include increased availability of soil P, increased soil Ca levels, increased soil pH, decreased concentrations of potentially toxic elements such as Al, Fe, Mn, and increased net negative charge, and less leaching of nutrient cations. The effects in the plant include increased level of P, increased root absorption of P, more effective utilization of plant P, decreased levels of toxic elements such as Fe, Al, Mn, increased levels of Ca, Mg, etc., and increased level of Si.

The Effect of Silicon on P Availability

Several opinions exist as to the P-Si interactions in soils and plants. Hall and Morrison (1906) believed that the seat of the reaction was in the plant rather than in the soil. Fisher (1929), however, indicated that the main effect of silicate is to increase the availability of soil P and has nothing to do with plant metabolism. The effects of Si on P in the soil and plants will be discussed separately as follows:

Soils: Tuilin (1936) suggested that silicate increased P availability due to a replacement of phosphate anions by silicate anions in the soil colloidal system. Similar suggestions have been made by Laws (1950).

Toth (1939) reported that silicate anions released fixed phosphate from soils in a manner similar to the acidoid displacement by organic anions like citrate and tartarate. Increased yields of barley associated with silicate have been suggested due to an increased availability of soil P rather than to fertilizer P (Cooke, 1956). Raupach and Piper (1959) reported an increased soil P release by silicate application in laterite soils, but indicated that the effect was temporary and did not last longer than a year. Jones and Handreck (1967) suggested that the release of P by Si was not due to anion exchange, but possibly to an increase in pH or to a decrease in Al activity which prevents P precipitation.

Several investigators have reported increased extractable soil P following Si treatments. Teranishi (1968) obtained the highest levels of extractable P at the highest level of applied Si in a Gibbsihumox measured after a nine-month crop of sugarcane. Since the experiment was designed to separate Si effects from pH effects, the increase can be attributed to Si alone. A similar but relatively smaller effect was observed on samples taken after the ratoon crop (Rosenau, 1969). Adlan (1969) reported no effect of Si on native soil P, but with added P, Si increased soil extractable P. Roy _et al_ (1971) found increased P desorption in the presence of Si in some Hawaiian Latosols. The desorption of adsorbed P was greater for the kaolinitic soils than for soils rich in gibbsite or amorphous oxides.

A decrease in the P fixation capacity of soils as a result of Si additions was demonstrated by Ikawa (1956) in a Low Humic, Humic Ferruginous and Humic Latosol and a Dark Magnesium Clay. The greatest reduction occurred in the Humic Latosol. Phosphorus fixation decreased from 95 per cent to 45 per cent with the addition of 5,000 pounds per acre of sodium silicate in the Humic Latosol. Roy _et al_ (1971) obtained a decrease of from 9 to 43% in the P requirements of some Hawaiian soils with silicate additions. The largest decrease was in the kaolin system and the smallest in the hydrated oxides. The residual effect of fertilizing a Gibbsihumox soil with 9 tons/ha of calcium silicate slag at 110 kg P/ha was to reduce the P requirement by 500 kg/ha (Roy _et al_, 1971). This Si effect on P sorption may be due to the interaction of Si compounds with sorption sites or the inactivation of Fe and Al by the formation of insoluble compounds with Si.

Hingston _et al_ (1968) also demonstrated decreased P sorption by geothite in the presence of Si which they attributed to the ability of Si to increase the negative surface charge. Obihara and Russell (1972) reported that the presence of Si in a mixed solution did not affect the amount of P absorbed unless the pH is over 6.5 to 7.0, at which point the maximum adsorption curve for Si crosses that of P. They explained their results on the basis of ligand exchange of Hingston et al (1968) described earlier.

It is apparent from the above findings that Si increases P availability by increasing solubility of sorbed P and by decreasing P fixation capacity of soils.

Plants: Silicon in the plant can perform some of the functions of P, and can be a means of economizing on the use of phosphate fertilizer (Brenchley et al, 1927). Okuda and Takahashi (1962) report that Si in the rice plant inhibits luxury consumption of P. Significant increases in crop yield, total plant uptake, and available soil P with $CaSiO_3$ were reported by Hunter (1965). He believed that the increased availability of soil P was due to anion exchange in the soil. He did not find any evidence of Si substitution for P in the plant.

The effect of Si on the yield and plant uptake of P have been described by several workers (Suehisa et al, 1963; Monteith and Sherman, 1963; Thiagalingam, 1971). These increases have been regarded as an effect of Si on P availability as discussed earlier. However, Ayers (1966) and Teranishi (1968) have concluded that increased P uptake resulted from increased yields rather than increased yield being the result of greater P uptake. Clements (1965) obtained decreased P concentration in sugarcane by applying TVA slag to an Aluminous Ferruginous Latosol, which he attributed to a dilution effect due to increased growth. Fox et al (1967b) demonstrated that the observed Si response did not result from improved P nutrition because a four-fold increase in P fertilizer had little effect on yield.

Silicon increases P absorption by roots (Rothbuhr and Scott, 1957; Roy, 1969), increases the efficiency of P utilization by the plant (Ali, 1966) and in some way decreases the internal P requirements of plants (Teranishi, 1968). Findings of Alexander (1968) that reactions involving leaf phosphatase, amylase, peroxidase and phenol oxidase in sugarcane can be suppressed by Si also suggest a role of Si in P metabolism.

Silicon Uptake by Plants

Silicon probably is absorbed by plants as mono-silicic acid and carried to the tops in the transpiration stream where it polymerizes to form solid silica (SiO_2) (Jones and Handreck, 1967). Yoshida et al (1962) found that silica gel, a polysilicic acid or a polymerized product of orthosilicic acid, accounts for 90 per cent of the total Si in the rice plant. The remaining Si is composed of 0.5 to 8 per cent silicic acid. Much of the Si absorbed by the rice plant was found in the epidermis of the leaf blade and husk. The authors suggested that Si distribution within rice tissues was closely related to transpiration and that the reutilization of Si once deposited was unlikely.

Fox et al (1968b) reported that both total and soluble Si were higher in sugarcane leaf sheaths than in sugarcane blades and that total Si was higher in the leaves than in the internodal tissue. They suggested that soluble Si in plants could be a useful index of the Si status of plants. They concluded that Si deposition in plants was not the passive result of transpiration.

Graminaceous species generally accumulate more Si than leguminous species (Russell, 1961; Jones and Handreck, 1965). Thiagalingam reported Si concentration in different plant groups in the order of grains $\geq$ grasses $\geqslant$ vegetables and fruits $\geqslant$ legumes except for two desmodiums in which Si concentrations were similar to those of grasses.

Although plant species differ in their ability to absorb Si (Okuda and Takahashi, 1964) the amount of Si in the soil solution is related to the amount found in plants (Fox <u>et al</u>, 1967; Thiagalingam, 1971). Views differ regarding the mechanism of Si uptake by plants. Yoshida <u>et al</u> (1962) concluded that Si uptake by rice plants was passive since silicic acid was constantly absorbed by rice roots along with water and accumulated in the aerial parts as water was lost by transpiration. Similar results were obtained by Mitsui and Takatoh (1963). Jones and Handreck (1965) reported that the amount of Si in the oat plant can be calculated from the concentration of silicic acid in the soil solution and the amount of water transpired, and that the uptake is passive. However, the same authors mentioned that leguminous species that contain relatively lower amounts of Si must have some mechanism for excluding Si at the root surface.

The assumption that Si is taken up actively with the utilization of respiratory energy is supported by several workers (Okuda and Takahashi, 1964; Barber and Shone, 1966; Tanaka and Park, 1966; Thiagalingam, 1971). Silicon uptake by rice was inhibited more severely than P uptake by 2-4-dinitrophenol, whereas sodium cyanide inhibited Si uptake as severely as P and K uptake (Okuda and Takahashi, 1964). They concluded that energy from aerobic respiration is required for the uptake of Si by rice. Barber and Shone (1966) recorded the effect of respiratory inhibitors on both transpiration and Si uptake while temperature affected Si uptake only and not transpiration in a 48-hour absorption study. From this, they concluded that absorption by roots was affected by metabolic energy.

Thiagalingam (1971) found a significant increase in transpiration with a decrease in relative humidity, but no significant increase in Si uptake resulted, suggesting that transport of Si from roots to tops was not related to transpiration. Also, Si concentrations in xylem exudates of desmodium, corn and sugarcane were greater than those of the external solution, indicating Si movement by active transport rather than by mass flow. In tomato and alfalfa, Si concentrations were lower in the exudates than in the external solution, supporting the presence of a selectivity mechanism.

Movement of Silicon in Soil

Roy (1969) studied Si movements in some Hawaiian soils in unsaturated flow and indicated that considerable Si applied to the 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. In a related study Roy (1969) reported that the amounts of Si leached through soil columns were related to their capacities for Si sorption. The order of sorption in Hawaiian soils studied was: Akaka > Wahiawa > Kapaa > Kawailoa. Movement of Si in soil profiles in the field was a function of the amounts of silicate applied and soil pH (Roy, 1969). Soluble Si was highest in profiles with low soil pH. Considerable Si had moved to 24 inches in the profiles of a Gibbsihumox soil during the nine months after silicate applications. Soluble Si in the profiles of a Hydrendept increased with increasing amounts of TVA slag applied five years earlier.

Hagihara (1971) reported that the loss of silicate by leaching in a Gibbsihumox soil was small. In a laboratory experiment, a loss of 3% of the applied silicate was obtained after 95 inches of water had percolated through a 12-inch soil column. He observed that most of the silicate applied was concentrated in the top 2-inch layer of soil below which extractable Si levels increased very slightly. Wong (1971) suggested that some loss of applied silicate occurred through leaching during crop growth, but supplied no data to support the contention.

Aluminum Toxicity in Plants

Aluminum has been considered toxic to crop plants by several workers (Gilbert and Pember, 1935; Ligon and Pierre, 1932; Foy and Brown, 1964; MacLeod and Jackson, 1965), although stimulating effects of this element at low concentrations have also been observed. McLean and Gilbert (1928) observed stimulating effects of Al at 6 to 13 ppm Al concentrations in culture solution while higher levels were toxic to plants. Ligon and Pierre (1932) found that Al present in nutrient solution at concentrations higher than 1 ppm caused injury to corn, sorghum and barley. Aimi and Murakami (1964) conducted nutrient culture studies to establish Al toxicity levels in various crop plants and showed that wheat and lettuce were susceptible to concentrations of Al below 0.9 ppm in solution. Growth of turnips and radish was suppressed between 0.9 and 9 ppm Al, while growth of rice, corn, cucumber and squash was inhibited only at Al concentrations above 90 ppm in solution. MacLeod and Jackson (1965) reported that lucerne and red clover had more vigorous establishment and higher yields in the presence of 0.1 to 0.2 ppm Al than without; but 1 ppm Al in solution restricted growth significantly.

Different strains and varieties of the same species demonstrate differential tolerance to Al injury. This phenomenon has been observed in wheat (Fleming and Roy, 1968), barley (Reid *et al*, 1969), cotton (Foy *et al*, 1967), soybean (Armiger *et al*, 1968), and various other crops (Elliot, 1973). Aluminum toxicity causes root injury (Ligon and Pierre, 1932) in which roots become brown with few rootlets (Gilbert and Pember, 1935) or they become stubby with no lateral roots (Otsuka, 1968). Dessureaux (1969) observed reduced root elongation of alfalfa seedlings at higher Al concentrations in nutrient culture studies. Inhibited cell division in adventitious root apices of *A. stelonifera* was observed by Clarkson (1966) as root growth of this species showed distinct signs of Al toxicity at 0.2 ppm Al in water culture studies.

Aluminum effects on top growth of tobacco have been described as a reduction in leaf and stem size with the growth reduction being more pronounced with age (Bortner, 1935). Results of experiments conducted by Cate and Sukhai (1964) indicate that Al concentrations as low as 1 to 2 ppm in the absence of nutrient cations markedly inhibit the growth of rice roots, and higher concentrations prevent root growth and cause brown mottling of leaves. Ota (1968) concluded from his review of physiological disorders of rice that bronzing is caused mainly by Al toxicity, and is particularly severe in soils low in exchangeable Ca. Long and Foy (1970) observed leaf rolling in Al-sensitive barley plants grown on unlimed soil and attributed this to Al-induced Ca deficiency.

Plant species vary widely in their capacity to accumulate Al. Accumulation of Al in the Australian and New Guinea flora is described by Webb (1954). Moomaw et al (1959) studied the Al content of 23 plant species growing on high Al bauxite soils of Hawaii. They described 13 species as Al accumulators with Al concentrations of more than 1,000 ppm. Humphreys and Truman (1964) reported that Pinus Spp. grown in highly acid soils of Australia accumulate 765 to 1,300 ppm Al in their foliage. Eucalyptus Spp. growing in similar sites generally contained less than 200 ppm Al.

The Effect of Al on Ca and P Uptake

In addition to its toxic effects on plant growth, Al inhibits the uptake of Ca and P by plants and reduces yields of crop plants. Johnson and Jackson (1964) demonstrated the effects of Al on the uptake and translocation of Ca by barley roots from a solution culture. The drastic reduction in Ca uptake by Al was not solely due to competition for exchange or carrier sites since reduction in Ca uptake was not diminished by supplying extra Ca. Transport of Ca to shoots was also restricted by Al, but not stopped completely. Schmehl et al (1952) suggested a possible antagonism between Al and Ca uptake by alfalfa as the absorption of Ca was greatly suppressed by the addition of Al to the nutrient solution. Ragland and Coleman (1959) found that 5 meq. of Al in the nutrient solution not only prevented Ca absorption by excised snap bean roots, but also caused a loss of Ca from the roots to the solution. Gangwar (1967) showed that Al depressed the sorption of Ca by excised pineapple and Kiami clover roots. He also studied the distribution of cations in the roots and tops and found that more than 80 per cent of the Ca absorbed was found in plant tops, whereas most of the Al was associated with roots. Plants also differ in their capacity to transfer Al to their shoots and it was reported that the net translocation of Al in Kiami clover was twice that of corn.

Precipitation of P and Al in the plant as aluminum phosphate has long been suggested (McGeorge, 1925). Wright (1937, 1943) observed a higher percentage of applied P in Al-treated barley plants than in the non-treated plants, and the differential was particularly marked in the roots. He concluded that P precipitation occurred mainly in the roots which resulted in marked reductions in yield presumably attributed to P deficiency in the meristematic region. Wright (1945), using microchemical tests to identify organically and inorganically bound P in roots, confirmed earlier findings that abundant P existed in roots in contact with Al and little or no P was found in roots from solutions without Al.

Clements (1962) showed that heavy applications of lime increased P concentrations in the plant and reduced soluble Al in the soils studied. Foy and Brown (1963) reported that yield and P uptake of cotton were increased in Al-containing nutrient solutions when pH was increased or P added, due to precipitation of Al. They suggested that a P/Al ratio greater than 2 is required to prevent a P deficiency in the nutrient solution. Less P was required when Al was added at pH 5 than at pH 4. Munns (1965) found increased accumulation of P in roots of lucerne growing in high Al media which depressed root elongation and yield due to induced P deficiency. Both lime and P additions alleviated Al toxicity and P deficiency symptoms.

Clarkson (1966) suggested that the reaction between Al and P, which results in the fixation of P by an absorption-precipitation mechanism, is superficial and occurs at the root surface or in the free space of the root. That the reaction does not depend on cellular metabolism is shown by the fact that low temperature and DNP have little effect on accumulation of extra P in Al-treated barley roots. Clarkson (1967) proposed that a larger proportion of Al in barley roots is associated with the cell wall as an amorphous precipitate of $(Al(OH)_3)_n$. This surface is positively charged and is known to adsorb and precipitate P from a solution that results in the formation of $Al(OH)_2H_2PO_4$. In soil conditions where Al and P ions arrive at the root continually, this process would effectively reduce the concentration of P available for active uptake.

McCormick and Borden (1972) employed photographic techniques to identify the sites of PO_4 fixation by Al in the barley and poplar roots. Color photomicrographs of the root sections showed a definite interaction of Al and PO_4 in the root cap and in the epidermal and cortical regions that extend back from the root tip 1 to 5 mm. The Al-PO_4 interaction appeared to be associated with the cell walls. Results also indicate that Al adsorbed by the root surface or absorbed in the intercellular free spaces may be capable of immobilizing PO_4 present in the root tissue or in the external solution.

Soil Aluminum

Aluminum is normally present in the soil as: 1) undecomposed fragments of primary alumino-silicate minerals; 2) secondary alumino-silicates; 3) relatively insoluble crystalline aluminum hydrous oxides, hydroxides, hydrated oxides, phosphates and silicates; and 4) as exchangeable Al (Rich, 1960; Jackson, 1961).

The amount of Al present in the soil solution depends largely on the nature of Al compounds and on soil pH. The solubility of Al is shown to be minimum between pH 5.0 and 7.5, but is appreciable at pH below 4.5 and above 9.0 (Magistad, 1925). Also, Al solubility in the soil solution is comparable to its solubility in water at the same pH. However, Pierre et al (1932) concluded that the concentration of Al in different soils of similar pH values varies greatly. They emphasized that more than one curve for the concentration of soil Al in displaced soil solutions exist at various pH values.

In very acid solutions, trivalent Al exists as the cation $Al(H_2O)_6^{3+}$, and with increased pH, more complex hydrolyzed and polymerized forms are formed by the loss of H^+ ions of H_2O groups (McLean, 1965). A scheme proposed to describe the nature of Al reactions with increased pH is as follows (Rich, 1960; Thomas, 1961; Jackson, 1961):

$$Al(H_2O)_6^{3+} \dashrightarrow Al(OH)^{2+} \cdot 5H_2O \dashrightarrow Al(OH)_2^{1+} \cdot 4H_2O \dashrightarrow Al(OH)_3 \cdot 3H_2O$$

Aluminum hydroxide ($Al(OH)_3 \cdot 3H_2O$) precipitates, thus lowering the concentration of soluble Al. At pH values above 7.5, aluminate ions ($Al(OH)_4 \cdot 2H_2O^-$) are formed, which increase the concentration of Al in solution, according to Magistad (1925).

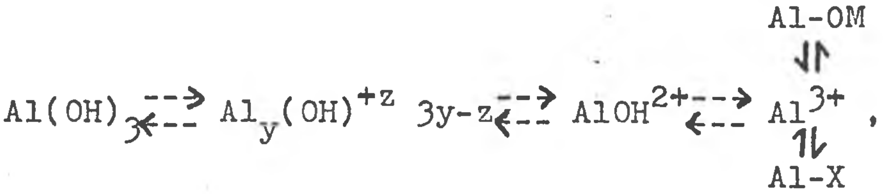
An appreciable fraction of the permanent negative charge of acid soils is countered by aluminum and hydrogen ions. The relative distribution of these ions on the exchange sites has been debated for 60 years (Jackson, 1963; Coleman and Thomas, 1967). Paver and Marshall (1934) and Schofield (1949) demonstrated the importance of Al in soil acidity and their work showed that Al was the main constituent of exchange acidity in clays. Yuan (1963) found that in very acid soils with pH less than 4.8 there were more hydrogen than aluminum ions; at higher pH values, there was more Al than H-ions, and both became negligible above pH 5.8. Coulter (1969) reviewed earlier work on soil acidity and concluded that acid soils are Al-saturated materials with apparent weak acid characteristics, due to the hydrolysis of adsorbed Al. Also, that

H-saturated clays are strongly acid but revert to Al-clays on standing.

Aluminum on the soil complex can be exchangeable to cations in neutral salt solutions or fixed in the interlayer spaces of 2:1 clays. Exchangeable Al is defined as the amount of soil Al that is extracted by a neutral unbuffered salt solution, whereas fixed Al is the amount replaced by a strongly buffered salt solution. (This includes exchangeable as well as non-exchangeable Al adsorbed by the colloids, McLean, 1965). Hsu and Rich (1960), working with synthetic exchangers, reported that exchangeable Al was trivalent and fixed Al was monovalent. Rich (1960) proposed that interlayer Al consisted of positively charged hydroxy-Al polymers that acted as props which prevent NH_4 fixation. Chakravarti and Talibudeen (1961) studied the nature of adsorbed Al in clays by measuring the Al content and pH in equilibrium suspensions of clays in dilute KCl at pH 3, 4, and 5. They found that pAl^{3+} was linearly related to pH with a slope of 1:1 in kaolinite and glauconite, and 1:1.6 in montmorillonite. They deduced that hydroxy-Al polymers were adsorbed on the octahedral edge faces of the minerals. Coulter (1969) has suggested that fixed Al is a hydroxy-Al polymer with a composition that may range from $Al_6(OH)_{12}^{6+}$ to $Al_n(OH)_{3n}$. He also concluded that measurements from titration curves of soils that contain fixed Al suggest that hydroxy-Al polymers are responsible for the pH-dependent charge of soils.

A large proportion of the fixed Al has also been found to be complexed with organic matter. McLean et al (1965) observed large increases in total exchangeable cations upon liming several acid soils, particularly when their organic matter content was high. These increases largely disappeared with the destruction of organic matter. They concluded that the pH-dependent charge was complexed by the organic matter which could not be released by neutral salt leaching.

Poinke and Corey (1967) proposed a reaction scheme that describes the relationship between various forms of Al postulated to exist in the soil:



$$\begin{tikzcd} & & & \mathrm{Al{-}OM} \arrow[d, shift left] \\ \mathrm{Al(OH)_3} \arrow[r, dashed, shift left] & \mathrm{Al_y(OH)^{+z}}\ 3y-z \arrow[l, dashed, shift left] \arrow[r, dashed, shift left] & \mathrm{AlOH^{2+}} \arrow[l, dashed, shift left] \arrow[r, dashed, shift left] & \mathrm{Al^{3+}}, \arrow[l, dashed, shift left] \arrow[u, shift left] \arrow[d, shift left] \\ & & & \mathrm{Al{-}X} \arrow[u, shift left] \end{tikzcd}$$

where Al^{3+} = activity of trivalent hydrated ions in the soil solution; Al-X = KCl-exchangeable Al; Al-OM = Al complexed by organic matter; and $(Al)_y(OH)^{+z}$ 3y-z = polymerized component of nonexchangeable Al. They found exchangeable Al concentrations to be primarily related to pH, while non-exchangeable acidic Al (pH 4.8 NH_4OAc-extractable Al minus KCl-exchangeable Al) was correlated best with organic matter, which implies the existence of an Al-OM complex in the soil. Reeve and Summer (1971) suggested a similar scheme for soil Al, and stated that the hydroxy-Al and organic matter complexed-Al are in equilibrium with exchangeable Al, depending on the cation exchange capacity and the amount of exchangeable bases present in the soil.

Methods of Soil Al Extraction

The Al content of displaced soil solutions was used in earlier studies to characterize the Al status of soils in relation to plant growth (Magistad, 1925; Pierre et al, 1932; Vlamis, 1953). During the past 15 years, a variety of salt solutions have been employed to extract the fraction of Al potentially detrimental to plant growth. Yuan and Fiskell (1959) used NH_4OAc, buffered to six different pH levels and showed that the lower the pH of the solution, the more Al was extracted. They compared normal neutral solutions of $BaCl_2$, $CaCl_2$, KCl, and NH_4Cl and concluded that divalent cations were more efficient than monovalent cations. McLean et al (1959) extracted comparable amounts of Al from acid clays and soils using NH_4OAc at pH 4.8, NaCl, and $BaCl_2$. On the basis of extractability and solubility of Al and the possible effects on the clay crystal stability, they suggested NH_4OAc at pH 4.8 to be superior as an extractant over unbuffered neutral salts. Lin and Coleman (1960) found that normal solutions of KCl, $CaCl_2$, and NaCl were equally capable of measuring exchangeable Al, provided that the extraction was sufficiently exhaustive. For limited leaching, KCl proved to be the most effective.

Pratt and Bair (1961) reported that 1N NH_4OAc at pH 4.8, extracted less Al from soils of lower pH and more Al from soils of higher pH than unbuffered $BaCl_2$ and KCl. They concluded that KCl extraction with a minimum time of contact of the first portion of the extractant with the soil gave a more reliable estimate of Al than NH_4OAc at pH 4.8. Chapman and Pratt (1961) proposed the use of 1<u>N</u> KCl for routine determinations of exchangeable Al in California soils. Immediate extraction after mixing followed by additional washings was suggested. McLean (1965) also proposed the use of unbuffered KCl for the extraction of Al adsorbed on the exchange sites of soils and clays. Rapid leaching with successive small aliquots was suggested so that only the exchangeable form of Al would be dissolved.

The use of 1<u>N</u> NH_4OAc at pH 4.8 is recommended to estimate extractable Al, which includes exchangeable Al plus $Al(OH)_3$, hydroxy Al monomers or polymers adsorbed by silicate layers and the Al complexed with organic matter (Pratt and Bair, 1961; Jackson, 1961). This fraction eventually reacts with the limestone added to soil (Shoemaker <u>et al</u>, 1961) and is a useful index of the aging status of recently formed $Al(OH)_3$ that resulted from liming (Pratt and Bair, 1961).

More emphasis has been placed on the exchangeable Al fraction in recent years as a criterion for liming acid soils. Kamprath (1970) reported that lime rates equivalent to the amount of exchangeable Al reduced Al saturation of the effective cation exchange capacity (CEC) to less than 30 per cent, a level that is safe for optimum crop growth. Effective CEC is defined as the Al, Ca and Mg determined in the 1N KCl extracts. Considering the soil and plant data of the limed soils, Kamprath suggested that lime applications based on the exchangeable Al extracted with a neutral unbuffered salt was a realistic approach for Ultisols and Oxisols. Working on Natal Oxisols, Reeve and Summer (1970) found liming to pH 6.5 unnecessary because crop response to liming ceased after applications of relatively small but sufficient amounts of lime to eliminate Al toxicity. They demonstrated that the amount of lime necessary for maximum growth and exchangeable Al control was approximately 1/6th the amount required to raise soil pH to 6.5.

Hoyt and Nyborg (1971) conducted a study on the extraction of Al from 40 acid soils that involved seven extraction methods and Al uptake by different plant species. Al extracted by various methods was correlated against Al concentrations in alfalfa tops in the unlimed soils, and against yield response to liming in barley, turnip, rape, and alfalfa. Aluminum extracted with 2N NaCl and 0.01M $CaCl_2$ correlated best with plant Al concentrations and yield. In continuation of this earlier work, Hoyt and Nyborg (1972) compared the amounts of Al and Mn extracted by different salt concentrations of $CaCl_2$ at different extraction time; and advocated the use of 0.02M $CaCl_2$ for simultaneous extraction of soil Al and Mn by shaking for one hour in a 1:2 soil-solution ratio. Hoyt and Nyborg

(1972) suggested that the diagnosis of the need for liming should be based on pH, Al, and Mn.

Most of the research on Al extraction procedures reported above has been carried out on temperate acid soils that possess different mineralogical and chemical characteristics than tropical soils in Hawaii. Although these tropical soils are very high in Al, little work has been conducted on the methodology of Al extraction in relation to plant uptake. Burgess (1923a, b) measured active Al levels of soils from various United States regions, including the territory of Hawaii and advocated the use of 0.5N acetic acid for soil Al extraction. Plucknett and Sherman (1963) used 1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8 to study the extractable Al levels of some Hawaiian soils and concluded that both soluble and exchangeable fractions of Al were extracted with this method. This procedure has also been used by various other workers (Fox et al, 1962; Rixon and Sherman, 1962; Rana, 1964; Reddy, 1964). The use of 1N $BaCl_2$ has been reported by Fox et al (1962) and Mahilum et al (1970) in their studies on soil Al. In recent years 1N KCl solution has been employed to study the so-called exchangeable Al in Hawaii soils (Teranishi, 1968; Rosenau, 1969; Roy, 1969).

Ayers et al (1965) conducted Al extraction studies, using water and solutions of NH_4OAc, pH 4.8 and KCl, on Humic, Hydrol Humic and Humic Ferruginous Latosols of Hawaii where gibbsite is known to occur in abundance. The data indicate that dissolution rather than exchange mechanisms account for much of the

Al that appeared in the extracts. Ammonium acetate-extractable Al increased markedly with degree of weathering, but degree of weathering had no effect on KCl- or water-extractable Al. Based on the laboratory research and field observations, the authors concluded that soil Al levels in Hawaiian soils were not sufficiently high to suppress sugarcane growth. No attempt was made to relate soil Al data to plant Al uptake in the study.

I. RESIDUAL EFFECTS OF SILICON, PHOSPHORUS, AND SOIL pH ON THE YIELD AND NUTRIENT UPTAKE OF DESMODIUM (*Desmodium aparines* L.) AND KIKUYU GRASS (*Pennisetum clandestinum* H.)

Materials and Methods

A field experiment was installed in 1966 by Teranishi (1968) on Halii soil at the Kauai Branch Station, to investigate the response to calcium silicate applications at various phosphorus and pH levels. The soil has been described in Section IV. A model profile of the Halii series is described below (Cline, 1955; USDA, 1972).

A_{11}--0 to 5 inches, dark greyish-brown gravelly silty clay; strong medium granular structure; friable when moist but slightly sticky when wet; pH 3.5 to 4.5; roots abundant; characterized by large amounts of ironstone that consists of a silty center coated with a crust of Fe.

A_{12}--5 to 12 inches, similar to A_{11} but brown or greyish brown, pH 4.0 to 5.0.

B --12 to 21 inches, red silty clay, weak fine blocky structure; friable, sticky, and plastic; pH 4.0 to 5.0; roots numerous, contains ironstones like those in the A horizon.

C_1 --21 to 42 inches, yellowish-red silty clay; similar to B horizon but containing soft weathered fragments.

C_2 --42 inches, red, yellow and grey soft weathered rock that retains the original rock structure; soil material encloses solid rock cores and grades to bedrock.

Sugarcane variety H53-263 was planted on November 20, 1966, and harvested on August 10, 1967, after nine months. A ratoon crop of sugarcane was harvested on June 17, 1968, by Rosenau

(1969). After sugarcane, a crop of corn was planted on August 14, 1968, and harvested by Thiagalingam (1971) on December 10, 1968. Details of fertilization and methods of crop management and harvesting have been described by Teranishi (1968), Rosenau (1969), and Thiagalingam (1971).

Plan of Experiment

Three replications of a 3 x 3 x 3 factorial experiment were laid out in a split-plot design. Whole plots were pH treatments (5.5, 6.0, 6.5) and subplots were Si (0, 830, and 1660 kg Si/ha) and P (110, 280, and 1120 kg P/ha) treatment combinations.

Supplementary plots were included to study the effects of increasing Si (0, 830, and 1660 kg Si/ha) at zero P and pH 6.0; and increasing P (110, 280, and 1120 kg P/ha) at 830 kg Si/ha and original field pH of 5.0. A control plot without Si, P, or pH treatments was also included in the experiment. These plots were not included in the statistical analysis of the split-plot design.

Cultural Practices

Whole plots were 18.3 x 27.4 meters and subplots were 6.1 x 9.1 meters as laid out in the initial experiment. After corn, the subplots were divided into two equal halves. One half was planted to *Desmodium aparines* L. (= *D. intortum M.*) hereafter referred to as desmodium, while the other half was planted to kikuyu grass (Pennisetum clandestinum H.). A blanket application of fertilizer was made to all plots (Table 1A) and additional amounts of P were added to the initial P treatments as shown in Table 1B. For the sake of continuity with the previous work, original P rates are referred to throughout this dissertation.

The field was tilled with a disc harrow to mix fertilizer material with the soil. Desmodium cuttings and kikuyu grass stolons were planted on January 30 and January 31, 1969, respectively. Seven rows of each species were planted approximately 0.68 meters apart. Seven consecutive cuttings were taken for both crops in a period of 29 months as shown by the harvest schedule in Table 2. After each harvest, N and K fertilizer was applied as shown in Table 2. Since there was adequate rainfall for plant growth, no irrigation was applied. Rainfall data for the entire experiment are given in Table 3.

Plant Sampling

A representative, well-mixed grab sample of about one kg of harvested material was taken from every plot of both species at each harvest for moisture determination and nutrient uptake studies. Index-tissue samples were collected before each harvest, for nutrient concentration studies. The index-tissue for kikuyu grass consisted of four newly developed leaves and sheaths including the spindle leaf.

Table 1

(A) Fertilizer materials and rates applied before planting kikuyu grass and desmodium

Element	Rate of application (kg/ha)	Source
N	50.0	urea (46% N), kikuyu grass plots only
K	75.0	KCl (50% K), all plots
Mg	7.2	$MgSO_4 \cdot 7H_2O$ (9.6% Mg), all plots
Zn	10.6	$ZnSO_4$ (36% Zn), all plots
B	0.8	borax (10.6% B), all plots
Cu	0.2	$CuSO_4$ (28% Cu), all plots
Mo	0.3	$NaMo_7O_{22}$ (39% Mo), all plots

(B) Fertilizer materials and rates of P and Si treatments

Element	Date of application Nov. 1966	 Aug. 1968	 Jan. 1969	Total	Source
	Rate of application (kg/ha)				
P	112	59	13	194	treble super phosphate (20% P)
	280	149	32	461	
	1120	596	130	1846	
Si	0	--	--		TVA slag (18.6% Si)
	833[a]	--	--		
	1666	--	--		

[a] These treatments will be referred to as 830 and 1660 throughout the manuscript

Table 2. Schedule of kikuyu grass and desmodium harvests and applications of additional N and K*

Harvest No.	Date of harvest	Additional date	Fertilizer applied (kg/ha) N**	K**
1	11/19/69	8/26/69	80	158
2	3/ 3/70	12/ 4/69	83	161
3	6/30/70	3/10/70	78	163
4	9/29/70	7/21/70	75	167
5	1/22/71	10/27/70	77	173
6	4/14/71	2/11/71	77	169
7	6/29/71	4/28/71	78	163

* Desmodium and kikuyu grass planted on January 30 and January 31, 1969, respectively. On August 26, 1969, the field was harvested once, and the yield of this cutting was not recorded because weeds dominated, and crop growth was very uneven.

** Applied as urea (N) and KCl (K). Nitrogen applied to kikuyu grass plots only.

Table 3. Rainfall distribution during the five-year period of the field experiment (cm)

Month	Year					
	1966	1967	1968	1969	1970	1971
Jan.		23.1	19.0	23.2	19.4	29.6
Feb.		28.0	9.1	19.1	2.5	15.9
March		34.9	26.9	11.3	4.9	28.1
April		15.1	28.1	15.3	22.4	37.1
May		23.9	5.3	18.3	17.0	9.8
June		10.7	7.4	6.8	9.3	9.7
July		14.6	12.5	25.2	14.8	7.5
August		16.0	12.6	11.4	12.8	
Sept.		13.7	14.5	14.8	11.7	
Oct.		15.2	26.5	12.0	13.4	
Nov.	10.0	27.9	40.5	26.2	24.5	
Dec.	11.3	40.9	54.8	22.6	25.6	
Year	21.3	264.0	257.2	206.2	178.3	137.7

Grand Total = 1064.7

Twenty such samples were taken from each kikuyu plot. For desmodium, 25 most recently matured leaves with petioles were collected from each plot. Whole-plant samples and index-tissues were dried at 70° C, weighed and ground in a Wiley mill for chemical analyses.

Soil Sampling

Soil samples were collected after the sugarcane plant and ratoon crops, corn, and harvests 2 and 7 of desmodium and kikuyu grass. Four subsamples of the surface soil (0-15 cm) were collected from each plot, composited and a subsample taken for chemical analysis. Soil samples were partially air-dried to allow them to pass through a 2-mm sieve and stored in polyethylene bags for determination of pH, Si, P, and Al and P sorption studies.

Plant Analysis

Whole-plant samples from harvests 1 through 6 were composited by treatment (three replicates together) in each harvest and analyzed for total Si, P, and Al. Analysis of harvest 7 was done on individual plots on all replicates for total Si, P, Al, Ca, Mg, K, Mn, and Zn in both species. Leaf tissue samples of both crops for harvest 7 were also analyzed for the above-mentioned elements. Methods of analysis are described in Appendix A.

Soil Analysis

Surface soil samples were analyzed for water-extractable Si, modified Truog-extractable P, and 1N $BaCl_2$-extractable Al. Details of extraction procedures and determinations are given in Appendix A.

Soil pH: The pH of surface samples was determined in a 1:2.5 soil-water suspension after 30 minutes of equilibration using a Beckman pH meter with glass electrode.

Phosphorus Sorption Studies: Residual effects of Si, P, and soil pH on phosphorus adsorbed by surface soil were measured in samples collected at the end of the experiment (after harvest 7) from kikuyu grass and desmodium plots. The method of Fox and Kamprath (1970) was followed, in which 3 g soil (oven-dry basis) was equilibrated for six days with 0.01M $CaCl_2$ solution containing several concentrations of P and 3 drops of toluene (added to inhibit microbial activity). Samples were shaken for ½ hour twice daily. After equilibration, samples were centrifuged, and P determined in the clear supernatant solution. Phosphorus sorption curves were constructed by plotting on semilog paper P concentration in the supernatant solution against P adsorbed by the soil. Values of P adsorbed at 0.2 ppm P in solution were recorded.

Statistical Analysis

Analyses of variance of experimental data were performed using the Factorial-Split Plot Analysis Program. Differences between treatment means were tested with Duncan's Modified (Bayesian) Least Significant Difference Test (DLSD), which was performed only if the F test of treatment effects was significant (Duncan, 1965). Multiple regression analyses were carried out with the BMD 02R, step-wise regression program (Dixon, 1968). All three programs were available at the University of Hawaii Computing Center.

Results and Discussion

The results will be discussed in the following order: (1) yield, (2) nutrients in the whole-plant, (3) nutrients in the index-tissue at the seventh harvest, (4) soil analysis, and (5) relationship of yield with soil and plant composition.

Yield

The combined dry matter yield of seven harvests increased significantly with increasing amounts of residual P in both plant species, but was not significantly affected by Si or pH treatments (Table 4). Yields of both crops tended to increase with P treatments at all levels of Si (Figure 1) and pH (Appendix Table 8 for kikuyu grass and 16 for desmodium). It should be noted that 7% of the total P applied was added before planting these two crops, while the remainder had been added to the preceding crops of sugarcane and corn (Table 1). A Si x P interaction is apparent, but not significant, in

Table 4. Analysis of variance of kikuyu grass and desmodium yields (total of 7 harvests)

Source of variation	d.f.	Kikuyu grass	Desmodium
		Mean squares	
Whole plots:			
Replications	2	9.09	6.18
pH	2	4.83	19.15
Error (a)	4	23.64	12.43
Subplots:			
Si	2	2.90	0.54
P	2	89.34	89.05**
Si x P	4	6.29	5.56
Si x pH	4	11.79	7.45
P x pH	4	18.70	6.00
Si x P x pH	8	8.02	10.18
Error (b)	48	11.20	5.16

** Significant at the 1% level

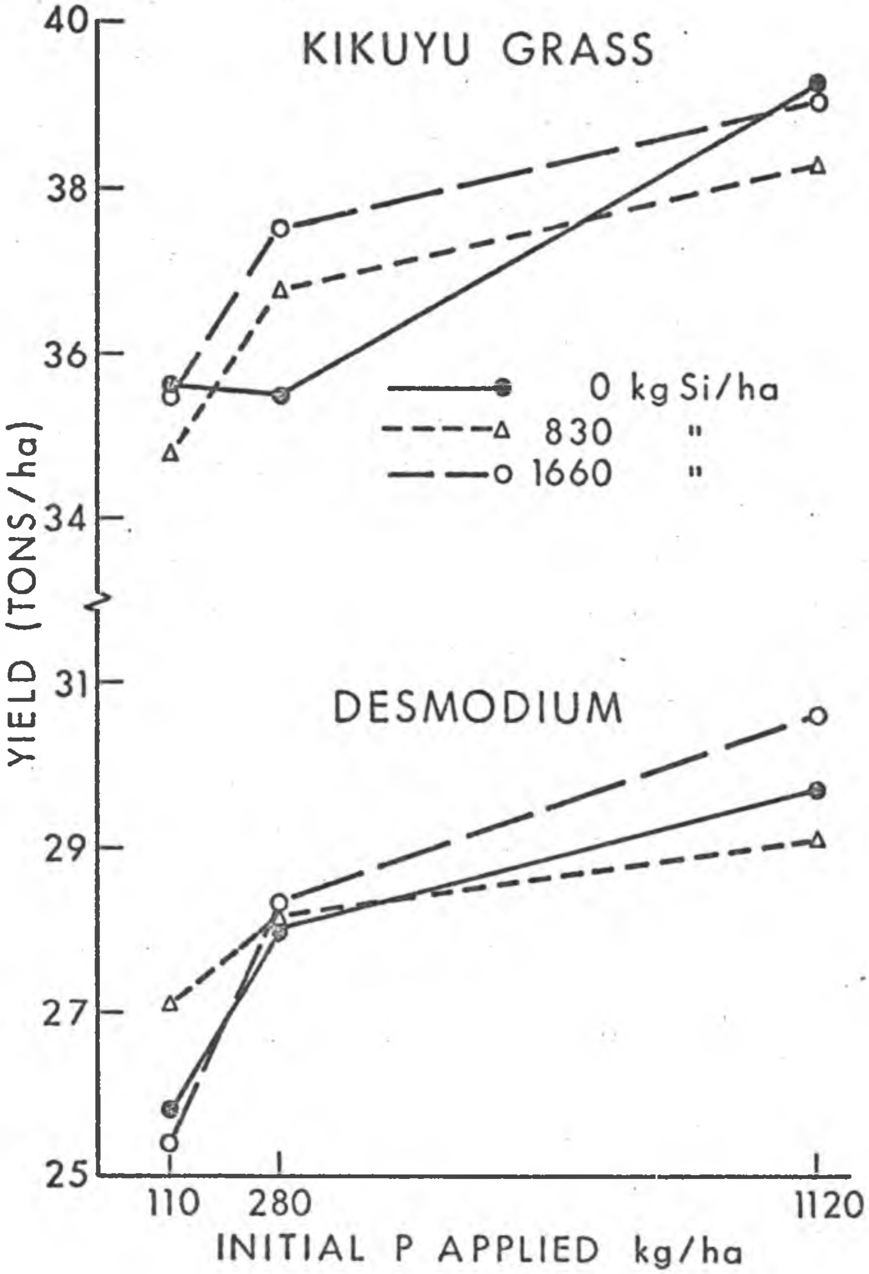


Figure 1. Yield response to residual P and Si by kikuyu grass and desmodium (total of 7 harvests)

desmodium (Figure 1), in which 1660 kg Si/ha produced higher yields than 0 and 830 kg Si/ha at 280 and 1120 kg P/ha levels. The effect in kikuyu grass was noticed at the 280 kg P/ha level only.

At pH 5.5, in both species, there is a trend for yields to increase with increasing residual Si levels (Figure 2). This may be explained on the basis of greater Si solubility at lower soil pH (the effect of soil pH on Si solubility will be discussed in more detail later). This effect was also noticed in the preceding crop of corn harvested at one month of age (Thiagalingam, 1971). At pH 6.5, yields with the 1660 kg Si treatment were lower than at zero Si, and this trend was obvious in both species.

Yield data for the individual harvests of kikuyu grass and desmodium are presented in Appendix Tables 1 to 7 and 9 to 16, respectively. A significant effect of residual P on dry matter yield was found in harvests 2, 5, 6, and 7 of desmodium, whereas only harvests 6 and 7 of kikuyu grass showed a significant response to P additions(Tables 6 and 5). No significant effect of residual Si or pH on yield was observed in any of the harvests. It should be pointed out that a significant Si x P interaction occurred in the first three cuttings of desmodium, but disappeared in the later harvests. In all harvests, except the first, yields of both plant species increased with increasing residual P, but the

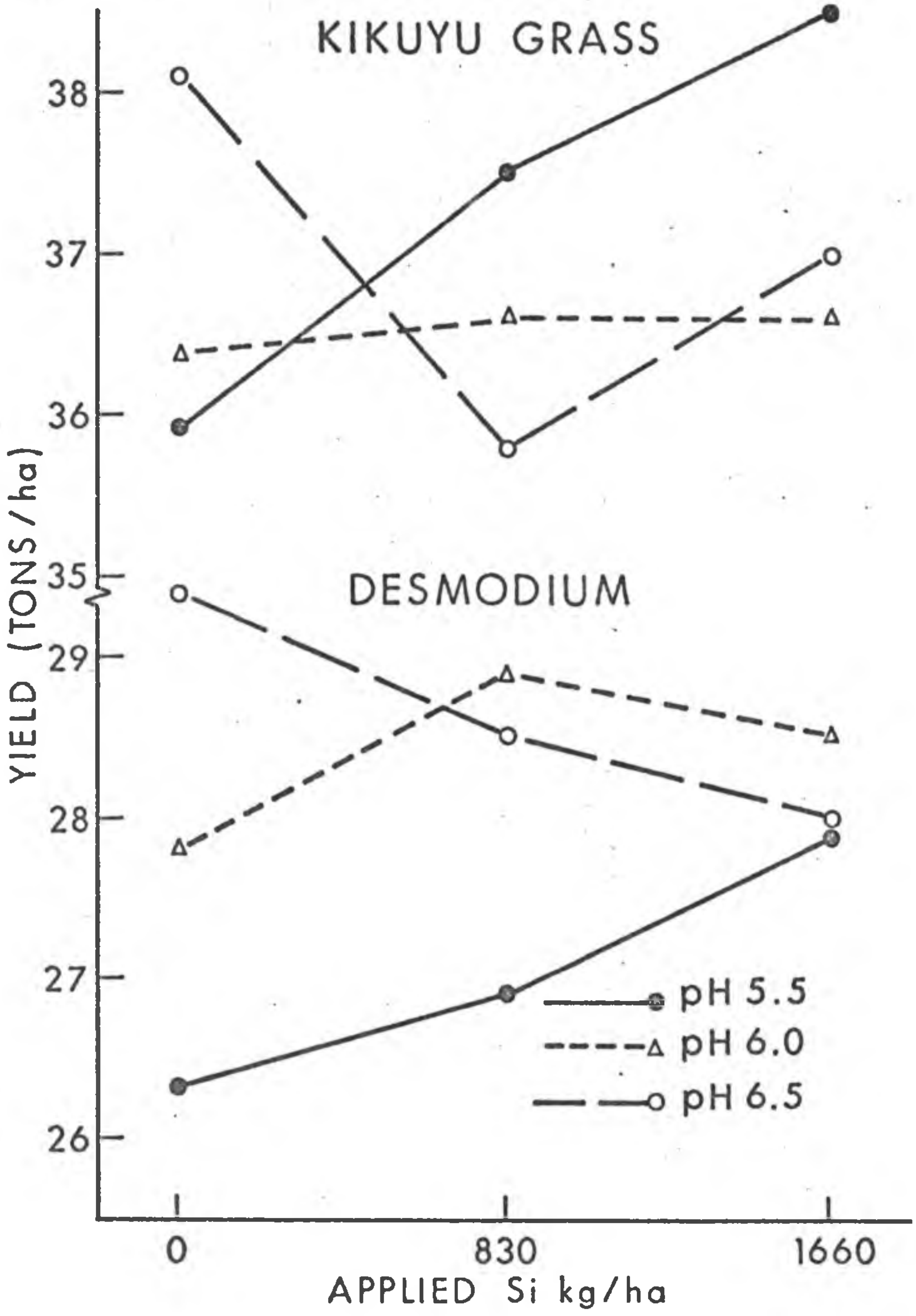


Figure 2. Yield response to residual Si and soil pH by kikuyu grass and desmodium (total of 7 harvests)

Table 5. Analysis of variance of kikuyu grass yields (individual harvests)

Source of variation	d.f.	Harvest No. 1	2	3	4	5	6	7
		Mean squares						
Whole plots:								
Replications	2	1821251	1955772	352785	1587820	147120	1414248	7286931
pH	2	1922144	271408	2959671	2514212	618554	642143	3080897
Error (a)	4	1878862	1293979	425795	1473223	1456515	829805	2263430
Subplots:								
Si	2	441850	299774	1310053	58036	922348	728183	363552
P	2	84840	585680	2143812	1209531	989354	3699502**	11284900**
Si x P	4	1073194	423522	1504367	276922	971663	360410	1114312
Si x pH	4	1146623	493967	1988986	37746	167214	223082	1073411
P x pH	4	1240124	225947	3401338	209360	179982	483645	491402
Si x P x pH	8	1184673	286577	812112	489026	80907	509009	831721
Error (b)	48	1082889	668481	1611745	597896	579452	511810	1271388

** Significant at the 1% level

Table 6. Analysis of variance of desmodium yields (individual harvests)

Source of variation	d.f.	Harvest No. 1	2	3	4	5	6	7
		Mean squares						
Whole plots:								
Replications	2	1214598	413705	7806559**	511134	1940428*	21422	32233
pH	2	1909180	743357	555578	855777	81820	1267849	399801
Error (a)	4	5178503	311234	433583	525478	262284	349254	1802080
Subplots:								
Si	2	110488	297106	2362679	221504	283703	140650	625589
P	2	1220771	3115405**	1001952	723968	1238774**	1167323**	10610783**
Si x P	4	2448298*	650918*	3607770*	275481	104473	43764	350533
Si x pH	4	844304	315764	876544	584336	400395	356791	114061
P x pH	4	554312	140976	3830354*	190426	103126	60609	138961
Si x P x pH	8	690257	479135	285652	254811	347657	442500	477704
Error (b)	48	806477	234882	1168644	261490	171582	215410	406478

* Significant at the 5% level

** Significant at the 1% level

magnitude of the response is greatest in the last two harvests (Figure 3). There was tremendous variation in yields of individual harvests, which was probably caused by seasonal variation in temperature and rainfall. These influences affect the availability and uptake of the essential nutrients and eventually affect growth. The average dry matter yield for the seven harvests ranged from 3.8 to 9.0 tons/ha in kikuyu grass and 2.3 to 7.3 tons/ha in desmodium. Maximum yields in both species were obtained in the third harvest.

Significant yield responses to P applications have been obtained in the preceding crops of sugarcane (plant crop) (Teranishi, 1968) and corn (Thiagalingam, 1971). In the sugarcane ratoon crop, however, there was no significant effect of P on yield, but slightly higher yields were obtained at 280 and 1120 kg P/ha treatments than at 110 kg P. In the present crops of kikuyu grass and desmodium harvested five years after the initial applications, yields were significantly higher at 1120 kg P than at 110 and 280 kg P. Figure 4(B) indicates that relative response to P applications was greater at 1120 kg P throughout the experiment and the decline with time was relatively small. This means that the efficiency of P applied 56 months ago in increasing crop yields in Halii soil was still high. The effect of increasing soil pH on plant growth was apparent in the sugarcane plant crop only (Teranishi, 1968). In the following crops of ratoon sugarcane and corn, no yield response to pH was

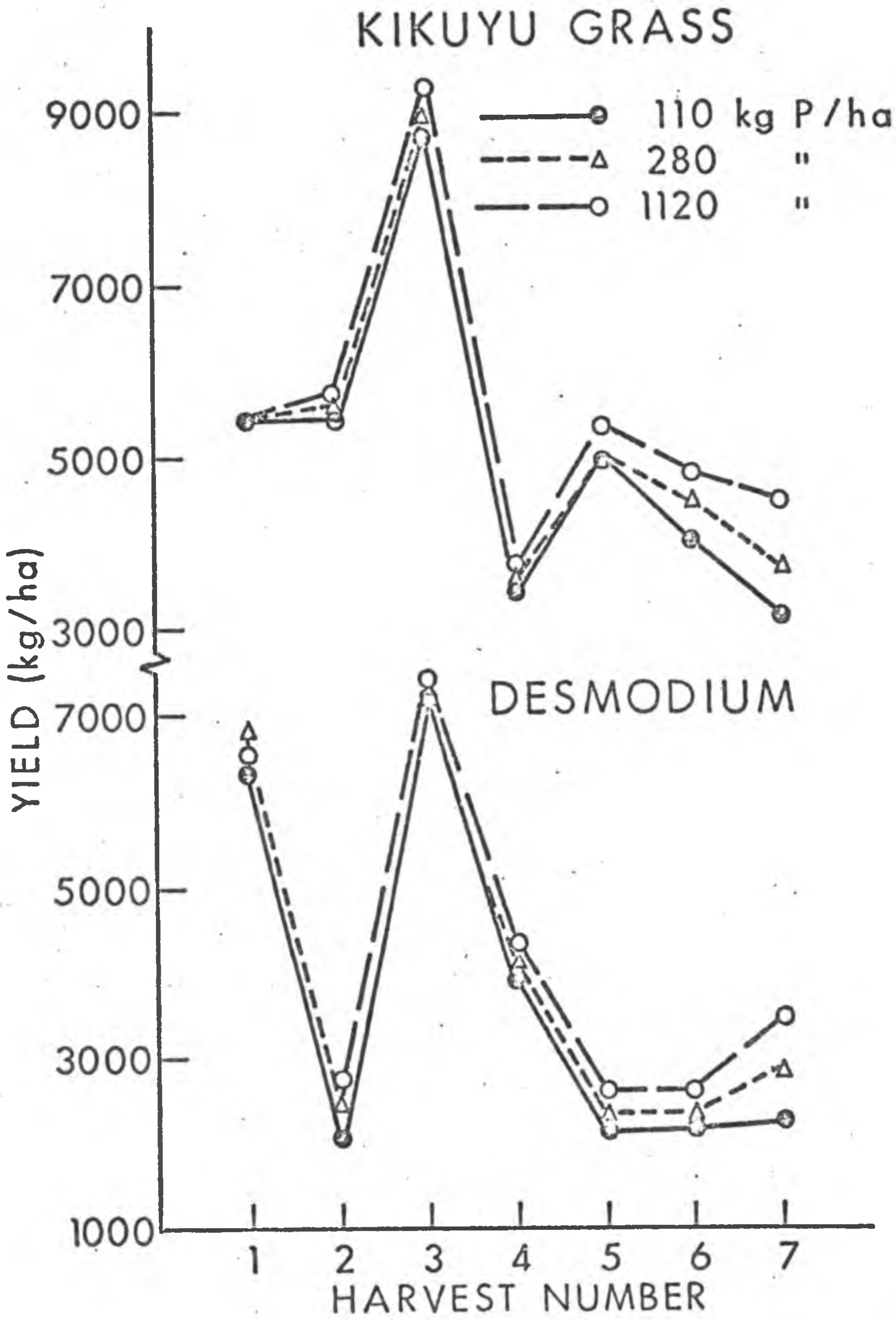


Figure 3. Yield response to residual P in 7 harvests of kikuyu grass and desmodium

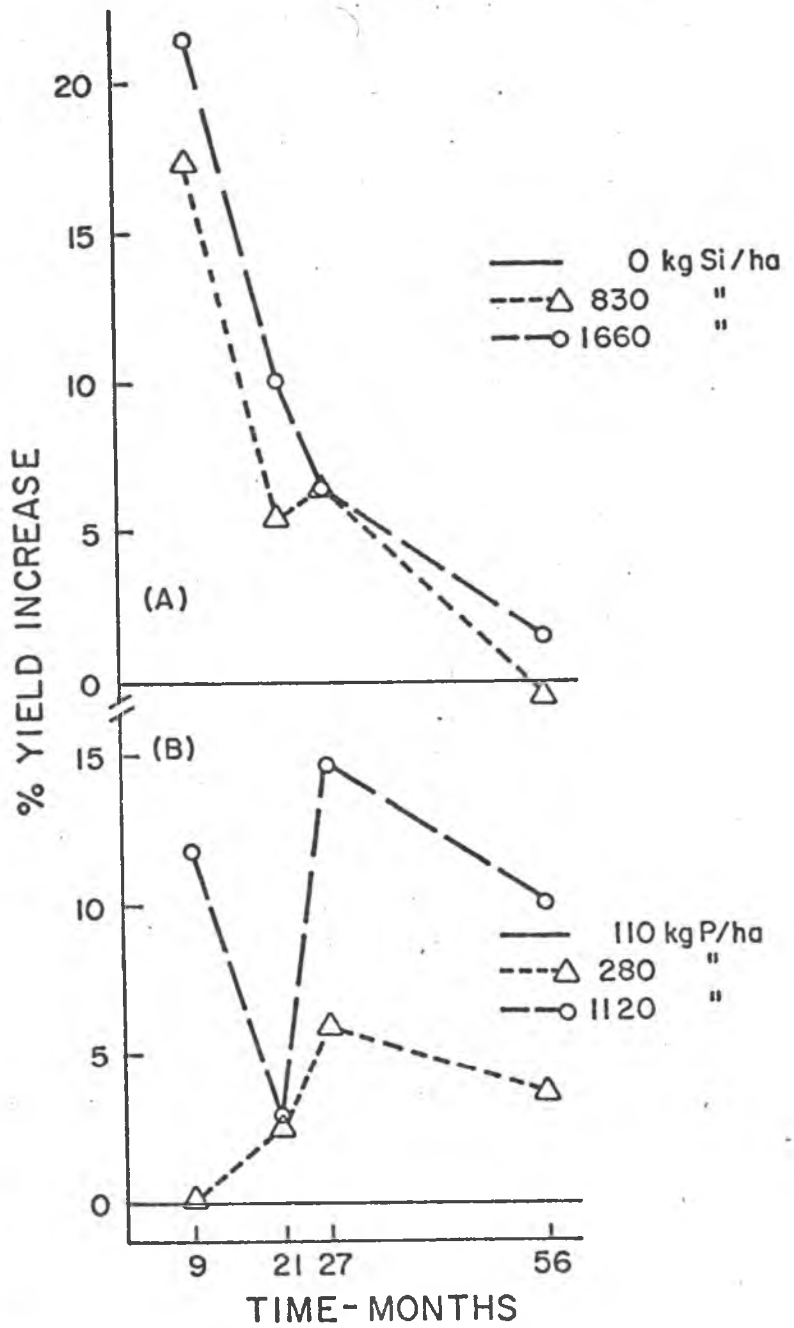


Figure 4. Relative yield increase (over the lowest treatment) with time to (A) applied Si and (B) applied P (9-month data points for sugarcane plant crop; 21-months for sugarcane ratoon crop; 27-months for corn; and 56-months for kikuyu grass, respectively)

observed (Rosenau, 1969; Thiagalingam, 1971). These results indicate that liming Halii soil to higher pH levels had no significant influence on yields during five years of cropping.

Yield responses to silicate applications in the Gibbsihumox soil has been reported in the literature (Ayers, 1966; Fox et al, 1967b). In the present experiment, Teranishi (1968) demonstrated a significant effect of Si applications on sugarcane grown for nine months after the initial treatment application. In the sugarcane ratoon crop, yields also increased with residual Si and the effect was significant at the 10% level (Rosenau, 1969). In the following crop of corn, harvested 27 months after the initial treatments, there was a significant increase in stover yields due to residual Si treatments (Thiagalingam, 1971). The decrease in effectiveness of silicates with time is illustrated in Figure 4(A), where relative yield increases with 830 and 1660 kg Si treatments over zero Si decreased sharply with time. At the end of 56 months, the yield with 1660 Si was only 2.5% higher than with zero Si, whereas yield of the 830 Si treatment dropped below that of zero Si. It should be pointed out that yield of the 1660 Si treatment was greater than yield of 0 or 830 Si treatments throughout the experiment. The lack of a yield response to residual Si levels suggests that levels of available Si in the soil may not be sufficiently high to influence, directly or indirectly, growth of the plant species under study. Possible factors responsible for this may be

(1) removal of large amounts of Si by the preceding crops of sugarcane and corn, thus depleting the available Si supply, (2) transformation of applied Si to less available forms in soil in the course of time, thus making it difficult for plants to absorb sufficient amounts of Si to enhance growth, and (3) leaching of applied Si to lower depths under heavy rainfall at the site resulting in reduced levels of Si easily available to plants. Another reason for the lack of response to Si may be the characteristics of the plant species. However, Thiagalingam (1971) conducted a pot study to measure the response to $CaSiO_3$ by various crop plants grown in Gibbsihumox soil collected from the site of this experiment and showed that kikuyu grass and desmodium responded significantly to additions of 2.2 tons $CaSiO_3$/ha. This shows that these two species have the capacity to respond to Si applications, at least in pots. The first three factors will be discussed later in appropriate sections.

Nutrients in the Whole-Plant

This section will cover total uptake of Si, P, and Al in all seven harvests of both forage species and also nutrient concentrations of whole-plant samples in the final harvest.

Plant Si: Silicon concentrations in whole-plant samples collected from each harvest increased with increasing residual Si levels in both kikuyu grass and desmodium (Figure 5, Appendix Tables 17 to 23). Whole-plant Si concentrations in

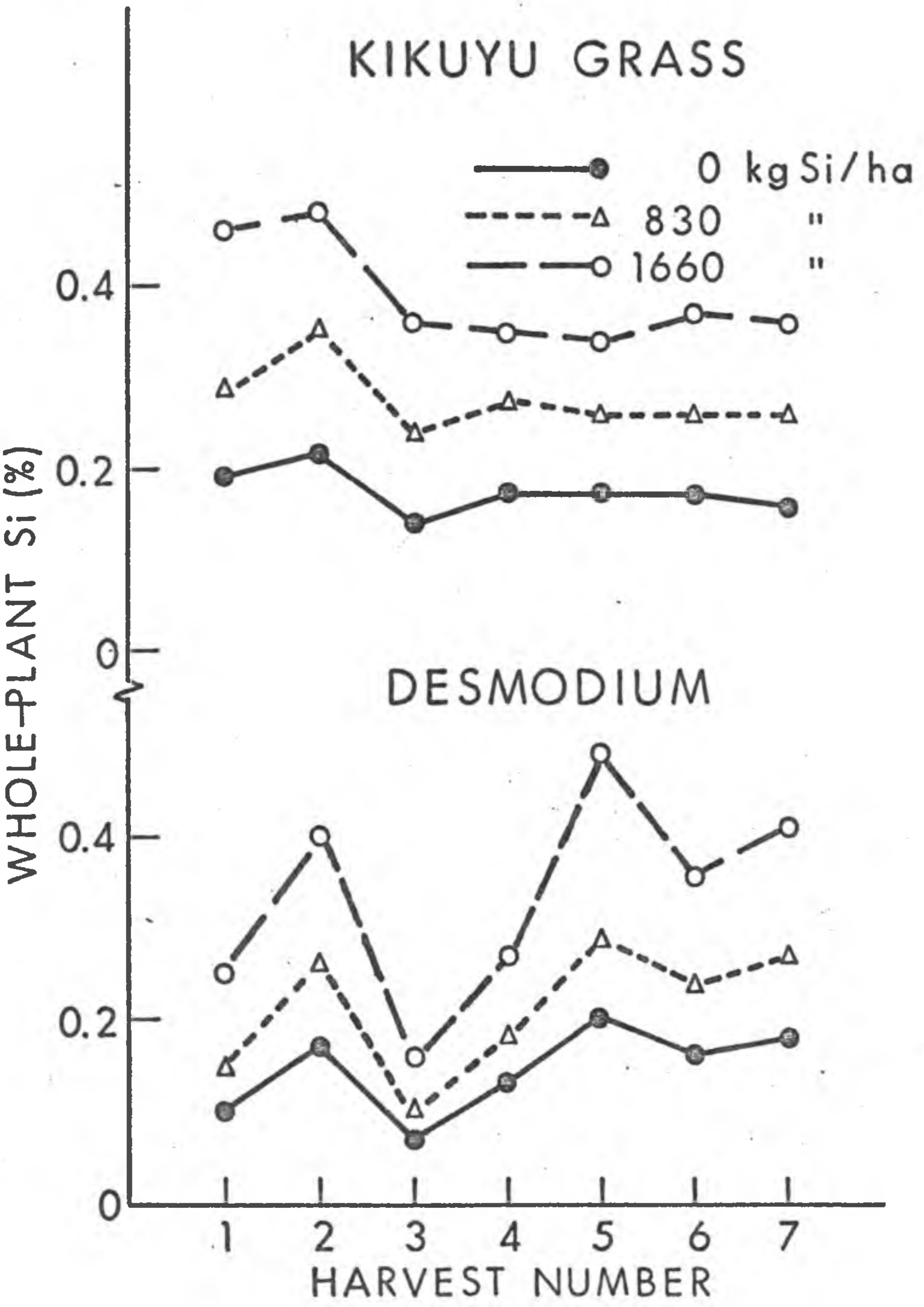


Figure 5. Influence of residual Si on whole-plant Si in seven harvests of kikuyu grass and desmodium

kikuyu grass ranged from 0.12 to 0.61% and in desmodium from 0.06 to 0.57% (two values were exceptionally high and are not included in the range). It may be pointed out that kikuyu grass tends to have slightly higher Si concentrations than desmodium in most harvests (Appendix Tables 17 to 23). The highest Si concentrations were found at pH 5.5. Silicon concentrations fluctuated greatly in the various harvests of desmodium (Figure 5). Fluctuations were less in the kikuyu grass. A close look at the yield data (Figure 3) indicates that dry matter production largely controls Si concentration in the plant. For example, dry matter yield in the third harvest was the highest of all harvests and plant Si levels were the lowest in both species at this harvest. When yield dropped in the fourth harvest, Si concentrations of both species increased.

The analysis of variance of Si concentration in whole-plant samples of kikuyu grass revealed a highly significant effect of residual Si, but the effects of residual P and soil pH on Si content were nonsignificant (Table 7). In desmodium, the effects of residual Si and P on whole-plant Si were highly significant (Table 8). Silicon concentrations decreased with P levels in desmodium (Fig. 6), which can be considered a dilution effect due to increased yield. In kikuyu grass, on the other hand, Si concentrations increased slightly with residual P levels (Figure 6). This indicates that P may have a stimulating effect on Si uptake in kikuyu grass and the site

Table 7. Summary of F-tests of analysis of variance of whole-plant Si, P, Al and K in kikuyu grass (Harvest 7)

Source of variation	d.f.	Si	P	Al	K
Whole plots:					
Replications	2		*		
pH	2				
Error (a)	4				
Subplots:					
Si	2	**			*
P	2		**		
Si x P	4		*		
Si x pH	4				
P x pH	4	*			
Si x P x pH	8				
Error (b)	48				

* Significant at the 5% level

** Significant at the 1% level

Table 8. Summary of F-tests of analysis of whole-plant Si, P, Al and K in desmodium (Harvest 7)

Source of variation	d.f.	Si	P	Al	K
Whole plots:					
Replications	2		*		
pH	2				
Error (a)	4				
Subplots:					
Si	2	**			
P	2	**	**		**
Si x P	4				
Si x pH	4		*		
P x pH	4				
Si x P x pH	8				
Error (b)	48				

* Significant at the 5% level

** Significant at the 1% level

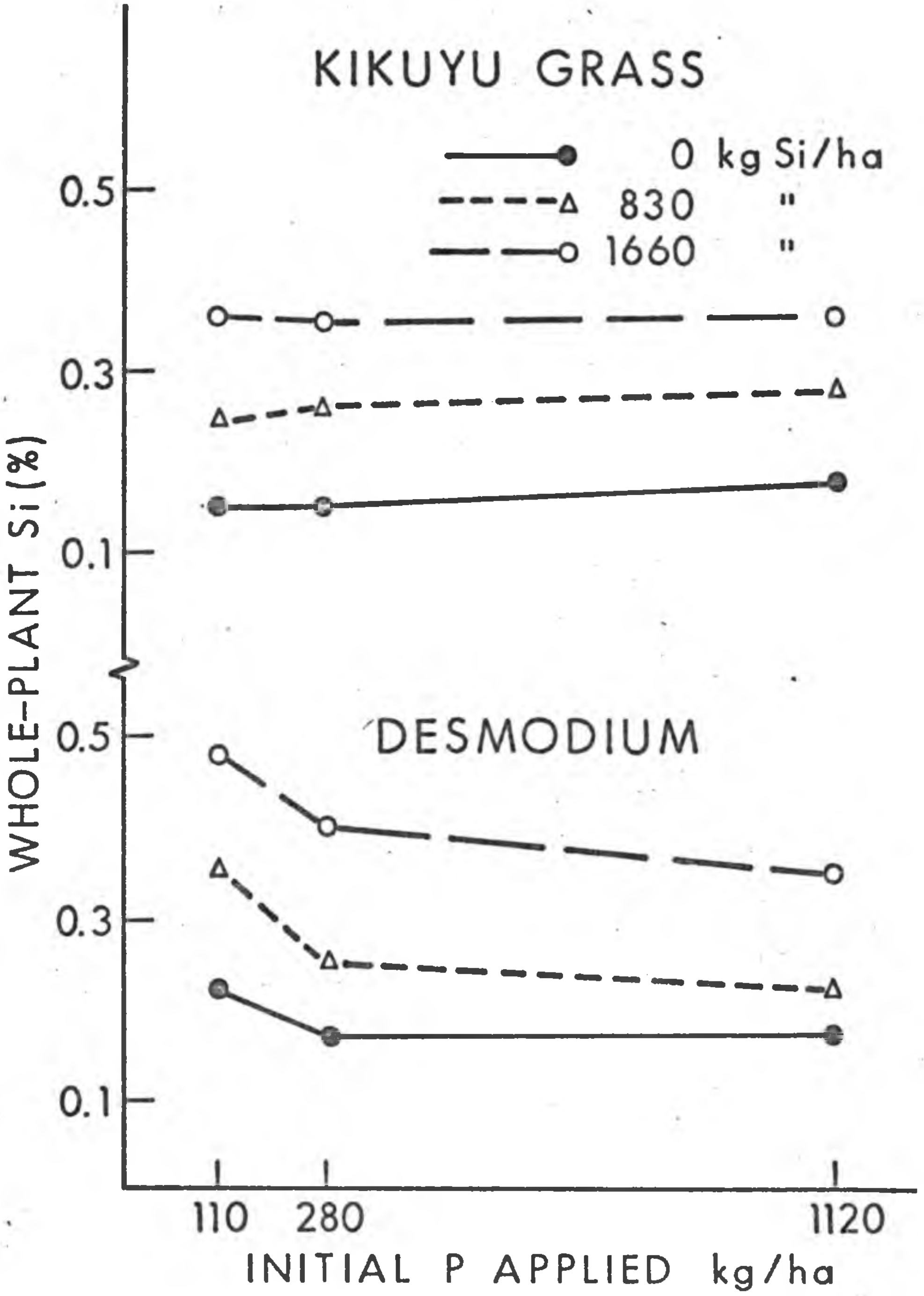


Figure 6. Influence of residual P and Si on whole-plant Si in kikuyu grass and desmodium (Harvest 7)

of reaction may be the roots. Absorption of Si by plants is controlled not only by soil Si levels, but by characteristics of plant species as well.

Silicon concentration in kikuyu grass was unaffected by pH, but in desmodium Si concentration decreased with increasing soil pH (Figure 7). This phenomenon was earlier observed in sheath and whole-plant Si concentrations in the sugarcane plant (Teranishi, 1968) and ratoon crops (Rosenau, 1969), where plant Si concentrations decreased significantly with increasing soil pH. Similar results were obtained in corn where leaf Si at silking and Si in the cob, as well as in the stover, decreased with increased soil pH (Thiagalingam, 1971). The decrease in plant Si concentration with pH in this study is probably the combined effect of soil Si solubility and dilution of plant Si by carbohydrate. Less Si is available for plant uptake at higher pH, while yield increased with pH (Figure 2, Appendix Table 15) resulting in lower Si concentrations at pH 6.0 and 6.5 than at 5.5. A significant P x pH interaction also occurred in kikuyu grass (Table 7).

Silicon uptake expressed as kg/ha, increased with residual Si levels in both kikuyu grass and desmodium (Appendix Tables 24 to 30). Generally more Si was taken up at the 1120 kg P level than at the 110 kg P level, and the differential was more pronounced in kikuyu grass than desmodium. Analysis of variance of Si uptake data for harvest 7 (56 months) showed

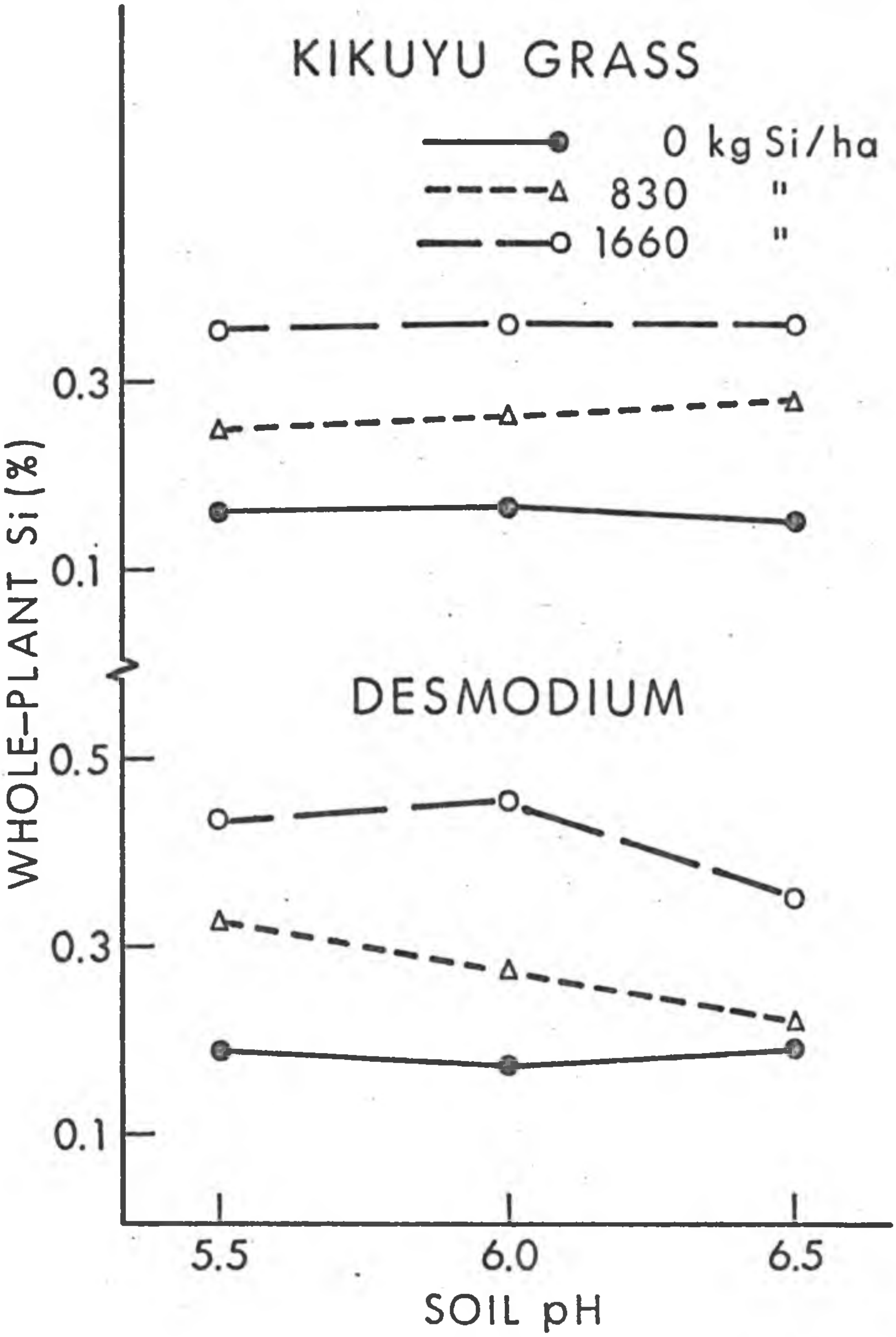


Figure 7. Influence of soil pH and residual Si on whole-plant Si in kikuyu grass and desmodium (Harvest 7)

highly significant effects of residual Si and P in kikuyu grass (Table 9), and of residual Si in desmodium (Table 10). When all harvests were combined, total Si uptake followed essentially the same pattern as Si concentrations in the individual harvests (for total Si uptake, see Appendix Table 31). Uptake of Si decreased slightly at higher pH values when Si was applied (Figure 8). In kikuyu grass, more Si was taken up at 1120 kg P/ha than at 110 (Figure 9), but this effect occurred only at the zero Si level in desmodium. Comparison of uptake figures of both crops demonstrates that kikuyu grass extracted about twice as much Si as desmodium. This difference can be accounted for largely by the difference in dry matter production, since kikuyu grass yields were about 37% greater than those of desmodium, as well as by the fact that kikuyu grass had slightly higher Si concentrations even with higher dry matter.

From the above results, it may be concluded that the effects of silicon applications were still apparent after five years of continous cropping. Although yield response of kikuyu grass and desmodium to residual silicon diminished after the corn harvest, they continued to extract significant amounts of Si added five years ago. This is evident in the analysis of variance of whole-plant Si concentration at the final harvest (56 months) (Tables 7 and 8). It is likely that Si levels in soil are not high enough to allow plants to extract sufficient quantities of Si to stimulate plant

Table 9. Summary of F-tests of analysis of variance of Si, P and Al uptake by kikuyu grass (Harvest 7)

Source of variation	d.f.	Si	P	Al
Whole plots:				
Replications	2			
pH	2			
Error (a)	4			
Subplots:				
Si	2	**		
P	2	**	**	
Si x P	4			
Si x pH	4			
P x pH	4			
Si x P x pH	8			
Error (b)	48			

** Significant at the 1% level

Table 10. Summary of F-tests of analysis of variance of Si, P and Al uptake by desmodium (Harvest 7)

Source of variation	d.f.	Si	P	Al
Whole plots:				
Replications	2			
pH	2			
Error (a)	4			
Subplots:				
Si	2	**		
P	2		**	
Si x P	4			
Si x pH	4			
P x pH	4			
Si x P x pH	8			
Error (b)	48			

** Significant at the 1% level

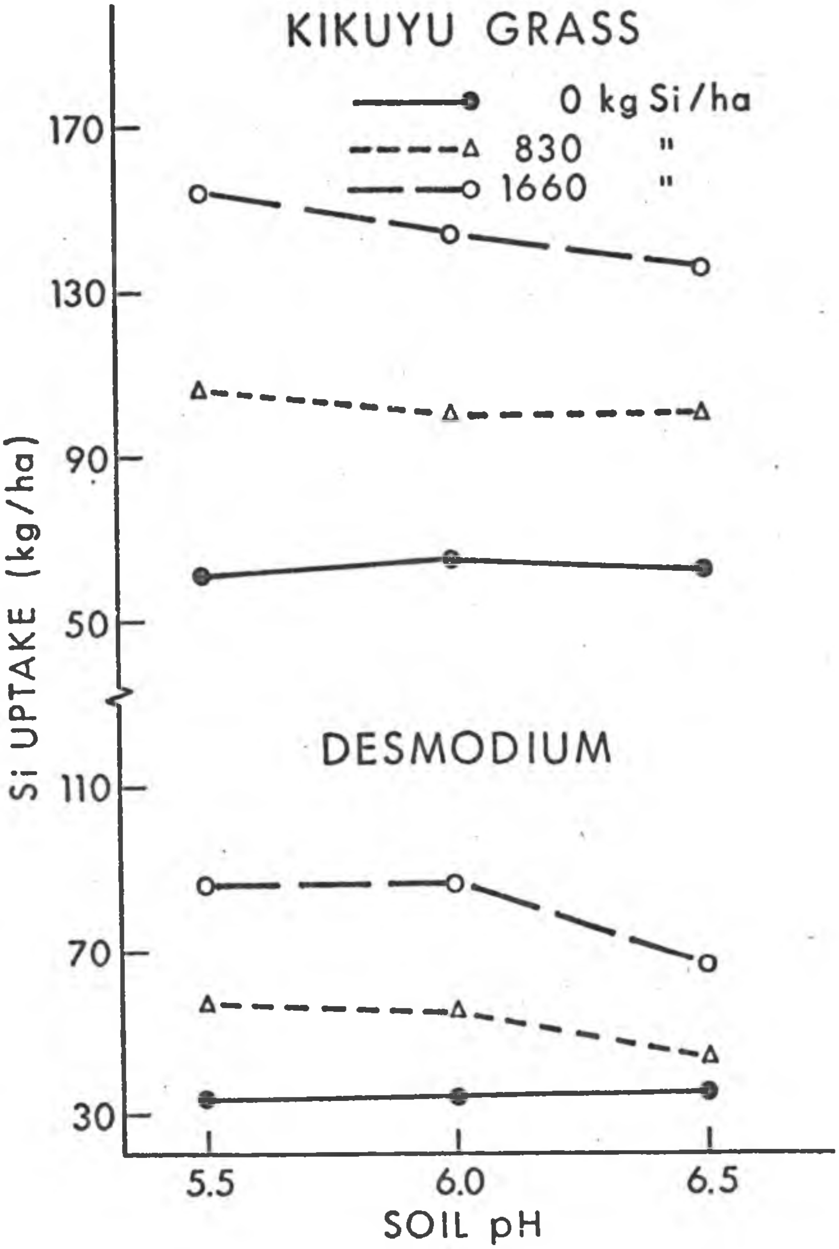


Figure 8. Influence of soil pH and residual Si on combined Si uptake of 7 harvests by kikuyu grass and desmodium

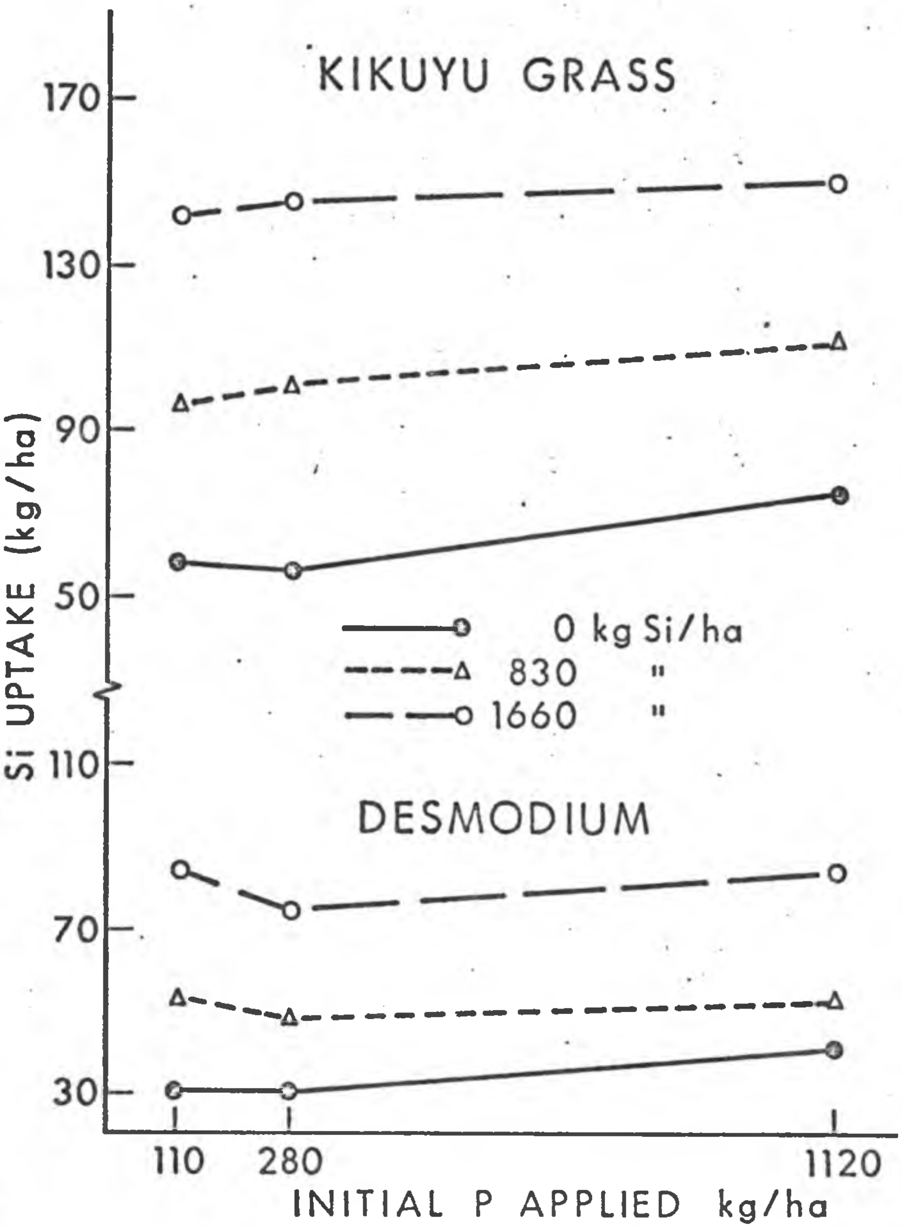


Figure 9. Influence of residual P and Si on combined Si uptake of 7 harvests by kikuyu grass and desmodium

growth directly or indirectly. This means that supplemental amounts of silicates may have to be added to soil to raise Si to levels which would enhance growth and thus produce higher yields. However, there is also a possibility that these two forage species do not respond to Si applications in the field.

Plant P: Whole-plant P concentrations of both species increased with residual P in all harvests (Figure 10), while residual Si and soil pH had no effect on P concentrations in any of the harvests (Appendix Tables 32 to 38). It should be noted that P levels were lowest in the third harvest for both crops. Yields in this harvest (Figure 3) were exceptionally high due to favorable climatic conditions. Phosphorus concentrations ranged from 0.09% to 0.32% in kikuyu grass and 0.14% to 0.39% in desmodium. In general, desmodium had higher P levels than kikuyu grass.

The amounts of P taken up by both species in the final harvest were significantly affected by residual P (Tables 9 and 10). The amounts of P taken up were significantly higher in the 280 and 1120 kg P/ha treatments than in the 110 kg P treatment (means for 3 P levels were 4.34, 5.69, and 8.64 kg P/ha for kikuyu grass and 4.21, 6.55, and 9.97 kg P/ha for desmodium, respectively. For data, see Appendix Table 39).

Total P taken up in all harvests combined increased markedly with residual P in both crops (Appendix Table 40).

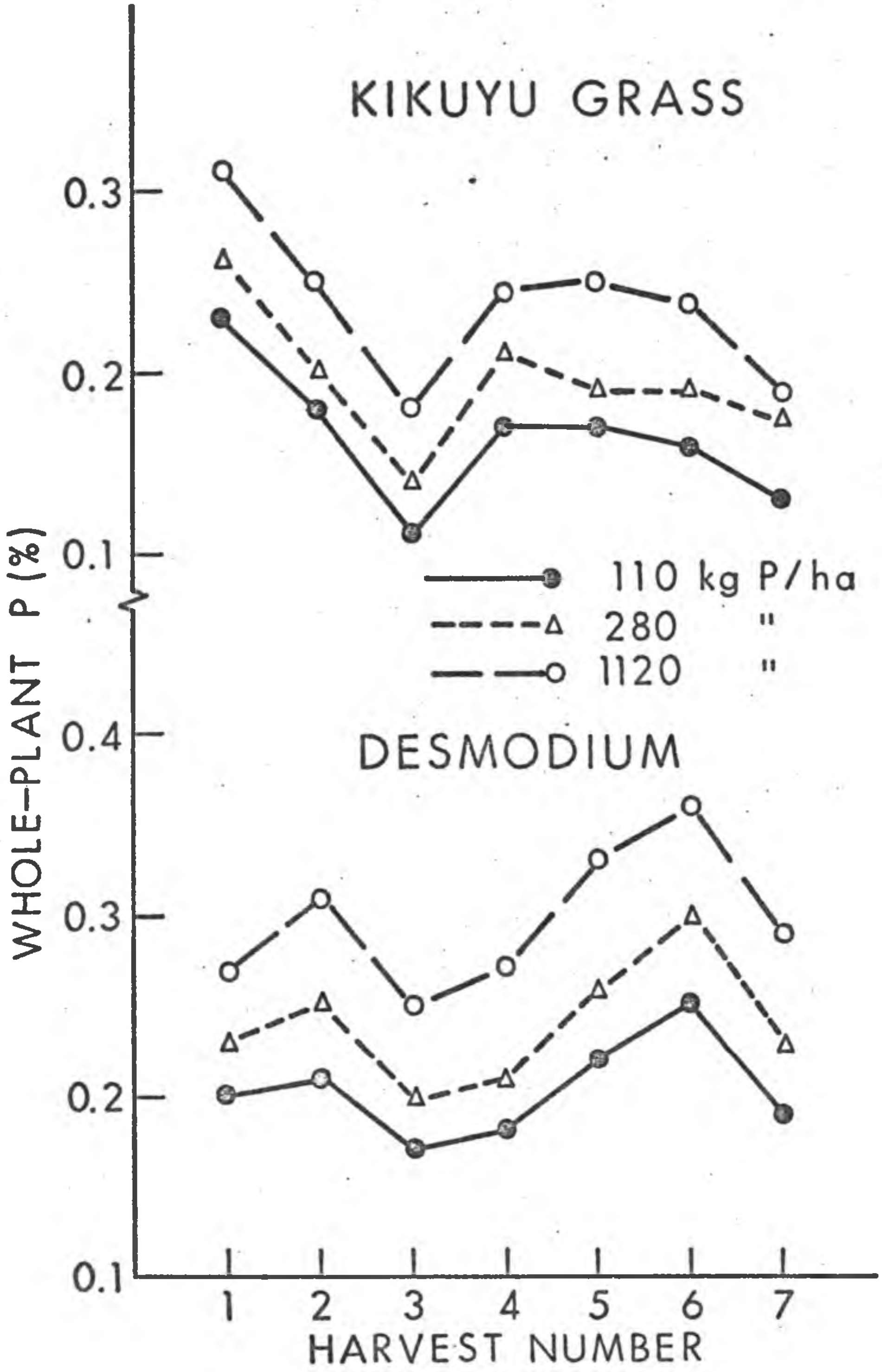


Figure 10. Influence of residual P on whole-plant P in seven harvests of kikuyu grass and desmodium

The relationship of P uptake with residual Si and P is illustrated in Figure 11, where slightly more P was taken up from the 1660 kg Si/ha treatment than from the zero Si treatment at all P levels in desmodium. This trend was also observed in kikuyu grass at the 280 kg P/ha level.

Plant Al: Whole-plant Al concentrations varied greatly within each harvest as well as among various harvests (Figure 12, Appendix Tables 41-47). Although no consistent influence of residual Si, P, or pH on plant Al was found, Al values in kikuyu grass were generally higher at pH 6.0 than at pH 5.5 or 6.5 (Figure 12). In desmodium, Al concentrations of harvests 4, 5, 6, and 7 were higher at pH 6.0 and 6.5 than at pH 5.5 (Figure 12). Aluminum levels in the whole-plant ranged from 420 to 3600 ppm in kikuyu grass and from 420 to 4770 ppm in desmodium. Analysis of variance of the final harvest data showed no significant effects of residual Si, P, and pH on Al concentrations (Tables 7 and 8) or Al uptake (Tables 9 and 10 and Appendix Table 48). Combined uptake of Al for all harvests increased slightly with increasing pH and P and decreased slightly with Si in desmodium (Appendix Table 49). In kikuyu grass, Al uptake increased from pH 5.5 to 6.0 and dropped at pH 6.5 (Appendix Table 49).

Plant K: Residual Si treatments had a significant effect on plant K concentrations in kikuyu grass (Table 7). Potassium contents were significantly higher at 830 kg Si/ha than at zero

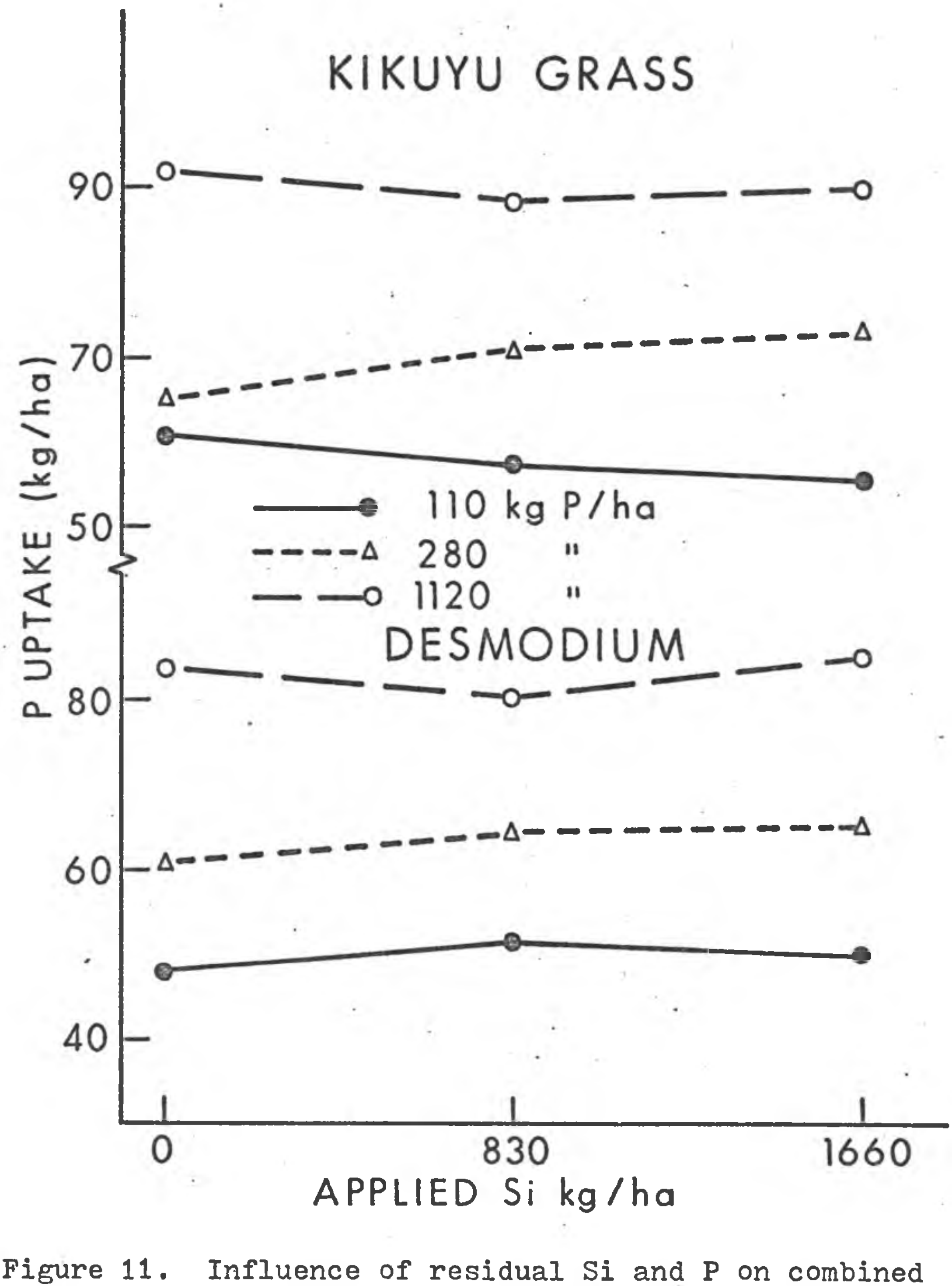


Figure 11. Influence of residual Si and P on combined P uptake of 7 harvests by kikuyu grass and desmodium

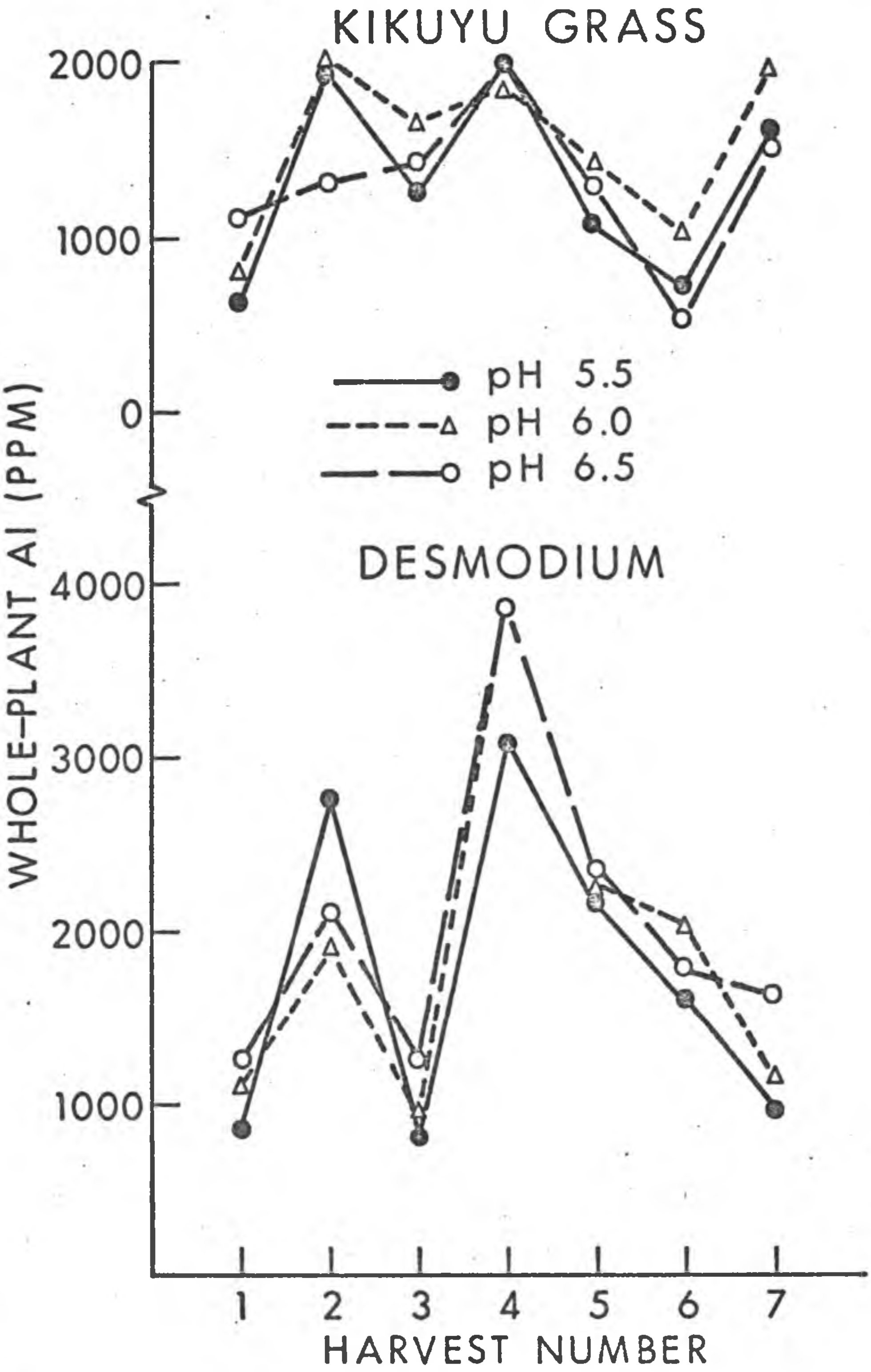


Figure 12. Influence of soil pH on whole-plant Al in 7 harvests of kikuyu grass and desmodium

or 1660 kg Si/ha (compare 2.59% vs. 2.49 and 2.48%); this is illustrated in Figure 13. Residual P and pH had no significant effect on plant K in this species. In desmodium, residual P treatments increased whole-plant K levels significantly (Table 8, Figure 13), and K values at 280 and 1120 kg P/ha were significantly higher than that at 110 kg P/ha (2.97 and 3.07% vs. 2.73%; for data see Appendix Table 50). Residual Si and pH had no effect on plant K. Potassium concentrations ranged from 2.40 to 2.68% in kikuyu grass and 2.50 to 3.20% in desmodium with K values in kikuyu grass generally lower than those in desmodium. Adequacy levels of K for these species will be discussed in the section on index-tissue potassium.

Plant Ca: Plant Ca increased significantly in both crops as pH increased in the final harvest (Figure 14, see Tables 11 and 12 for AOV). A significant P x pH interaction in kikuyu grass and a significant P effect in desmodium were also observed. Plant Ca levels in desmodium at 280 kg P/ha level were significantly greater than those at 1120 kg P (compare 0.94 vs. 0.88% Ca; for data see Appendix Table 51). In kikuyu grass a nonsignificant, but consistently increasing trend was observed with residual P (0.33, 0.34 and 0.35% Ca at 110, 280 and 1120 kg P levels, respectively). Silicon treatments as distinct from pH had no effect on plant Ca in either crop. Plant Ca concentrations ranged from 0.26 to 0.39% in kikuyu grass and from 0.72% to 1.1% in desmodium.

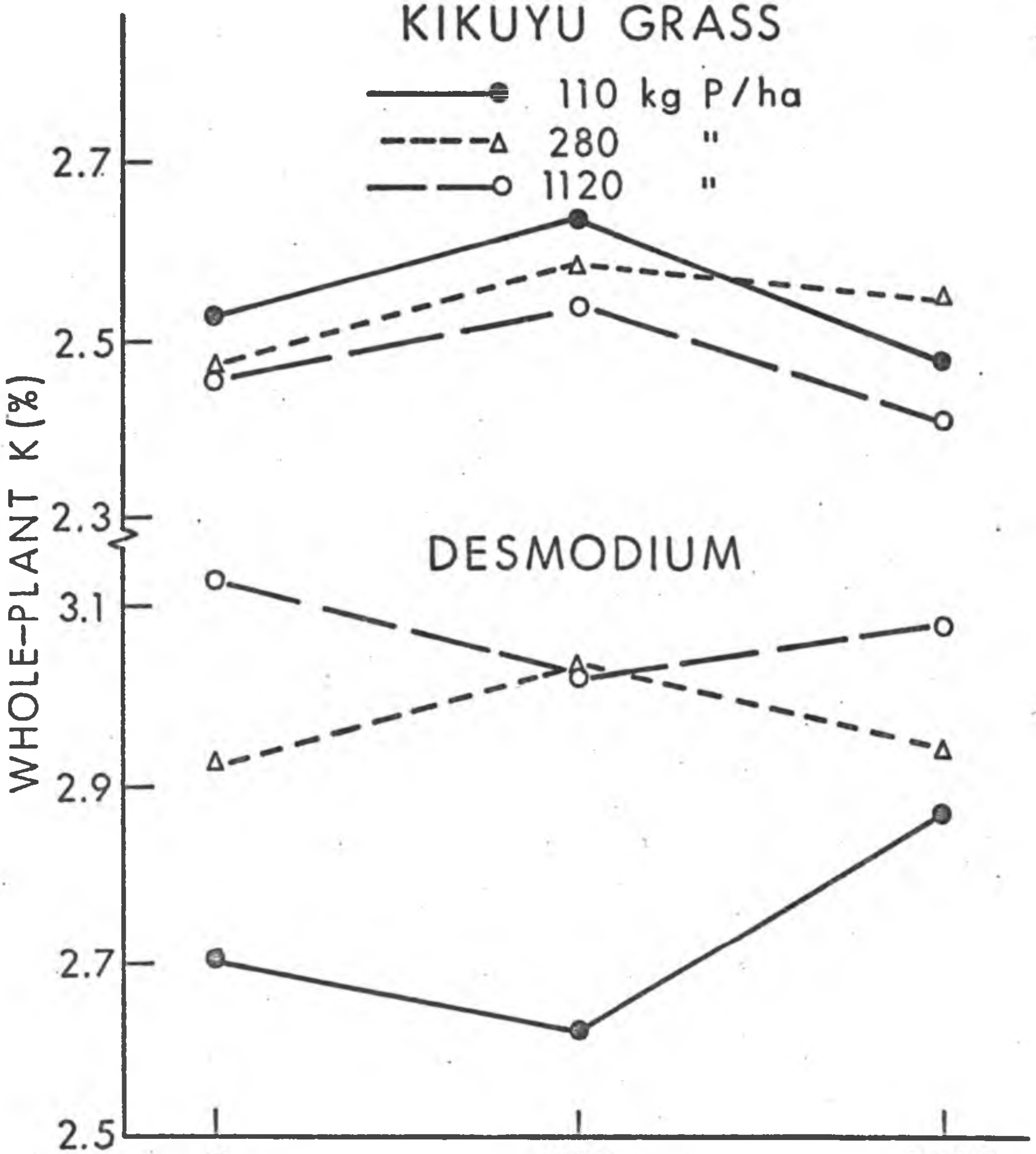


Figure 13. Influence of residual Si and P on whole-plant K in kikuyu grass and desmodium (Harvest 7)

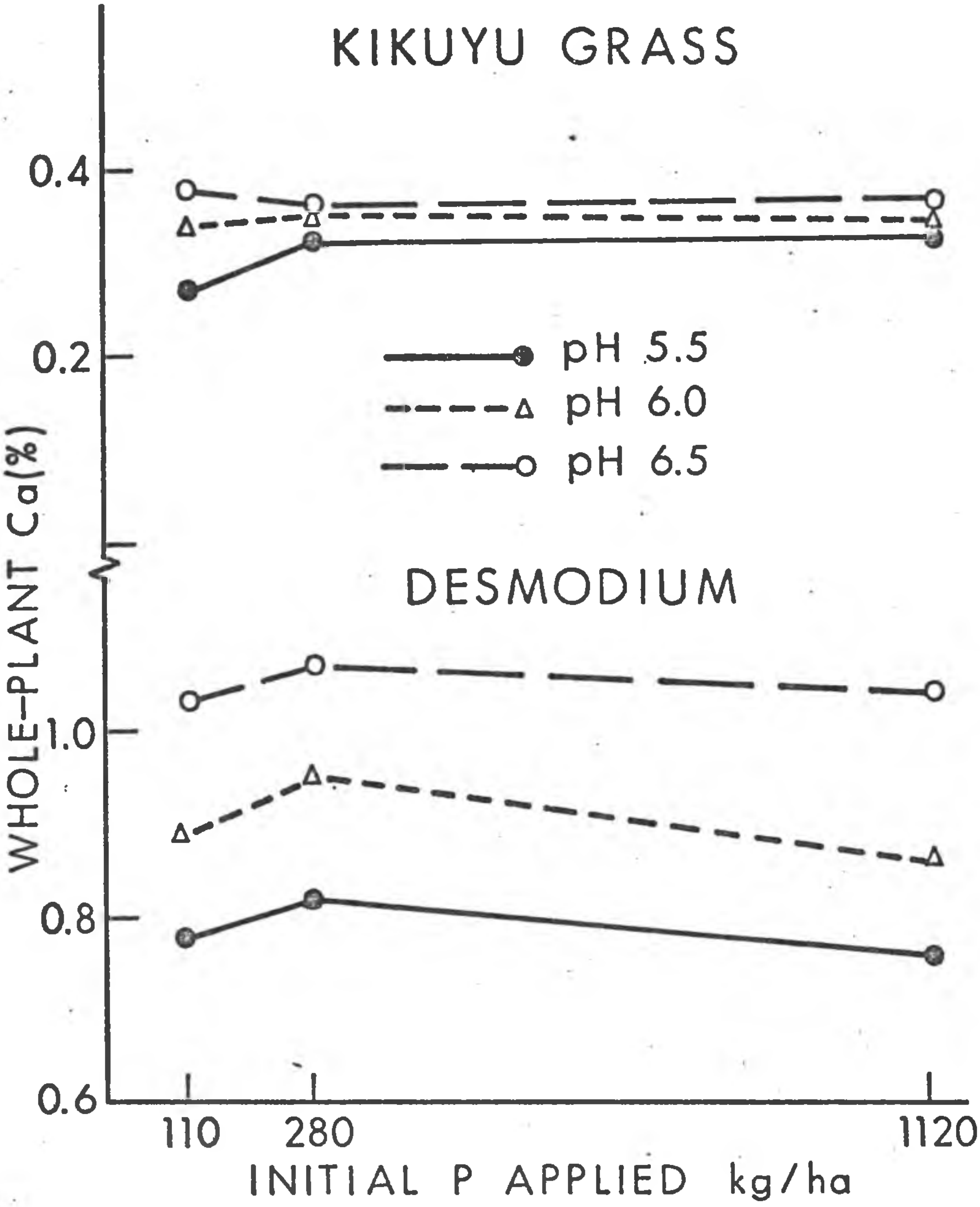


Figure 14. Influence of residual P and soil pH on whole-plant Ca in kikuyu grass and desmodium (Harvest 7)

Table 11. Summary of F-tests of analysis of variance of whole-plant Ca, Mg, Mn and Zn in kikuyu grass (Harvest 7)

Source of variation	d.f.	Ca	Mg	Mn	Zn
Whole plots:					
Replications	2	**			
pH	2	**	**	**	
Error (a)	4				
Subplots:					
Si	2		*		
P	2		*		
Si x P	4				
Si x pH	4				*
P x pH	4	**			
Si x P x pH	8				
Error (b)	48				

* Significant at the 5% level

** Significant at the 1% level

Table 12. Summary of F-tests of analysis of variance of whole-plant Ca, Mg, Mn and Zn in desmodium (Harvest 7)

Source of variation	d.f.	Ca	Mg	Mn	Zn
Whole plots:					
Replications	2				
pH	2	**		**	**
Error (a)	4				
Subplots:					
Si	2				
P	2	**	**	**	
Si x P	4				
Si x pH	4				
P x pH	4				
Si x P x pH	8		**		
Error (b)	48				

** Significant at the 1% level

An examination of the above results indicates that only Ca applied initially to adjust soil pH still had a significant effect on plant Ca five years after the initial applications were made. At the start of the experiment, soil pH was raised to various levels by addition of $CaCO_3$ and/or $CaSiO_3$ which increased exchangeable Ca on the soil complex. Also, treble superphosphate added to obtain the three P levels at each pH added additional Ca to the soil. However, the amount of Ca added with initial pH adjustments was 3.2 times greater than that added with P treatments, and 3.8 times greater than that added with Si treatments. Teranishi (1968) found no significant effects of Si, P or pH on sheath Ca of the nine-month cane crop grown after the initial treatments. Since an attempt had been made to supply adequate amounts of soil Ca in all treatments initially, uptake of Ca by sugarcane was not affected by Ca differentials in any treatments. During the course of five years of continued cropping substantial amounts of Ca were taken up by successive crops and also may have leached into the profile, reducing effects of Ca differentials in the silicate and phosphate treatments.

Soil pH also controls soil Al solubility which in turn influences Ca availability. A highly significant correlation was found between soil Al determined after the final harvest and whole-plant Ca of the final harvest ($r = -0.65$ for kikuyu grass and -0.80 for desmodium). Antagonistic effects of Al on Ca absorption and transport have also been reported in the literature (Schmehl et al, 1952; Ragland and Coleman, 1959; Gangwar, 1967).

Plant Mg: Residual P had a significant effect on plant Mg in both kikuyu grass and desmodium (Tables 11 and 12, Appendix Table 52) and Duncan's Least Significant Difference test showed that Mg levels at 110 kg P were significantly lower than those at 280 and 1120 kg P (0.119% vs. 0.115 and 0.111% in kikuyu grass and 0.145% vs. 0.131 and 0.124% in desmodium). A yield-induced dilution effect on Mg concentrations may be responsible for lower Mg levels with increasing residual P. Soil pH and residual Si had no influence on Mg levels in desmodium while in kikuyu grass residual Si and soil pH treatments increased plant Mg significantly. Higher Mg concentrations at pH 6.5 than at pH 5.5 and 6.0 (0.128% vs. 0.105 and 0.112%) may be due to greater adsorption of Mg on the exchange complex at higher pH as reported by Rosenau (1969).

Plant Mn: Highly significant reductions in plant Mn with increasing soil pH occurred in the final harvest of kikuyu grass and desmodium (Figure 15, Tables 11 and 12, Appendix Table 53). Residual P decreased Mn values in desmodium as shown in Figure 15 where Mn values at 110 kg P are significantly higher than those at 280 and 1120 kg P. Soil pH plays an important role in the absorption of Mn by plants through its effects of soil Mn solubility. McGeorge (1925) and Reid (1965) reported decreasing concentrations of soil Mn with increasing pH. Although soil samples were not

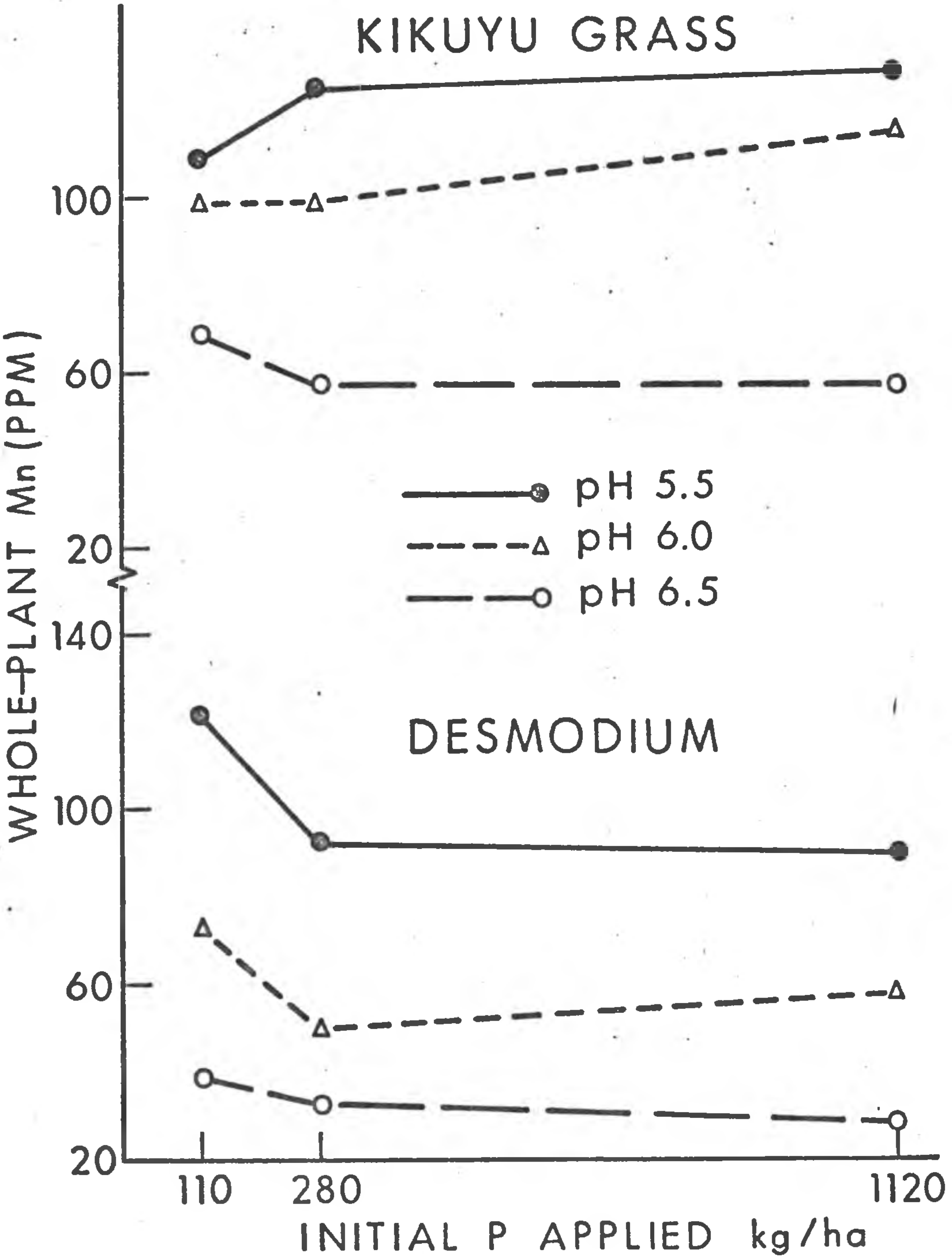


Figure 15. Influence of residual P and soil pH on whole-plant Mn in kikuyu grass and desmodium (Harvest 7)

analyzed for Mn after the final harvest, it is quite likely that plant Mn levels reflect soil Mn solubility. Residual Si treatments had no significant influence on plant Mn.

Plant Zn: Plant Zn values in the final harvest of desmodium decreased significantly with soil pH (Table 12, Appendix Table 54). Although the effect was nonsignificant in kikuyu grass, Zn also tended to decrease with pH (Table 11, Appendix Table 54). Residual Si and P had no influence on Zn in either plant species.

Nutrients in Index-Tissue at the Seventh Harvest

Twenty samples comprising four recently developed top leaves including the spindle leaf were collected from each kikuyu grass plot and 25 recently matured leaves with petioles were collected from each desmodium plot at the time of final harvest. Replicates of various treatments were composited and analysed for total Si, P, Al, K, Ca, Mg, Mn, and Zn. These samples were collected to investigate effects of residual Si, P, and soil pH on various nutrient elements in recently matured tissues and to study the relationship between yield and mineral composition in these indicator tissues.

Silicon: Silicon in the index-tissues of both crops increased with increasing levels of residual Si and decreased slightly with pH only in the 1660 kg Si/ha treatment (Figure 16, Appendix Table 55). Leaf silicon decreased with increasing

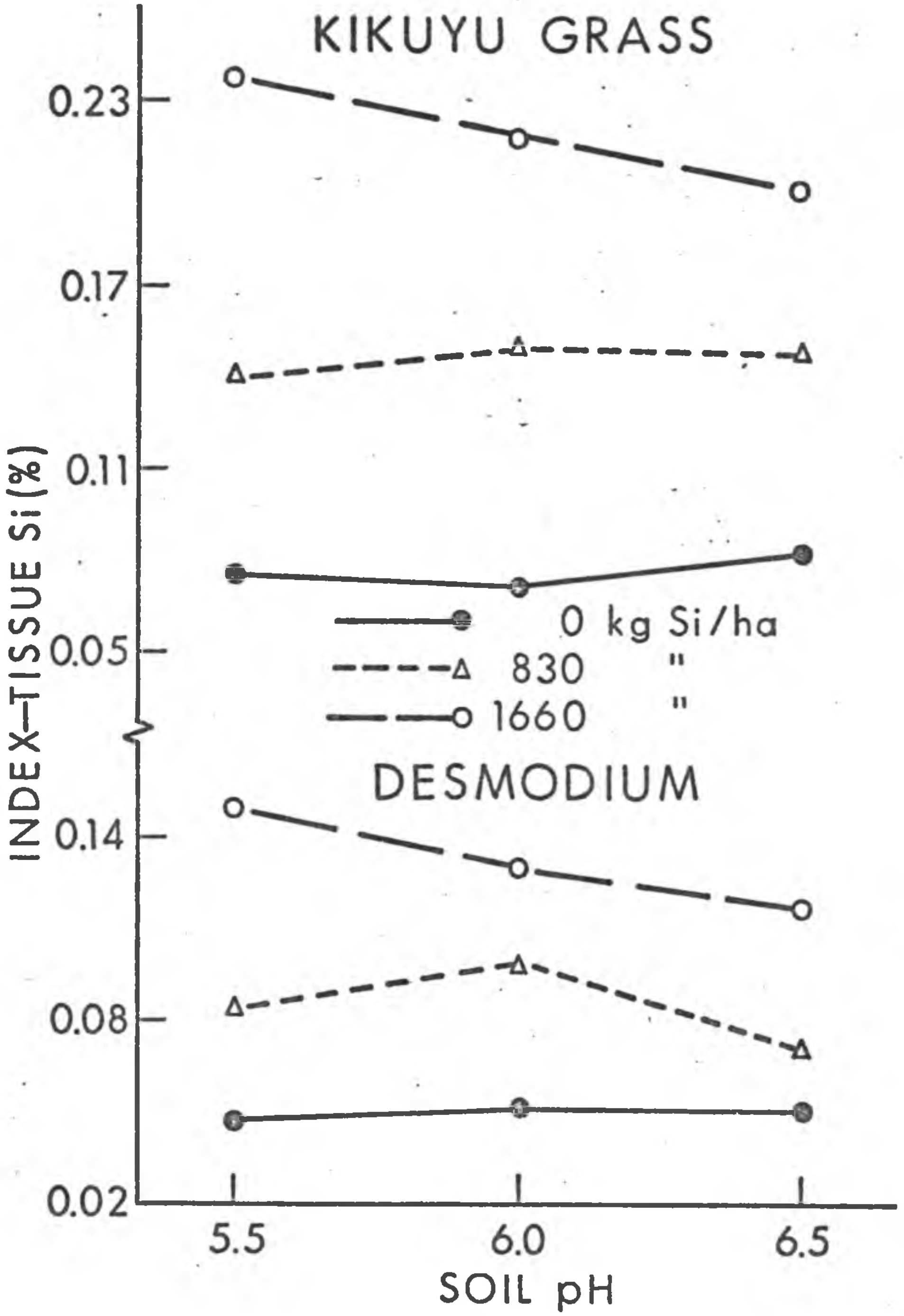


Figure 16. Influence of soil pH and residual Si on index-tissue Si in kikuyu grass and desmodium (Harvest 7)

levels of P in desmodium, but increased with P levels in kikuyu grass (Figure 17). In addition to dilution effects due to increased yields there is the possibility of an antagonistic effect of P on Si absorption in desmodium. In kikuyu grass, on the other hand, there is perhaps a mechanism operating at the root surface which enhances the absorption of Si with increasing P in this species. This contrasting mode of action of P on Si uptake in desmodium and kikuyu grass demonstrates that Si-P interactions in the plant are species characterics.

Kikuyu grass generally had higher Si concentrations in the index-tissues (0.061 to 0.263%) than desmodium (0.037 to 0.175%) which agrees with the earlier work of Russell (1961) and Jones and Handreck (1965) that showed graminaceous species accumulate more Si than leguminous species. Thiagalingam (1971) also found higher Si concentrations in kikuyu grass than in desmodium grown in two different soils in pot studies.

Phosphorus: Index-tissue P concentrations in both crops increased with increasing levels of residual P (Appendix Table 56), but there appeared to be no effect of residual Si or soil pH. No significant influence of Si application on tissue P was observed in any of the preceding crops (Teranishi, 1968; Rosenau, 1969; Thiagalingam, 1971) although Teranishi reported that sheath P values of sugarcane tended to increase with Si treatment.

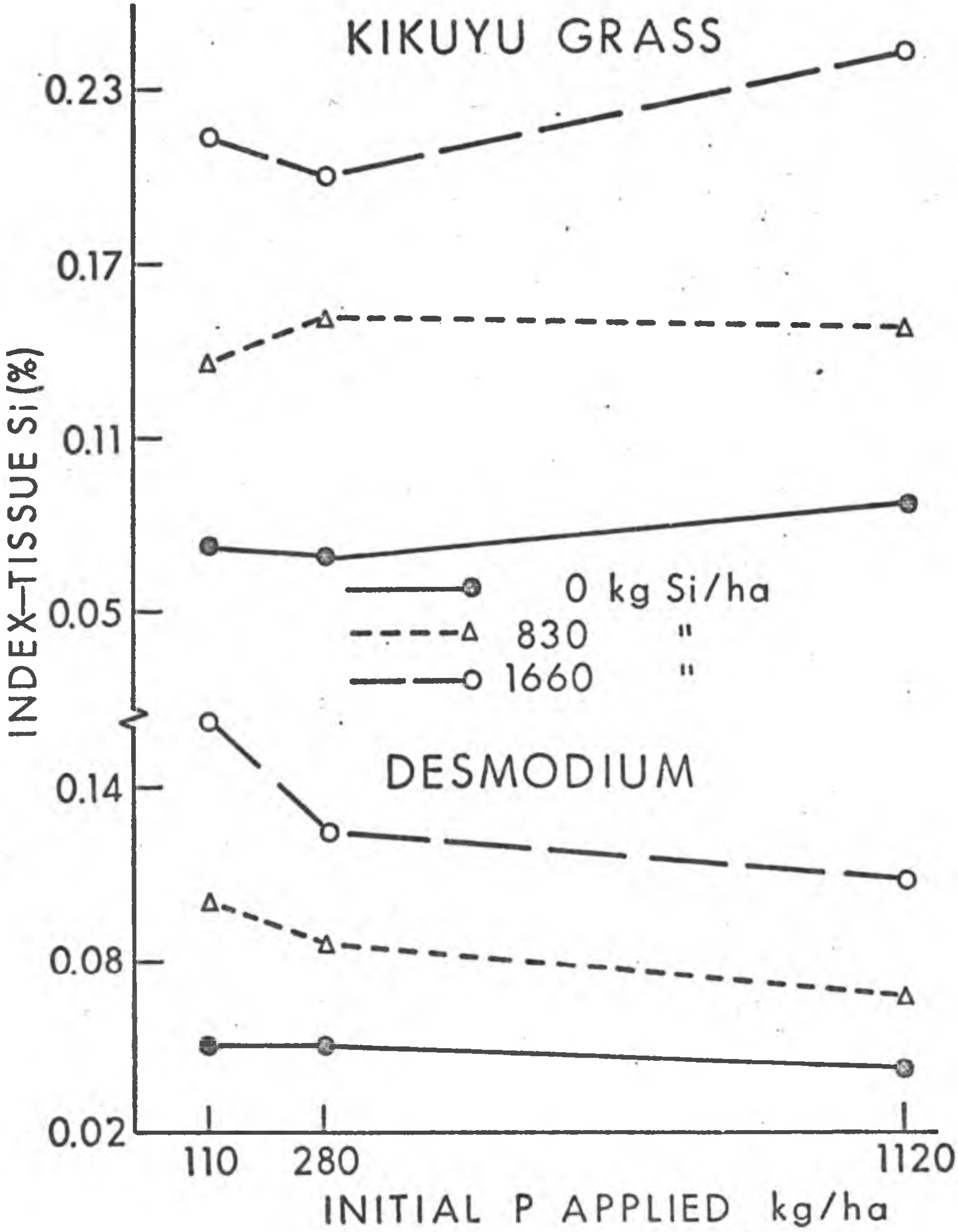


Figure 17. Influence of residual P and Si on index-tissue Si in kikuyu grass and desmodium (Harvest 7)

Aluminum: The data for Al values in index-tissues of kikuyu grass and desmodium are presented in Appendix Table 57. An effect of pH was apparent in that Al concentrations were slightly lower at pH 6.5 than at pH 5.5. In addition, there was a trend for Al concentrations to increase with P application. Whole-plant Al levels in both species in the final harvest were considerably higher than index-tissue concentrations indicating Al accumulated in the older parts of the plants and small amounts were transported to rapidly growing tissues.

Potassium: In desmodium, index-tissue K decreased slightly with residual Si and with increasing pH (Appendix Table 58), but residual P had no influence on K concentration. In kikuyu grass, K concentrations were not affected by any treatments (Appendix Table 58). Potassium values ranged from 1.95 to 2.3% in desmodium and 2.3 to 2.4% in kikuyu grass. In both cases values were lower than those in the whole-plant samples at final harvest. In the preceding crops of ratoon sugarcane (Rosenau, 1969) and corn (Thiagalingam, 1971) K deficiency was reported to be severe enough to affect plant growth. However, in addition to the blanket application of K before planting desmodium and kikuyu grass, regular applications of about 165 kg K/ha were made after each harvest. Presumably levels of adsorbed K in the soil were high enough to permit large amounts of K to be taken up by plants without depleting reserves. This may account for high K levels in whole-plant as well as index-tissue samples in both species. Although specific references in the literature on the critical levels of K for these forage crops were not found, data for several other legumes and grasses indicate that deficiency is not likely to occur until leaf or sheath K concentrations drop to 1.7% or less (Chapman, 1967). Potassium data from both whole-plant and index-tissue samples suggest that K did not limit plant growth of these crops.

Calcium and Magnesium: Calcium in index-tissues of both crops increased with soil pH but did not appear to be affected by residual Si or P (Appendix Table 59). It should be noted that Ca concentrations in desmodium are about five times higher than those in kikuyu grass which illustrates the different Ca requirements of these two species.

Index-tissue Mg followed the same trend noted for whole-plant Mg, i.e., it increased with soil pH and decreased slightly with increasing residual P (Appendix Table 60). Mg concentrations in desmodium were about 1½ times higher than those in kikuyu grass.

Manganese and Zinc: Index-tissue Mn decreased with soil pH and P, but was unaffected by Si in desmodium. In kikuyu grass, Mn concentrations also decreased with soil pH and P, but increased with residual Si (Appendix Table 61). Similar results were found in the whole-plant samples discussed earlier. Less Mn was found in the growing tissue than in older parts of the plant. Since there was no yield reduction at lower pH levels, and soil pH controls Mn availability, it can be deduced that plant Mn was not toxic to plant growth within the pH range 5.5 to 6.5.

Zinc contents of index-tissue did not vary with Si or P treatments in desmodium, but were reduced by increasing pH. Zinc concentration at pH 6.5 was almost 50% of that at pH 5.5 (Appendix Table 62). In kikuyu grass, Zn concentration was not affected by any of the treatments. Index-tissue Zn levels which were lower than those in whole-plant samples, ranged from 10 to 46 ppm in desmodium and 10 to 32 ppm in kikuyu grass.

Soil Analysis

Soil samples collected from the 0 to 15 cm depth were analyzed for water-extractable Si, modified Truog-extractable P, P sorbed at 0.2 ppm P in solution, $BaCl_2$-extractable Al and soil pH. The residual effects of Si, P and soil pH on these parameters are discussed below.

Soil Si: Residual Si treatments significantly increased water-extractable soil Si in both kikuyu grass and desmodium sites 56 months after the initial treatments (Tables 13 and 14, Figure 18). Effects of residual P and soil pH were not significant. In the samples from kikuyu grass sites, however, Si solubility decreased slightly from pH 5.5 to pH 6.5 at all

Table 13. Summary of F-tests of analysis of variance of soil analyses at 56 months (kikuyu grass sites)

Source of variation	d.f.	H_2O-ext. Si	Mod. Truog-ext. P	P Sorbed	Soil pH	$BaCl_2$-ext. Al
Whole plots:						
Replications	2					
pH	2				**	**
Error (a)	4					
Subplots:						
Si	2	**	*			
P	2		**	**		
Si x P	4					
Si x pH	4					
P x pH	4					
Si x P x pH	8					
Error (b)	48					

* Significant at the 5% level

** Significant at the 1% level

Table 14. Summary of F-tests of analysis of variance of soil analyses at 56 months (desmodium sites)

Source of variation	d.f.	H_2O-ext. Si	Mod. Truog-ext. P	P Sorbed	Soil pH	$BaCl_2$-ext. P
Whole plots:						
Replications	2		*	**		*
pH	2				**	**
Error (a)	4					
Subplots:						
Si	2	**		*		
P	2		**	**		
Si x P	4					
Si x pH	4					
P x pH	4					
Si x P x pH	8					
Error (b)	48					

* Significant at the 5% level

** Significant at the 1% level

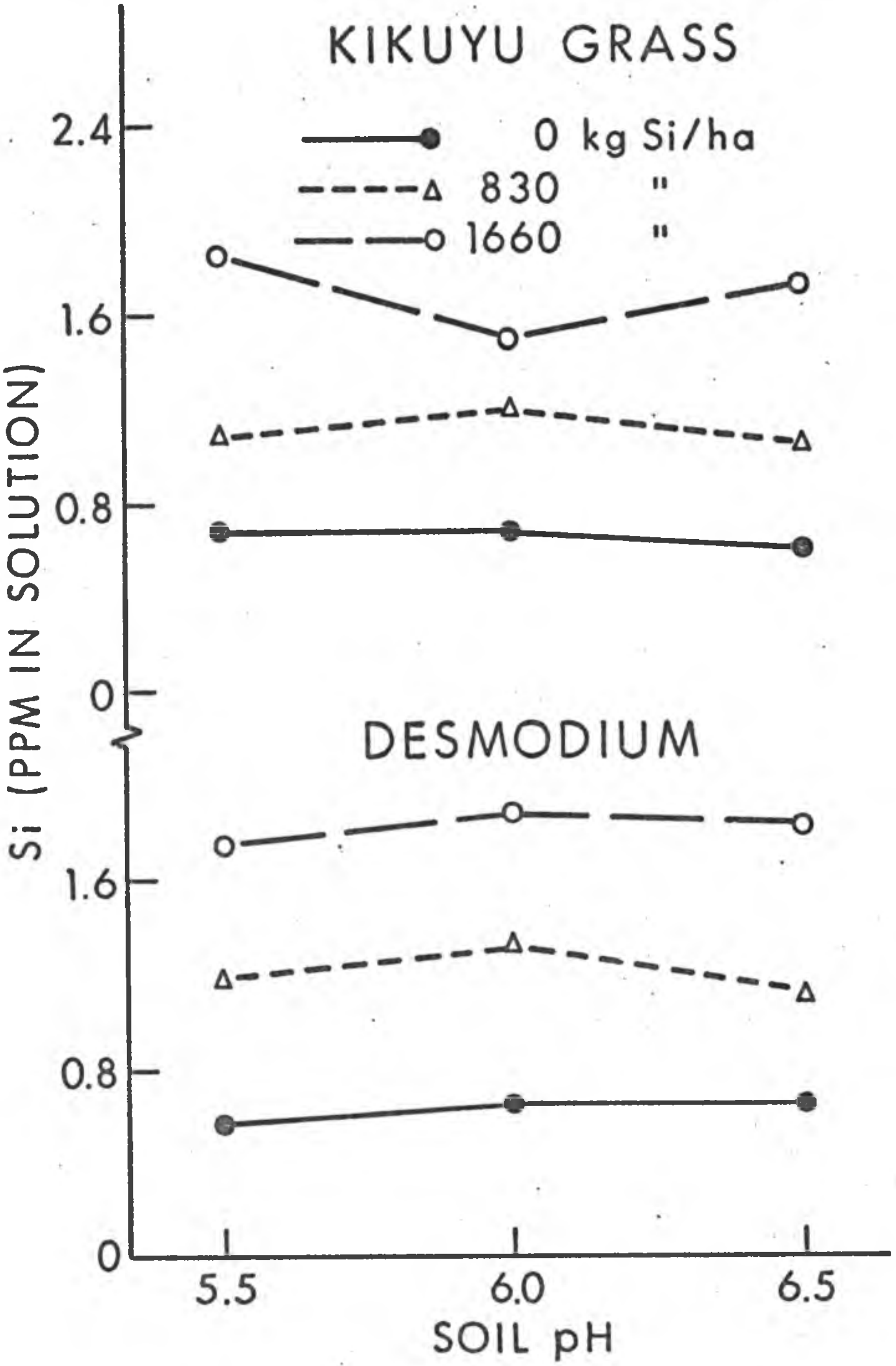


Figure 18. Influence of soil pH and residual Si on water-extractable soil Si at 56 months

levels of applied Si (Figure 18). In desmodium sites no consistent trend was observed.

Effects of residual P on water-extractable Si were not significant in samples from either species at 56 months. Increasing levels of residual P did not increase Si solubility significantly in samples from preceding crops except in the 9-month samples (Figure 19(A)), where water-extractable Si in the 1120 kg P/ha treatment was significantly higher than that in the 110 and 280 kg P treatments (Teranishi, 1968). However, Si solubility in the 1120 kg P/ha treatment was consistently higher than that in the 110 kg P/ha treatment for the entire 56 month period. It should be noted that data points in Figure 19 at 40 and 56 months are for kikuyu grass sites, but the values at desmodium sites were similar. Data for kikuyu grass were plotted to maintain continuity in having graminaceous crops throughout the experiment.

Soil pH did not affect water-extractable Si levels significantly in samples collected at 56 months. However, in soil samples collected 9 months after the initial treatment increasing soil pH significantly decreased Si solubility, and the difference was greater at the highest level of applied Si (Teranishi, 1968). A significant Si x P interaction was observed in water-extractable Si from soil samples collected 21 months after the initial application (Rosenau, 1969). Again, water-extractable soil Si determined after corn, 27

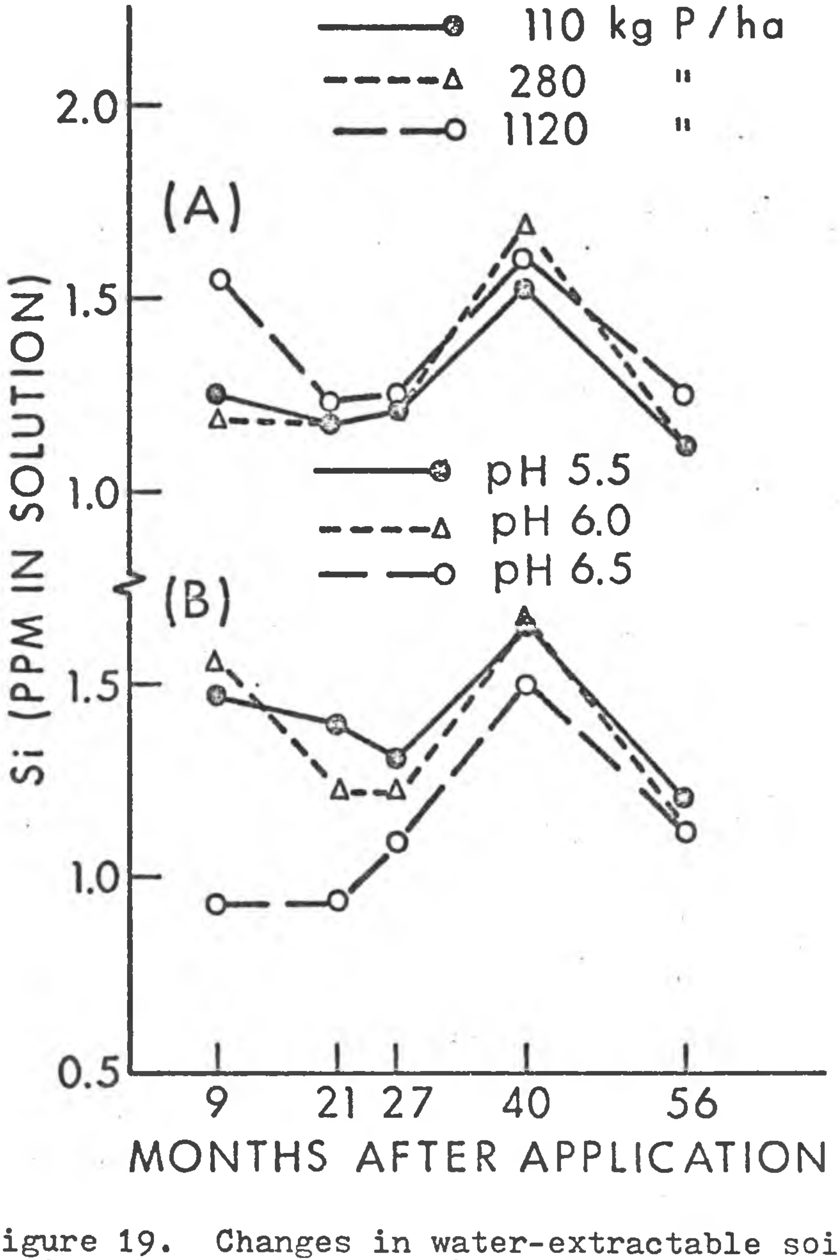


Figure 19. Changes in water-extractable soil Si with time as affected by (A) applied P and (B) soil pH (data points at 40 and 56 months are for kikuyu grass sites)

months after the start of the experiment, was significantly lower at pH 6.5 than at pH 6.0 or 5.5 (Table 15, 1.10 vs. 1.23 and 1.31 ppm Si in solution, respectively. For data see Appendix Table 63). The effects of soil pH on Si solubility at various times of sampling are plotted in Figure 19(B), and although the three curves for soluble Si differ markedly with pH in the first 27 months, they essentially converge at 56 months.

Variation in several factors, including Si uptake by plants, leaching of Si in the profile and Si fixation by soil may account for the Si levels observed. Sugarcane plant and ratoon crops, corn, and seven harvests of desmodium and kikuyu grass extracted Si from soil in amounts which decreased in the order pH 5.5 > pH 6.0 > pH 6.5, and the magnitude of the difference was larger in the first three crops. Also, there is some evidence that more Si leached from the surface layers at pH 5.5 than at pH 6.5 (see Section II on Si movement in soil) reducing Si reserves in the soil complex. Leaching of Si at pH 6.0 and 6.5 was negligible, due to lower Si solubility, and resulted in greater Si adsorption in the surface layers. This is shown in Section II, where greater amounts of Si were extracted with phosphate-extracting solution at pH 6.5 than at pH 5.5. There is also the possibility that five years after $CaSiO_3$ application some unreacted material remained which contributed to the fraction of Si recovered. Since Si solubility in equilibrium with the soil system is governed by

Table 15. Summary of F-tests of analysis of variance of soil analyses at 27 months (after corn)

Source of variation	d.f.	H_2O-ext. Si	Mod. Truog-ext. P	Soil pH	$BaCl_2$-ext. Al
Whole plots:					
Replications	2				
pH	2	*		**	**
Error (a)	4				
Subplots:					
Si	2	**			
P	2		**		
Si x P	4	*			
Si x pH	4				
P x pH	4	*			
Si x P x pH	8				
Error (b)	48				

* Significant at the 5% level

** Significant at the 1% level

both soil reaction and the pool of adsorbed Si in the soil, the greater Si solubility at lower pH was compensated for by the larger reserves of adsorbed Si at higher pH. This resulted in smaller differences in water-extractable Si between pH 5.5 and 6.5 at the end of five years.

It may be pointed out that water-extractable Si was higher at 40 months than at either 27 or 56 months (Figure 20, Appendix Tables 63, 64 and 65). A possible reason for this is that after planting desmodium and kikuyu grass only two cuttings were obtained in the following 13 months due to slow growth, and relatively small quantities of Si were removed from the soil. Thus more water-extractable Si was present in the soil at 40 months. In the following 16 months, 5 harvests of both species were made and larger amounts of Si were extracted from the soil, depleting it of easily-available forms of Si. This may have resulted in lower amounts of water-extractable Si at 56 months.

Levels of water-extractable Si found in the soil after five years of cropping were lower than those set by Fox et al (1967b) as deficient for sugarcane growth. Silicon levels in the zero Si treatments were in the deficiency probable range and in both the 830 and 1660 Si levels were in the deficiency questionable range. Although these Si levels cannot be strictly applied to desmodium and kikuyu grass because of the differential species requirements for Si, they do indicate that Si status of the soil was low.

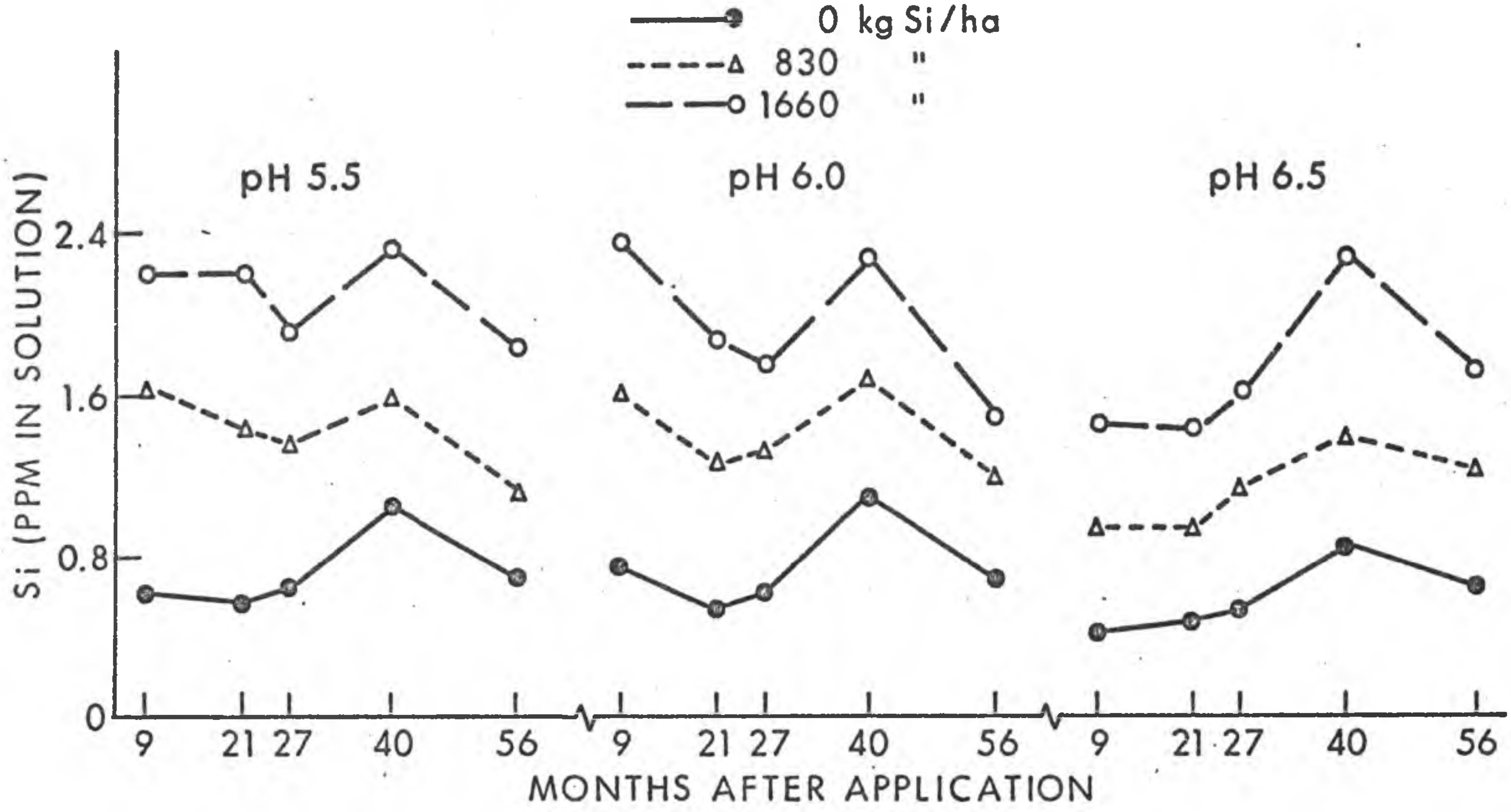


Figure 20. Changes in water-extractable soil Si with time as affected by soil pH and applied Si (data points at 40 and 56 months represent kikuyu grass sites)

A highly significant correlation was found between index-tissue Si in the final harvest of kikuyu grass and water-extractable Si in soil samples collected after harvest ($r = 0.95$); the correlation between whole-plant Si and soil Si was 0.87. This agrees with the earlier findings of Fox _et al_ (1967b), Teranishi (1968), Rosenau (1969), and Thiagalingam (1971) that leaf Si is very closely related to water-extractable soil Si. In desmodium, however, whole-plant Si was more closely related to soil Si than was index-tissue Si ($r = 0.72$ for whole-plant Si, and $r = 0.39$ for index-tissue Si).

From soil and plant analyses, it is apparent that effects of residual Si on plant and soil Si were still highly significant five years after application. The lack of yield response to residual Si in both species may be due to Si becoming more strongly adsorbed with time, and thus insufficient Si was available to stimulate growth.

Extractable Soil P: Soil samples collected in the 9- to 56-month period were extracted for modified Truog-extractable P. As mentioned earlier, about 7% of the total P applied was added before planting the two forage species so the effect of P was from both recently added and residual P. Modified Truog-extractable P increased significantly with increasing levels of residual P at 27 months (Table 15; 28, 54, and 206 ppm P, respectively. For data see Appendix Table 63). Residual Si and soil pH had no significant effect on soil P at 27 months, but there was a trend for soil P to increase as soil pH increased.

Extractable soil P of composited samples collected at 40 months had a tendency to increase with residual Si at all residual P and soil pH levels (Appendix Table 66). Soil P also increased very sharply with increasing residual P and was higher at pH 6.5 than at pH 5.5 in both kikuyu grass and desmodium sites. The effect of pH was greater at the highest level of residual P.

Extractable soil P at 56 months increased significantly ($P < 0.01$) with increasing residual P in both species (Tables 13 and 14, Appendix Table 67). In the kikuyu grass sites residual Si had a significant effect on extractable P and values at 1660 kg Si were significantly higher than those at 0 Si (61 vs. 53 ppm P). In the desmodium sites more P was extracted at 1660 kg Si than at zero Si although the difference was nonsignificant. The effect of soil pH was nonsignificant for both species.

An increase in extractable soil P with applied Si was also found in the first crop in this experiment. Teranishi (1968) observed a large increase in extractable soil P at the 1660 kg Si level over that of zero Si following the sugarcane plant crop which was harvested 9 months after silicate application. A similar trend was also observed by Rosenau (1969) after the sugarcane ratoon crop, 21 months after silicate application, but the increase in P was smaller. However, no effect of residual Si on extractable P was observed at 27 months. Apparently the effect of Si on soil P solubility persisted for 56 months after silicate had been applied. This does not agree with the work of Raupach and Piper (1959), who reported that the effect of silicate on P solubility was temporary and did not last over a year. The fact that the effect of residual Si on P solubility was significant after five years of cropping confirms the usefulness of silicate in enhancing P availability. The influence of Si in increasing soil P solubility has also been reported by Toth (1939), Adlan (1969) and Roy et al (1971).

Changes in extractable soil P during five years of cropping are plotted in Figure 21. It should be noted that the data points at 40 and 56 months are for kikuyu grass sites, but the values at desmodium sites are similar. The following observations may be made from Figure 21: (1) Extractable soil P at 21 months was higher than at 9 months, and the trend was apparent at all levels of Si and P. This implies that applied P became more available with time in spite of the fact that two crops of sugarcane extracted P from the soil in that period. The levels of extractable P at 27, 40 and 56 months were generally lower than at 21 months. It should be pointed out that the decrease from 40 to 56 months was very sharp, especially at the highest level of residual P, which reflects plant uptake by five kikuyu harvests in the 16 month period.

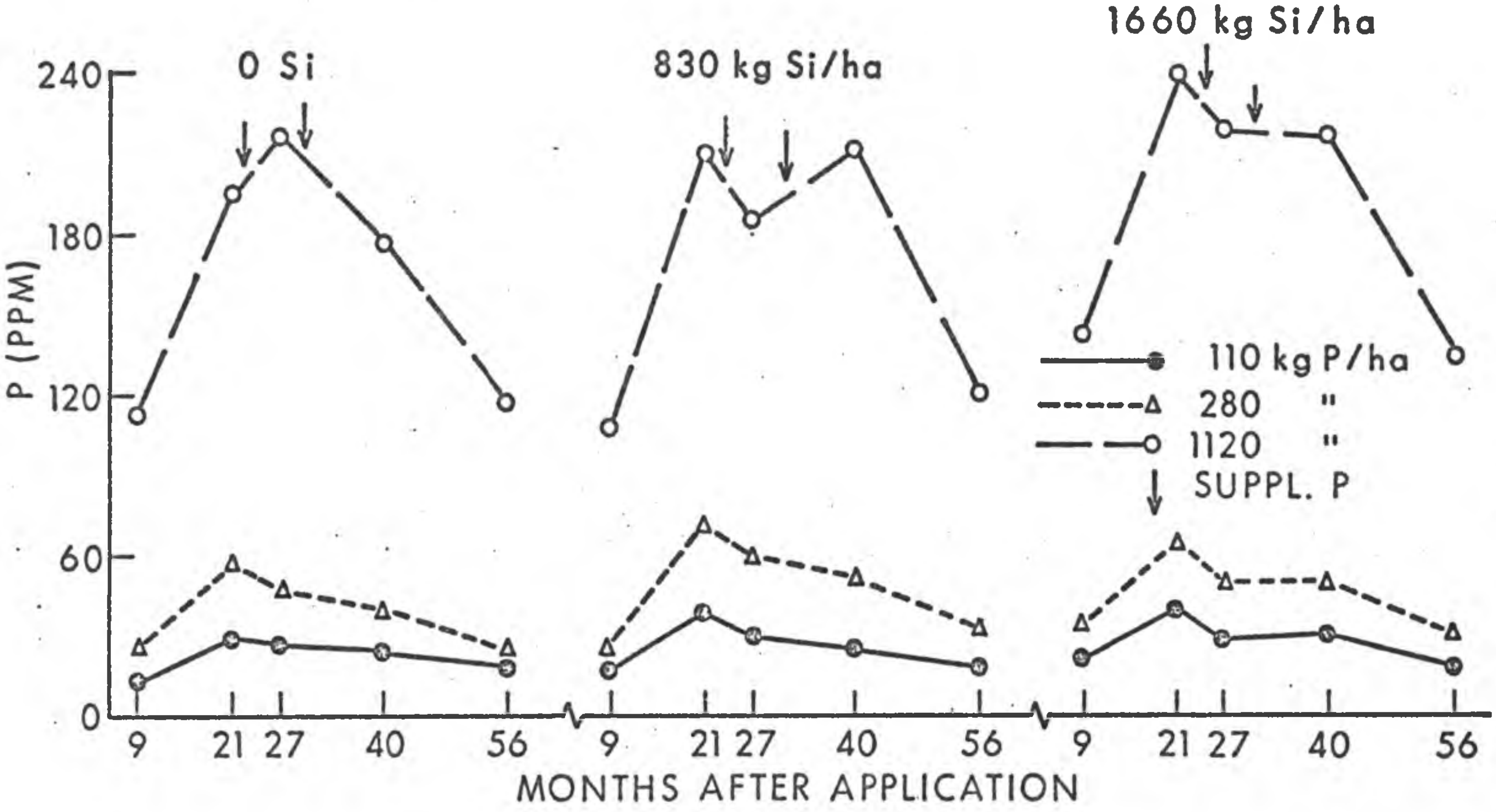


Figure 21. Changes in modified Truog-extractable soil P as affected by applied P and Si (data points at 40 and 56 months represent kikuyu grass sites. Supplemental P was added to all P treatments)

(2) Levels of extractable P in the 110 and 280 kg P treatments were low compared to that in the 1120 kg P treatment throughout the experiment and were in the deficiency range for crop production (Younge and Plucknett, 1966). (3) Extractable P levels at the end of the experiment were very close to those in the 9-month samples although two supplemental P addition were made at 21 and 27 months.

Phosphorus Sorbed: Phosphate sorption curves were constructed for soil samples collected five years after the experiment was started. The amount of P sorbed at 0.2 ppm P in solution (P requirements) was significantly affected by residual P (Tables 13 and 14, Appendix Table 68) in both sampling sites. In kikuyu grass sites significantly less P was sorbed at 1120 kg P than at 110 and 280 kg P (570 ppm vs. 847 and 815 ppm P sorbed), but the difference in P sorbed at 110 and 280 P was not significant (for data see Appendix Table 69). In desmodium sites, P sorption decreased significantly with each level of residual P (793, 731 and 510 ppm P sorbed for 110, 280 and 1120 P levels, respectively). The P requirements of kikuyu grass and desmodium plots decreased by 350 μg P/g soil and 470 μg P/g soil, respectively, from those of control plots (no treatments added) with the application of 1120 kg P. It should be noted that 30 months after the last supplemental P addition (56 months after the initial treatment) P requirements were decreased 280 μg P/g soil by the 1120 P level from that of the 110 P level, while the decrease nine months after the initial application was only 150 μg P/g soil (Roy, 1969). The effectiveness of residual P in decreasing P sorption has been demonstrated by Younge and Plucknett (1966) in a similar Gibbsihumox. They obtained maximum yields from 1200 lbs P/A applied six years earlier. Fox et al (1968a) also showed that P applied to a soil rich in gibbsite effectively reduced P requirements of the soil nine years later, and the residual efficiency of fertilizer P was 64 to 80%. Similar results were obtained in some North Carolina soils where P was applied 10 years earlier (Fox and Kamprath, 1970). The residual P effect, although smaller than that reported for the bauxite soil of Hawaii, still substantially reduced P sorption.

Residual Si from the 1660 kg Si level reduced P sorption significantly ($P < 0.05$) from the zero Si treatments in the desmodium sites (Table 15, 657 ppm vs. 700 ppm P sorbed). In the kikuyu grass sites sorbed P tended to decrease with increasing residual Si, but the effect was not statistically significant (values of 767, 740, and 725 ppm P sorbed with increasing Si levels. See Appendix Table 69 for data). In both sampling sites, the decrease in P sorption with increasing residual Si was consistent at all P and pH levels.

Soil pH had no significant effect on P sorption, but the values at pH 6.5 were higher than at pH 5.5. This differs from the earlier work of Roy et al (1971) who observed greater P sorption at pH 5.5 than at 6.2.

The effect of Si and pH on sorbed P in the 9- and 56-month soil samples shown below indicates that Si became less effective in decreasing P sorption with time.

pH	Si applied	P* sorbed (µg/g soil)		
	kg/ha	9 months	56 months	
		sugarcane	kikuyu grass	desmodium
5.5	0	910	855	843
5.5	1660	580	823	763
6.5	0	800	918	876
6.5	1660	675	880	800

* Residual P level = 110 kg P/ha

The 1660 kg Si treatment at pH 5.5 decreased the P requirement by 330 µg P/g soil nine months after application while the reduction was only 32 µg P/g soil in the kikuyu grass sites and 70 µg P/g soil in the desmodium sites at 56 months. At pH 6.5 the reduction in P requirement at nine months was 125 µg P/g soil compared to 38 and 76 µg P/g soil at 56 months for kikuyu grass and desmodium, respectively.

The simple correlation coefficients for the relationship between yield and soil P below indicates that P requirement is more closely related to yield than modified Truog-extractable P in both species:

Kikuyu grass	yield vs. P sorbed	r = -0.75
	yield vs. Truog P	r = 0.65
Desmodium	yield vs. P sorbed	r = -0.80
	yield vs. Truog P	r = 0.65

This indicates that P requirement is a better indicator of plant needs for P than extractable P which is conventionally used for soil testing. However, P requirements and modified Truog-extractable P were highly correlated (r = -0.93 for both sampling sites).

The data for P sorption obtained after 56 months of continuous cropping shows that residual P was about 7 times more effective than residual Si in decreasing P requirements. This does not agree with the work of Roy et al (1971) who showed that in soil samples collected nine months after the initial treatments residual Si was more efficient than residual P in decreasing P requirements. Apparently residual Si became more strongly immobilized in the soil and less able to displace adsorbed P with time, therefore it was not as effective in reducing P sorption as was residual P.

Soil pH: Increasing levels of Si and P had little effect on soil pH values determined at 27, 40, and 56 months (Tables 13, 14, 15, Appendix Tables 69, 70, 71). The pH values were initially adjusted to 5.5, 6.0 and 6.5 and after 56 months the differences in actual soil pH were highly significant in both kikuyu grass and desmodium sites (Tables 13, 14). The average pH values at the end of the experiment (56 months) were 5.3, 5.8 and 6.4 in kikuyu grass sites; and 5.4, 5.8 and 6.2 in desmodium sites. Soil pH values throughout the experiment were close to the initially adjusted levels except at 40 months where they were lower than the initial levels by

0.2 to 0.6 units (Figure 22). The slight decrease in soil pH values toward the end of the experiment was probably due to decreased adsorbed Ca levels with time which resulted in lower pH and hence greater Al activity.

Soil Al: Aluminum was extracted with unbuffered 1N $BaCl_2$ solution from surface soil samples (0 to 15 cm) collected 27, 40 and 56 months after the start of the experiment. Highly significant decreases in extractable Al were observed with increasing soil pH in the 27- and 56-month samples (Tables 13, 14 and 15, Appendix Tables 69, 73) and residual P and Si also had significant effects on extractable Al. Similar trends were observed in the 40-month samples, but statistics were not performed because replicates had been composited for chemical analysis (Appendix Table 72).

Extractable Al in samples collected at the end of the experiment decreased sharply as soil pH increased to 5.8 (Figure 23). As pH increased above 6.0, the decrease was relatively small, but Al values were less than 5 ppm due to most of the Al becoming insoluble and thus not extractable with $BaCl_2$ solution. A highly significant correlation was found between $BaCl_2$-extractable Al and pH determined at 56 months (desmodium sites, $r = -0.92$; kikuyu grass sites, $r = -0.85$). Rosenau (1968) also observed a significant decrease in KCl-extractable Al with increasing soil pH in the 21-month soil samples. Working on a Gibbsihumox soil, Fox et al (1962, 1964) and DeDatta et al (1963) obtained similar reductions in

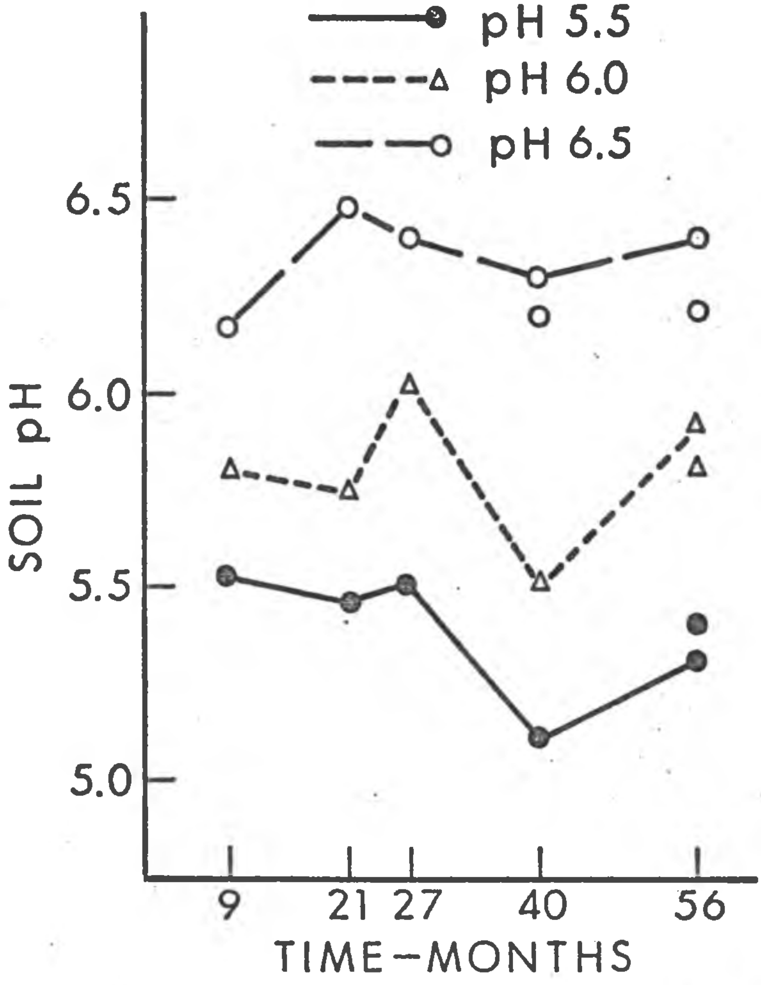


Figure 22. Changes in actual soil pH with time after initial pH adjustments (points not connected represent desmodium sites)

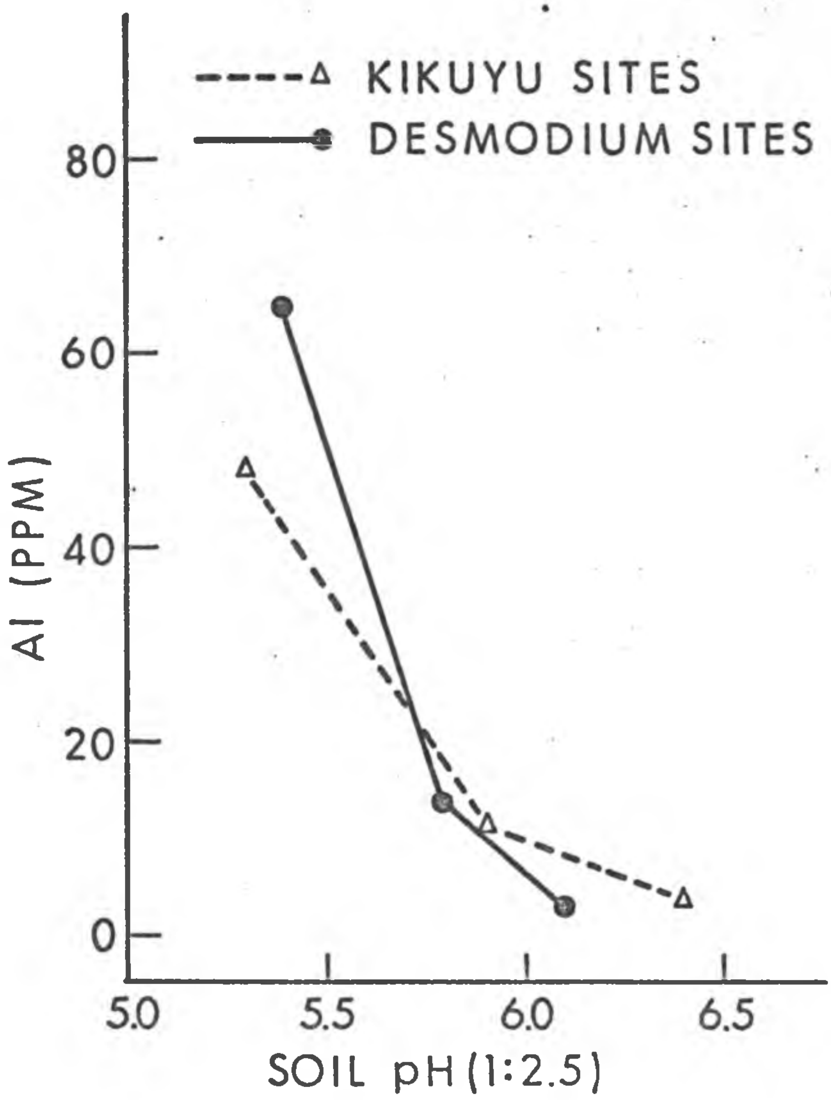


Figure 23. Relationship between actual soil pH and $BaCl_2$-extractable soil Al at 56 months

$BaCl_2$-extractable Al above pH 6.0, which agrees with the present investigation. Mahilum *et al* (1970) reported that Al extracted with 1*N* $BaCl_2$ was reduced drastically with $CaCO_3$ or $CaSiO_3$ applications in an Hydrendept soil. The shape of the curves constructed in the present experiment with residual $CaCO_3/CaSiO_3$ treatments (Figure 23) resemble that obtained by Mahilum *et al* (1970) with $CaCO_3$ five years after application.

It is apparent from Figure 24 that extractable Al values were higher at 40 months than at 27 or 56 months. This corresponds to lower soil pH values at that time (see Figure 22). The Al values dropped at 56 months, but were still higher than at 27 months, most probably due to decreasing effectiveness of $CaCO_3/CaSiO_3$ with time.

The lack of significant correlation between soil Al and whole-plant or index-tissue Al determined at final harvest indicates that soil Al solubility did not influence Al uptake.

Relationship of Yield with Soil and Plant Composition

Multiple regression analyses were performed on the preceding crops in this experiment to investigate the importance of various soil and plant parameters and the applied treatments in explaining the yield variations. Teranishi (1968) developed an equation that included applied treatments and 19 soil and plant variables, and which explained 59% of the yield variation in the sugarcane plant crop. He found that pH x Si and pH x P interactions were the two most important factors that affected

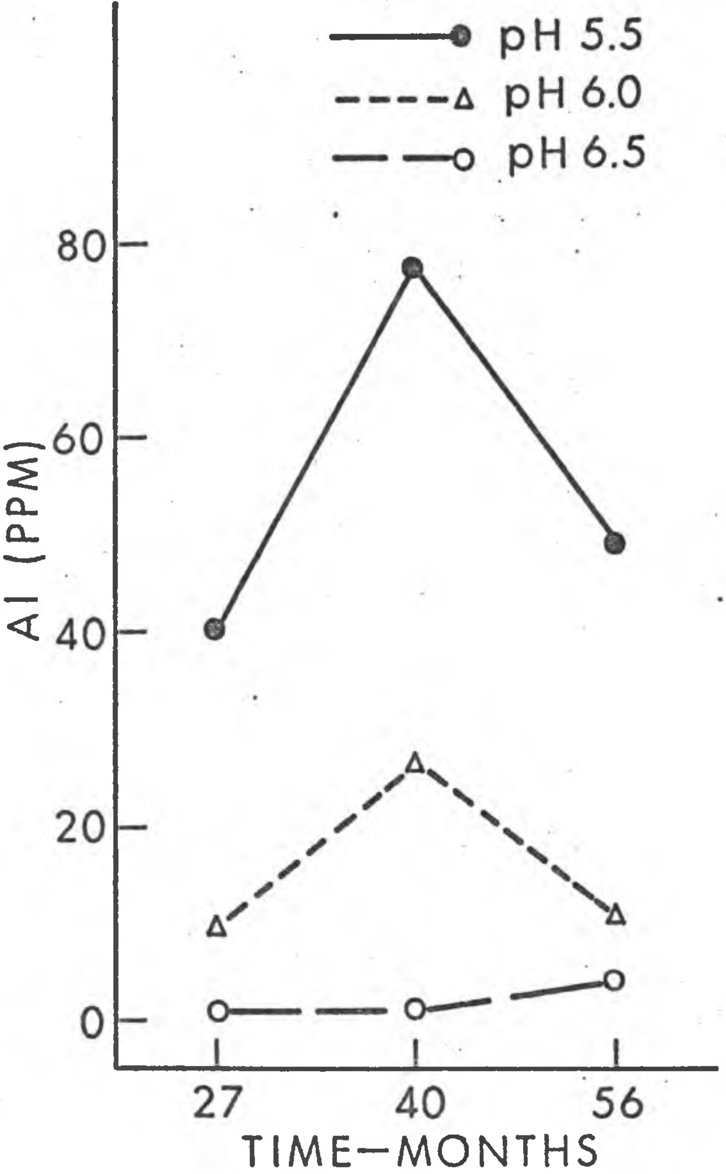


Figure 24. Changes in $BaCl_2$-extractable soil Al with time as affected by soil pH (data points at 40 and 56 months represent kikuyu grass sites)

yield. Rosenau (1969) worked with 55 variables that included applied treatments, and attributed 77% of the yield variations in the ratoon crop to these parameters. Most important of the factors in the ratoon crop were green sheath weight and plant Mg. While applied treatments accounted for most of the variation in the plant crop, these made a relatively small contribution to the explanation of yield variation in the ratoon.

Thiagalingam (1971) studied 31 variables that included Si, P and pH treatments, and explained 55% of the variation in ear corn yield. Soil P, stover P and leaf Ca were the most important variables for ear corn production, while water soluble Si and applied P explained most of the variation in stover yield. In the present study, multiple regression techniques were used to study the relationships between the yields of kikuyu grass and desmodium in the final harvest, and 39 variables that included applied Si, P and pH treatments, their squares and interactions. The results are discussed as follows:

<u>Kikuyu grass</u>: Multiple regression analysis was performed on kikuyu grass yield (averaged over replicates) in the final harvest with Si, P and soil pH initially applied five years ago, their squares and interactions as independent variables to study the effect of these parameters on yield. The computations showed that applied P, P^2, P x pH, Si^2 and Si were the most important variables which explained 62% of the yield variation. Based on these results a second yield equation

was developed using the five treatment parameters mentioned above as forced variables and 35 other variables including the remaining treatment factors, soil and plant analyses performed at harvest 7. This technique of forcing variables is used to develop equations which are more logical and still allow other important variables to be included in the equation if further increase in R^2 is obtained with them. This equation which included 40 variables accounted for 89% of the yield variation. After excluding factors which contributed less than 2% to R^2, equation (1) was obtained which included 8 variables and accounted for 79% of the yield variation (Table 16).

$$\begin{aligned} Y = {} & 6710 + 1.48\ (\text{treatment P}) - 0.0009\ (\text{treatment P}^2) \\ & - 0.02\ (\text{treatment P x pH}) + 0.0003\ (\text{treatment Si}^2) \\ & + 0.03\ (\text{treatment Si}) - 0.004\ (\text{P sorbed})^2 \\ & - 5140\ (\text{whole-plant Si}) + 0.25\ (\text{whole-plant Al}) \end{aligned} \tag{1}$$

In addition to the initially applied variables which had been forced in, $(\text{P sorbed})^2$ and whole-plant Si and Al were added and they accounted for 16% of the yield variation in this equation.

Another equation which utilized applied treatments, their squares and interactions and 31 soil and plant variables, all as free variables, was calculated. When only the variables which contributed more than 2% to R^2 were included, the 6 variable equation (2) explained 77% of the variation in kikuyu

Table 16. The contribution of applied treatments, and soil and plant variables to yield of kikuyu grass in the 7th harvest as determined by step-wise regression analysis (n = 34)

Variable	R^a	R^2 x 100	Simple correlation coefficient (r) with yield
Equation 1. Applied variables forced, plant and soil analyses variables free			
Treatment P	0.70	48.4	0.70**
Treatment P^2	0.75	56.4	0.64**
Treatment P x pH	0.76	58.2	0.67**
Treatment Si^2	0.77	59.7	0.14^{ns}
Treatment Si	0.79	62.4	0.11^{ns}
$(P\ sorbed)^2$	0.85	72.1	-0.76**
Whole-plant Si	0.86	74.8	-0.07^{ns}
Whole-plant Al	0.88	78.7	0.16^{ns}
Equation 2. Applied variables, and plant and soil analyses variables free			
Index-tissue P	0.76	58.6	0.76**
Index-tissue Mg	0.79	63.1	-0.36*
$BaCl_2$-ext. soil Al^2	0.83	68.5	-0.30^{ns}
Whole-plant K	0.85	72.2	-0.46**
Whole-plant Mg	0.86	74.8	-0.37*
$(P\ sorbed)^2$	0.87	76.6	-0.76**
Equation 3. $(P\ sorbed)^2$ forced and applied variables, and plant and soil analyses variables free			
$(P\ sorbed)^2$	0.76	57.7	-0.76**
Whole-plant K	0.78	61.5	-0.46**
Index-tissue Mg	0.84	70.1	-0.36*
Whole-plant Zn	0.88	76.8	-0.01^{ns}
Whole-plant Al	0.89	78.6	0.16^{ns}
Whole-plant Mn	0.90	81.3	-0.23^{ns}
Whole-plant Mg	0.91	83.4	-0.37*
Whole-plant Ca	0.92	84.9	-0.05^{ns}

[a] The R value applies to the relationship between the variable opposite it and all the variables above it and yield in a step-wise regression analysis

* Significant at the 5% level

** Significant at the 1% level

ns Nonsignificant

grass yield (Table 16).

$$Y = 14489 + 0.47\ (\text{index-tissue P}) - 4.17\ (\text{index-tissue Mg}) - 0.04\ (\text{soil Al}^2) - 3517\ (\text{whole-plant K}) + 15038\ (\text{whole-plant Mg}) - 0.001\ (\text{P sorbed})^2 \quad (2)$$

Index-tissue P and Mg, soil Al^2 and whole-plant K entered first and explained 72% of the yield variation. It should be pointed out that none of the Si parameters entered the equation which may imply that Si had no direct effects on kikuyu grass yield. Also, no applied treatments entered the equation. An equation developed by Thiagalingam (1971) to predict corn yield (ears and stover combined), 27 months after the initial treatment application, also did not include any applied treatments. This apparent decrease in effectiveness of applied treatments on yield compared to that in the sugarcane plant crop (Teranishi, 1968) may be due to the change in level of applied nutrients in the soil resulting from plant uptake, leaching and fixation. This results in plant nutrients reflecting more closely to levels of applied nutrients available to plants during crop growth in later periods. However, it must be emphasized that the correlation between plant and soil P parameters and applied P was very high ($r = 0.93$ to 0.97). Due to this high correlation, the entry of index-tissue P into the equation accounted for most of the variation attributed to other P parameters. This caused the other P parameters to make a relatively small additional contribution to R^2 and they entered the equation after several other parameters, or not at all.

Inspection of correlation coefficients revealed that kikuyu grass yield was closely related to both index-tissue P and $(P \text{ sorbed})^2$ (r = 0.760, and 0.765 for index-tissue P and $(P \text{ sorbed})^2$, respectively. Since index-tissue P had been selected first in equation 2 because it had a slightly higher r value, P sorbed was forced into equation 3 and only 8 factors entered the equation which explained 85% of the yield variation (Table 16).

$$\begin{aligned} Y = 15640 &- 0.003\,(P\ \text{sorbed})^2 - 2160\,(\text{whole-plant K}) \\ &- 4.85\,(\text{index-tissue Mg}) - 28.4\,(\text{whole-plant Zn}) \\ &+ 0.31\,(\text{whole-plant Al}) - 5.62\,(\text{whole-plant Mn}) \\ &+ 18024\,(\text{whole-plant Mg}) - 4027\,(\text{whole-plant Ca}) \end{aligned} \qquad (3)$$

Whole-plant K, index-tissue Mg and whole-plant Zn followed $(P \text{ sorbed})^2$ in this equation and explained 18% of the variation in yield. Apparently $(P \text{ sorbed})^2$ accounted for much of the variation explained by index-tissue P plus additional variation because it was included in equation 2 with index-tissue P, but index-tissue P was not included when $(P \text{ sorbed})^2$ was entered first. Equations 2 and 3 differ in that only $(P \text{ sorbed})^2$, index-tissue Mg and whole-plant K are common to both equations and these variables are the first three variables in equation 3. Both equations include measures of Al, but equation 2 includes soil Al while equation 3 includes plant Al. A measure of Zn and Mn is present only in equation

3. These variations in parameters reflect the high degree of correlation among the so-called independent variables which make clear-cut interpretation of these equations difficult. Equation 1 probably comes the closest to having truely independent variables and interpretation of effects of variables on yield may be more correct.

From examination of these equations it appears that in addition to the initially applied treatments, soil P and Al were important in kikuyu grass yield. Plant variables which appear to be important for kikuyu grass production in this Gibbsihumox were P, K. Mg and possibly also Zn, Al, Mn, and Ca.

Desmodium: Regression of applied treatments, their squares and interactions on desmodium yield (averaged over replicates) in the final harvest showed that P, P^2, Si, and P x pH were the most important variables affecting growth and accounted for 75% of the yield variation. It should be noted that P parameters explained most of the variation followed by Si. Soil pH apparently had no direct effect on desmodium yield. These four applied variables mentioned were forced into another equation first and the remaining treatment variables and 31 soil and plant analyses were allowed to come in as free variables. This 40 variable equation accounted for 99% of the yield variation in desmodium. When factors which contributed less than 1% to R^2 were excluded an eight factor equation (4) which accounted for 92% of the yield variation was obtained (Table 17).

$$Y = 4550 + 2.93 \text{ (treatment P)} - 0.001 \text{ (treatment P}^2\text{)} + 0.05 \text{ (treatment Si)} - 0.01 \text{ (treatment P x pH)} - 0.04 \text{ (soil Al}^2\text{)} + 11.05 \text{ (mod. Truog-ext. soil P)} - 7202 \text{ (whole-plant Mg)} - 698 \text{ (whole-plant K)} \quad (4)$$

The variables which entered the equation after the forced treatments were $BaCl_2$-extractable soil Al^2, modified Truog-extractable soil P and whole-plant Mg and K which explained 20% of the yield variation in this equation. Variables which contributed less than 1% to R^2 were not included. This equation differs from equation 1 in that whole-plant Mg and K explained some of the yield variation in desmodium whereas these two variables were not present in equation 1 for kikuyu grass.

Another equation which treated applied treatments, their squares and interactions, and 31 soil and plant analyses as free variables accounted for 99% of the yield variation in the 7th harvest of desmodium. After factors which contributed less than 1% to R^2 were eliminated, equation 5 below included 9 variables and accounted for 95% of the variation in yield (Table 17).

$$Y = 6148 - 9899 \text{ (whole-plant Mg)} + 7.94 \text{ (mod. Truog-ext. soil P)} - 2.84 \text{ (index-tissue Mn)} - 0.002 \text{ (treatment P}^2\text{)} + 14732 \text{ (whole-plant P}^2\text{)} + 3.56 \text{ (treatment P)} - 0.0001 \text{ (index-tissue P}^2\text{)} - 933 \text{ (whole-plant K)} - 157 \text{ (index-tissue K)} \quad (5)$$

Table 17. The contribution of applied treatments, and soil and plant variables to yield of desmodium in the 7th harvest as determined by stepwise regression analysis (n = 34)

Variable	R^a	R^2 x 100	Simple correlation coefficient (r) with yield
Equation 4. Applied variables forced, and plant and soil analyses variables free			
Treatment P	0.73	53.7	0.73**
Treatment P^2	0.84	70.5	0.66**
Treatment Si	0.85	71.7	0.16^{ns}
Treatment P x pH	0.85	72.2	0.70**
$BaCl_2$-ext. Al^2	0.93	86.4	-0.45**
Mod. Truog-ext. P	0.94	88.7	0.73**
Whole-plant Mg	0.95	90.9	-0.83**
Whole-plant K	0.96	92.1	-0.68**
Equation 5. Applied variables, and plant and soil analyses variables free			
Whole-plant Mg	0.83	68.9	-0.83**
Mod. Truog-ext. P	0.92	84.4	0.73**
Index-tissue Mn	0.93	87.3	-0.67**
Treatment P^2	0.94	88.9	0.66**
Whole-plant P^2	0.95	90.5	0.71**
Treatment P	0.96	91.7	0.73**
Index-tissue P^2	0.96	92.7	0.56**
Whole-plant K	0.97	93.9	-0.68**
Index-tissue K	0.97	95.1	0.25^{ns}
Equation 6. $(P \text{ sorbed})^2$ forced and applied variables, and plant and soil analyses variables free			
$(P \text{ sorbed})^2$	0.82	67.4	-0.82**
Whole-plant Mn	0.90	81.2	-0.71**
Whole-plant Mg	0.92	84.1	-0.83**
Mod. Truog-ext. P	0.93	86.8	0.73**
Whole-plant P	0.94	88.2	0.72**
Treatment P^2	0.95	89.5	0.66**
Treatment P	0.95	91.2	0.73**
Whole-plant K	0.96	92.5	0.68**
Index-tissue P	0.97	93.6	0.50**
Index-tissue K	0.97	95.0	0.25^{ns}

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[a] The R value applies to the relationship between the variable opposite it as well as all the variables above it and yield in a multiple regression analysis

** Significant at the 1% level

ns Nonsignificant

Whole-plant Mg, modified Truog-extractable P and index-tissue Mn explained 69%, 15% and 3% of the yield variation, respectively, while the remaining 6 variables explained only 8% of the total variation in desmodium yield in this equation. It is interesting to note that several P parameters including two applied treatment variables entered the equation and explained 21% of the total variation. However, it must be emphasized that (P sorbed)^2 which had the highest r value (-0.82) of all P parameters when correlated with yield was not included in the equation. It was decided to force (P sorbed)^2 into the equation first and let the other 39 variables enter as free variables to study the effect of (P sorbed)^2 on the inter-relationships of other factors. A new equation (6) with 10 variables (variables which contributed more than 1% to R^2 were included) explained 95% of the yield variation (Table 17).

$$\begin{aligned} Y = {} & 5421 + 0.0002\ (\text{P sorbed})^2 - 2.04\ (\text{whole-plant Mn}) \\ & - 8752\ (\text{whole-plant Mg}) + 6.86\ (\text{mod. Truog-ext. P}) \\ & + 6993\ (\text{whole-plant P}) - 0.002\ (\text{treatment P}^2) \\ & + 3.92\ (\text{treatment P}) - 1066\ (\text{whole-plant K}) \\ & - 0.0001\ (\text{index-tissue P}) - 173\ (\text{index-tissue K}) \end{aligned} \tag{6}$$

In addition to the 67% variation accounted for by (P sorbed)^2, whole-plant Mn and Mg and Truog-extractable soil P explained 18% of the total variation and were the next most important variables. Again, P parameters which included applied treatments, soil and plant analyses entered the equation and accounted for 74% of the yield variation. Comparison of equations 5 and 6 show that plant Mg, Mn, K and modified Truog-extractable soil P were present in both equations which indicate their relative importance in desmodium yield. Other soil variables and applied treatments had no direct influence on yield.

It is apparent from regression equations for both kikuyu grass and desmodium yields that soil and plant variables are highly inter-related and that they reflect the effects of initially applied treatments which are the only truly independent variables. Based on the results above it may be concluded that in addition to the initially applied treatments which explained 62 and 75% of the yield variation in kikuyu grass and desmodium, respectively, soil factors which were most important for crop production in both species included P sorbed, modified Truog-extractable P and soil Al. Plant nutrients which appeared to be important were P, Mg, and K, and possibly also Mn, Al, Zn, and Ca.

Conclusions

The combined dry matter yield of seven harvests of kikuyu grass and desmodium were increased significantly by residual P treatments, but were not significantly affected by residual Si or soil pH. However, at pH 5.5, in both species, yield increased with residual Si treatments which may be the result of increased Si solubility at lower soil pH. The relative yield differential between the three Si treatments decreased sharply with time and at the end of 56 months yield from 1660 Si was only 2.5% higher than that without Si whereas yield from 830 Si was less than the yield without Si. The decline with time in relative yield response to P applications, on the other hand, was small indicating a continued efficiency of P applied 56 months ago in increasing yields on a Gibbsihumox. However, it should be pointed out that two supplemental additions of P were made after the initial applications which affected crop yield.

Silicon concentrations in the whole-plant and uptake of Si by both species in the last harvest increased significantly with increasing residual Si treatments. Also, index-tissue Si concentrations in the last harvest increased markedly with residual Si levels as did total Si uptake of all harvests combined. Similar results were obtained in the preceding plant and ratoon crops of sugarcane and corn growth on the site. Residual Si treatments produced highly significant increases in water-extractable soil Si in both kikuyu grass and desmodium sites 56 months after the initial treatments.

From plant and soil analysis it is apparent that effects of applied Si on plant and soil Si were still highly significant five years after application. The lack of yield response to residual Si in both species may be due to Si becoming strongly immobilized with time, thus leaving insufficient Si available to stimulate growth. This suggests that supplemental amounts of silicates may have to be added to raise Si to levels which would enhance growth and thus produce higher yields. There is also a possibility that these forage species do not respond to Si.

More total P was taken up from the 1660 Si than from the zero Si treatments in all harvests combined for both kikuyu grass and desmodium. Modified Truog-extractable soil P was significantly higher at 1660 kg Si than at zero Si in soil samples collected after 56 months and also in samples collected at 9-, 21-, and 40-months. This persistence of applied Si effects on P solubility for five years confirms the usefulness of silicate applications in enhancing P availability.

Sorption studies performed on samples collected at the end of the experiment showed that the amount of P sorbed at 0.2 ppm P in solution (P requirement) was significantly reduced by residual Si and P treatments. However, residual P was about 7 times more effective than residual Si in decreasing P requirements. This differs from the work of Roy et al (1971) who reported that in soil samples collected 9 months after the initial treatment application in the same experiment Si was more efficient than P in decreasing P requirements. Apparently Si became more strongly adsorbed on the soil with time than P and therefore was less effective in reducing P sorption than was residual P.

Of the two methods for assessing soil P, P requirement was more closely related to yields than modified Truog-extractable P in both species. This means that P requirement is a better indicator of plant needs for P than modified Truog-extractable P which is conventionally used. Barium chloride-extractable soil Al decreased sharply with increased soil pH at all sampling dates, but plant Al in both species was not affected by pH. This indicates that Al uptake by kikuyu grass and desmodium in the field was not closely related to soil Al.

Multiple regression analyses showed that in addition to the treatments applied five years ago, the soil factors important to plant growth in both species were P sorbed, modified Truog-extractable P and $BaCl_2$-extractable Al. Plant nutrients which appeared to be important for crop production included P, K, and Mg and possibly also Mn, Zn, Al and Ca.

II. EFFECT OF SILICON AND SOIL pH ON THE MOVEMENT OF NUTRIENTS IN THE PROFILE OF HALII SOIL

Materials and Methods

Soil Sampling

Profile samples were collected from the field experiment described in Section I after the sugarcane plant crop, corn, and harvests 2 and 7 of kikuyu grass (9, 27, 40, and 56 months, respectively, after the initial silicate treatments were applied). Samples were taken from the three Si treatments (0, 830, and 1660 kg Si/ha), three pH levels (5.5, 6.0, and 6.5) and one phosphorus level (280 kg P/ha). Depths sampled were 0-15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-120 cm.

A profile sample from the control plot was also collected. Soil samples were partially air-dried to pass through a 2-mm sieve and stored in polyethylene bags for laboratory analysis.

Soil Analysis

The pH of a saturated soil paste, water-soluble Si, modified Truog P, and 1N $BaCl_2$-extractable Al were determined on all soil samples. Details of methods for extraction and analysis are given in the Appendix.

Exhaustive Phosphate-Extraction of Soil Si: An attempt was made in this study to determine the amount of applied silicon retained by the soil after crop removal and the amount leached into the profile during the course of the experiment.

Three grams of soil (oven-dried basis) were shaken for four hours with 30 ml of 0.1N acetic acid adjusted to pH 3.5 with NH_4OH and containing 50 ppm P as $Ca(H_2PO_4)_2$. The suspension was centrifuged and Si measured in the supernatant. The same soil sample was repeatedly extracted with phosphate solution until the difference between the zero Si treatment and the 1660 kg Si/ha treatment was minimal and constant. Thirteen successive extractions were required to reach a constant rate of Si release for the 0-15 cm depth samples (Figure 25). Nine and seven successive extractions were needed for the 15-30 cm and 30-120 cm soil depths, respectively.

Results and Discussion

Results of these studies will be discussed in the following order: (1) water-extractable Si, (2) phosphate-extractable Si, (3) recovery of Si after five years of cropping, (4) soil P, (5) soil pH, and (6) soil Al.

Water-Extractable Si

Changes in water-extractable soil Si during the five-year cropping period for the 0 to 15 and 15 to 30 cm soil depths are presented in Figure 26. The Si differential is more pronounced in the 0 to 15 cm depth than in the 15 to 30 cm depth and remains constant throughout the experiment and at all pH levels. This is also supported by the analysis of variance, where effects of residual Si on water-extractable Si in the surface layer were highly significant in 27, 40,

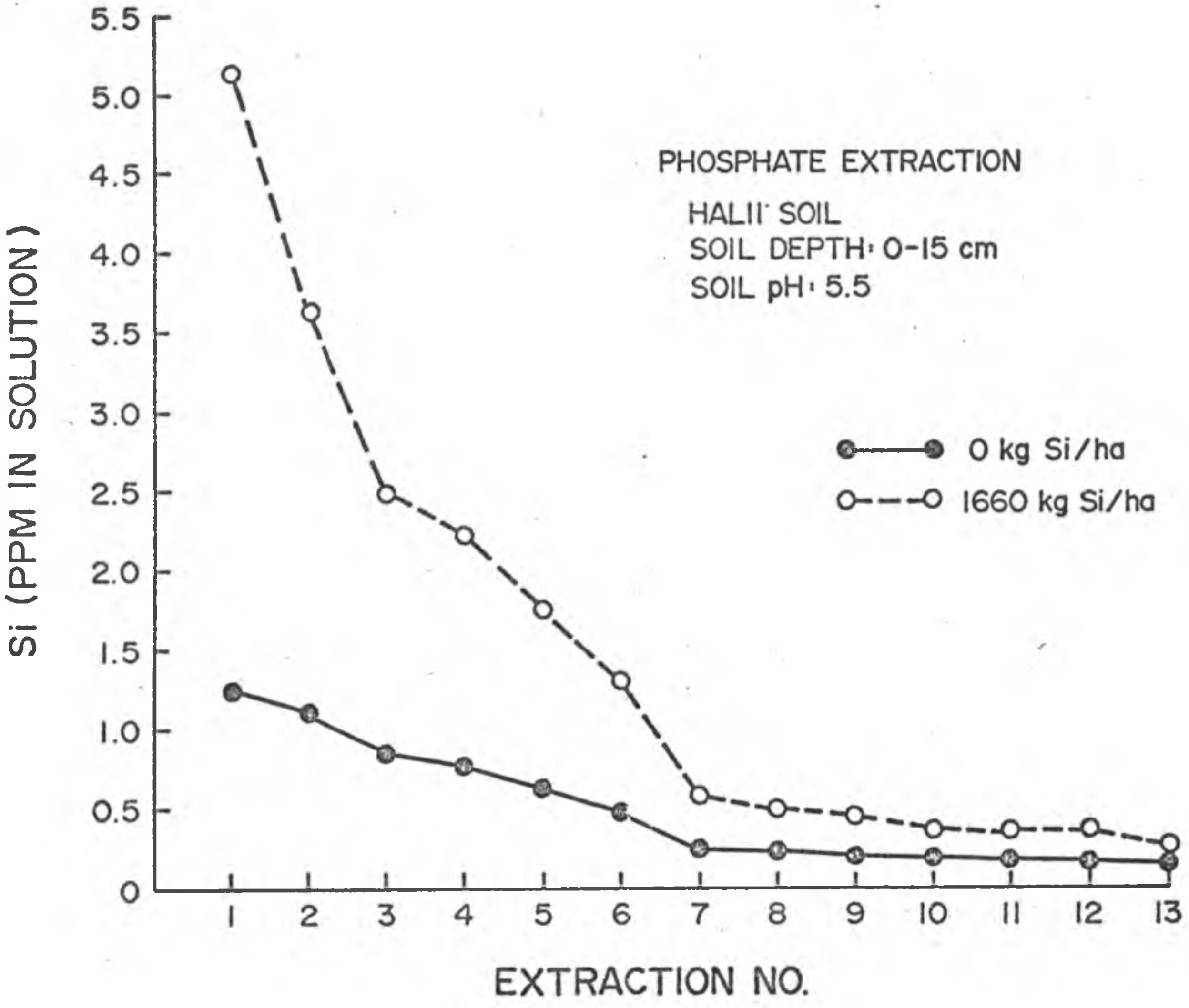

Figure 25. Soil Si removed by successive extractions with phosphate solution

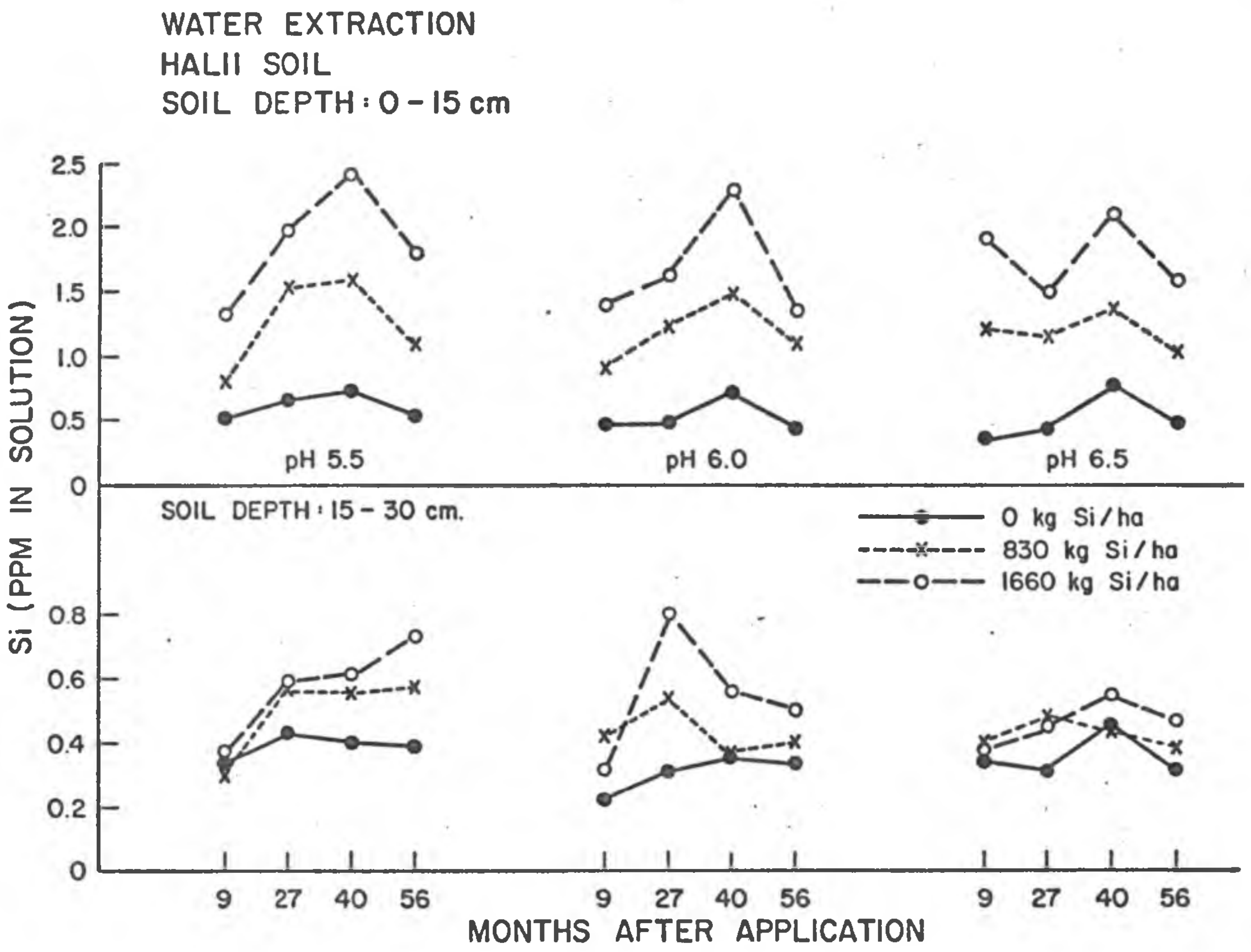

Figure 26. Changes in water-extractable soil Si in the 0-15 and 15-30 cm depths with time as influenced by soil pH and applied Si

and 56 months (Table 18). There is a tendency for Si concentration to increase from 9 to 40 months, and decrease at 56 months in the 0 to 15 cm layer. In the 15-30 cm depth, there is a trend for Si concentrations to increase sharply from 9 to 27 months at pH 5.5 and 6.0, while the increase at pH 6.5 is slight. The effects of the Si differential became more pronounced with time, particularly at pH 5.5 and 6.0. This suggests that Si leached from the surface to this layer. The possibility of mechanical mixing of Si into the 15 to 30 cm layer during tillage operations following sugarcane cannot be ruled out completely. However, the fact that this pattern is not shown at pH 6.5 suggests that Si leaching, due to the greater Si solubility at pH 5.5 and 6.0, rather than mechanical mixing is responsible for the increased Si concentration in this layer. The assumption that some Si moved with rain water to the 15 to 30 cm layer with time is further supported by analysis of variance results. The influence of residual Si treatments in increasing Si concentrations in the 15 to 30 cm layer was significant at the 10% level at 27 months. Significance increased to 5% at 40 months and to 1% at 56 months (Table 18). It should be noted that there were no tillage operations between the 40 and 56 month samples. Silicon values in the 0 to 15 cm horizon were 2 to 3 times higher than those in the 15 to 30 cm horizon (Appendix Tables 74 to 77).

Distribution of water-extractable Si in profiles of pH 5.5, 6.0, and 6.5 treatments was similar in that highest

Table 18. Summary of F-tests of analysis of variance of water-extractable soil Si of profile samples at 27, 40 and 56 months

Source of variation	d.f.	27 months		40 months		56 months	
		Depth (cm)					
		0-15	15-30	0-15	15-30	0-15	15-30
Whole plots:							
Replications	2						
pH	2	**					
Error (a)	4						
Subplots:							
Si	2	**	+	**	*	**	**
Si x pH	4						
Error (b)	12						

+ Significant at the 10% level

* Significant at the 5% level

** Significant at the 1% level

concentrations occurred in the 0 to 15 cm depth, sharply lower levels in the 15 to 30 cm horizon, and very low and constant amounts in the deeper layers (Figures 27, 28, and 29). Below 30 cm, Si levels are essentially the same for all Si treatments throughout the experiment. From this it appears that there was no substantial movement of Si beyond 30 cm.

Phosphate-Extractable Si

Exhaustive extraction with phosphate solution removed considerably larger amounts of Si from the higher Si treatments in the 0 to 15 cm layer (Figure 30). More Si was extracted at pH 6.5 than at pH 5.5 and 6.0, which may indicate that less Si was removed by plant uptake or by leaching at this pH. Significantly greater amounts of Si were removed at pH 6.5 than at pH 5.5 and 6.0 in the 0 to 15 cm layer at 56 months (compare 197 ppm Si at pH 6.5 versus 118 and 120 ppm Si at pH 5.5 and 6.0, respectively. See Table 19.) It should be pointed out that phosphate-extractable Si is an index of the amount of Si that remains in the soil in an adsorbed form (capacity factor), while water-extractable Si is a measure of the solution concentration at equilibrium with the soil system (intensity factor). Phosphate extractable Si tends to increase from 9 to 27 months, then decrease gradually to 56 months. The substantial increase in Si values with time at pH 5.5 in the 15 to 30 cm depth is similar to that observed with water-extractable Si.. Distribution of Si in this layer is not proportional to amounts of applied Si,

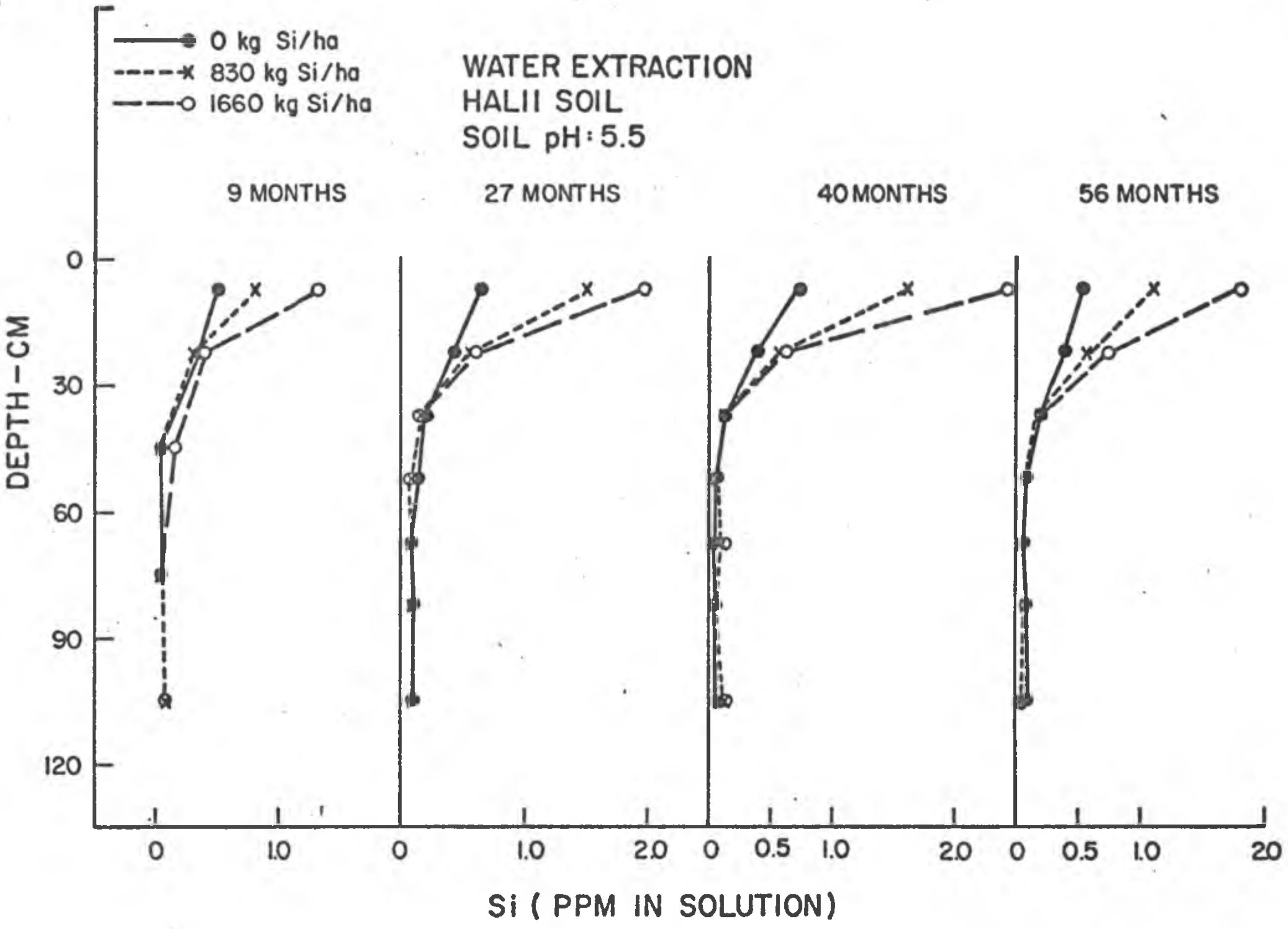

Figure 27. Influence of applied Si on water-extractable soil Si distribution in profiles at pH 5.5 at 4 sampling dates

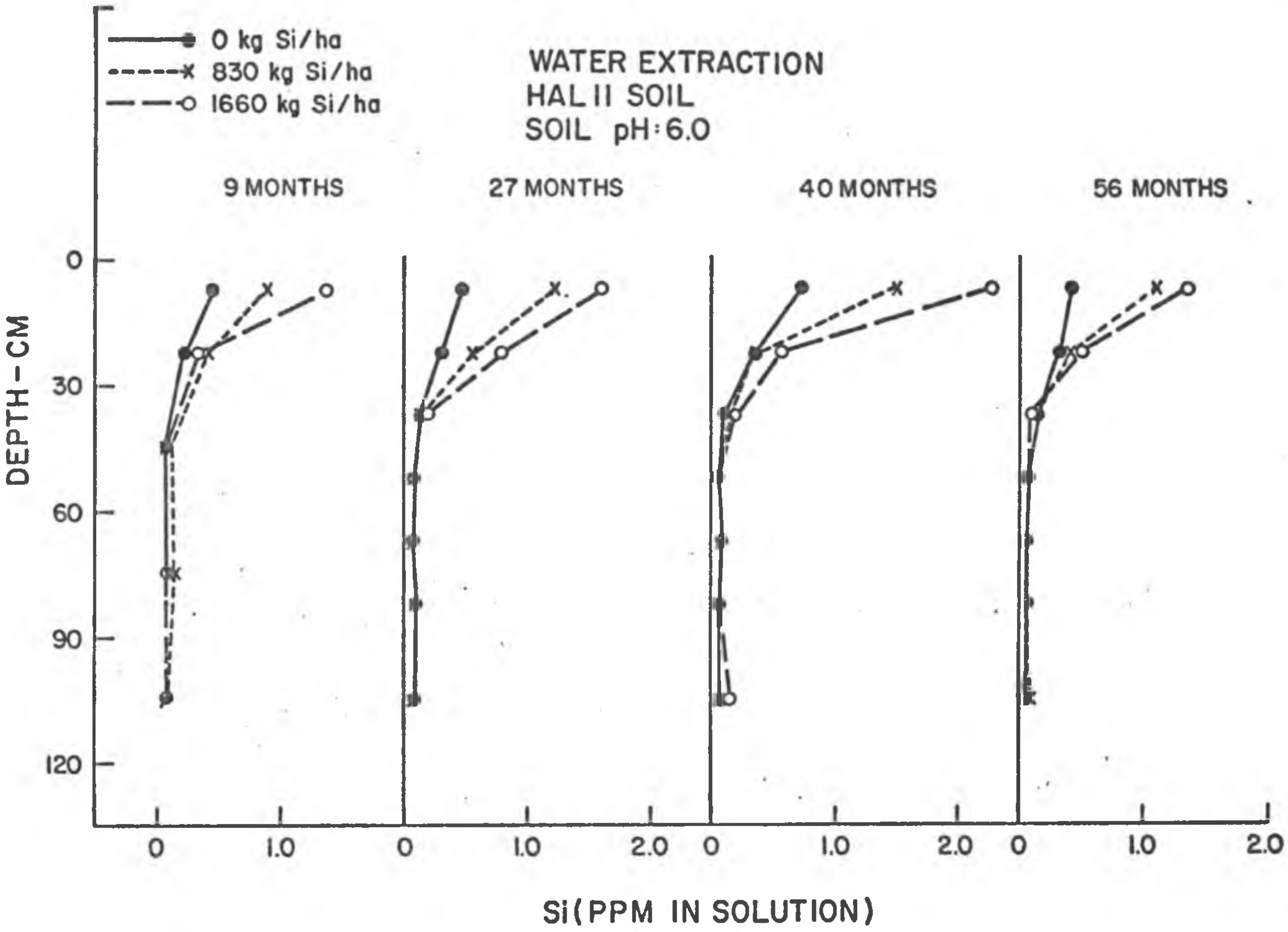

Figure 28. Influence of applied Si on water-extractable soil Si distribution in profiles at pH 6.0 at 4 sampling dates

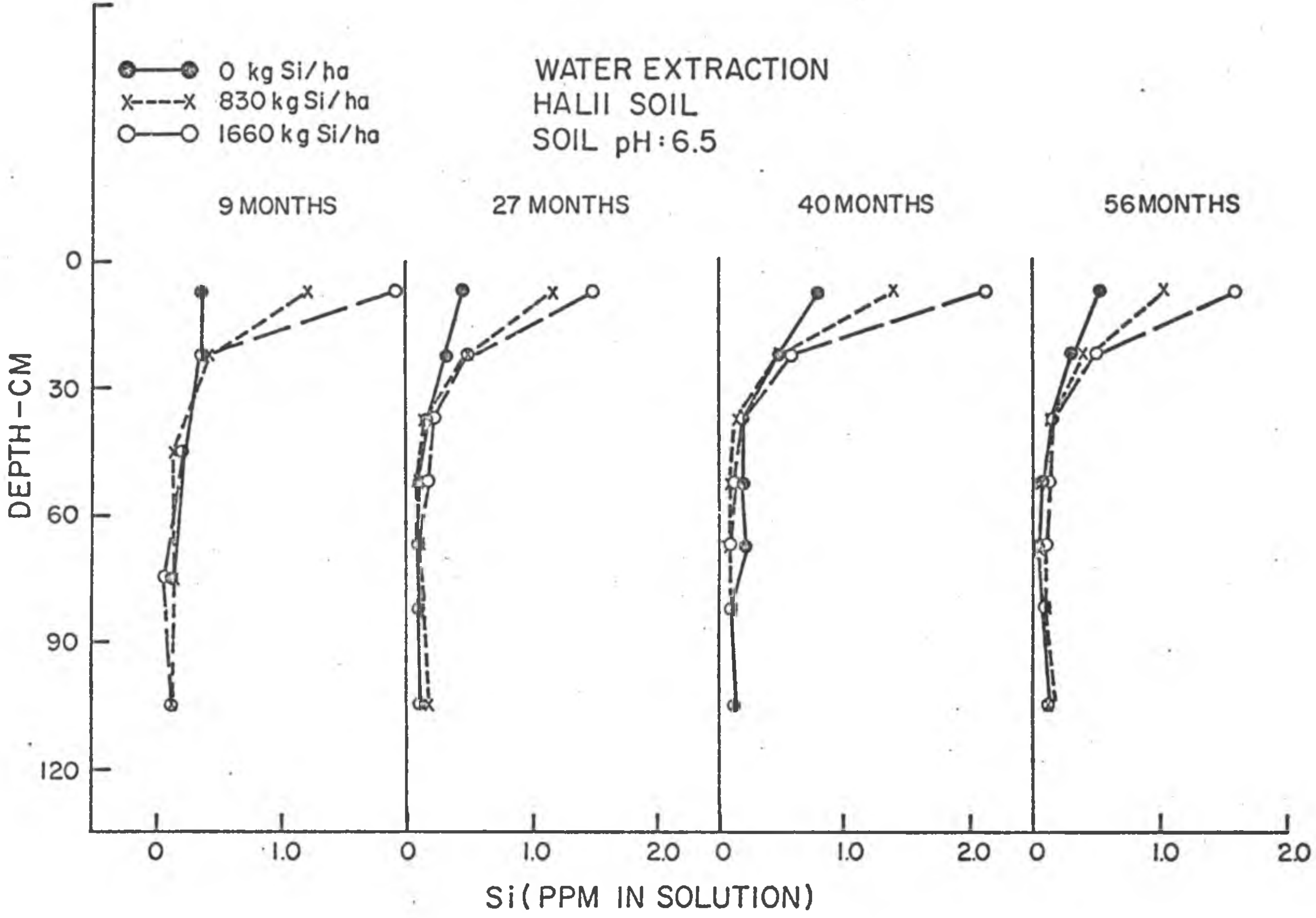

Figure 29. Influence of applied Si on water-extractable soil Si distribution in profiles at pH 6.5 at 4 sampling dates

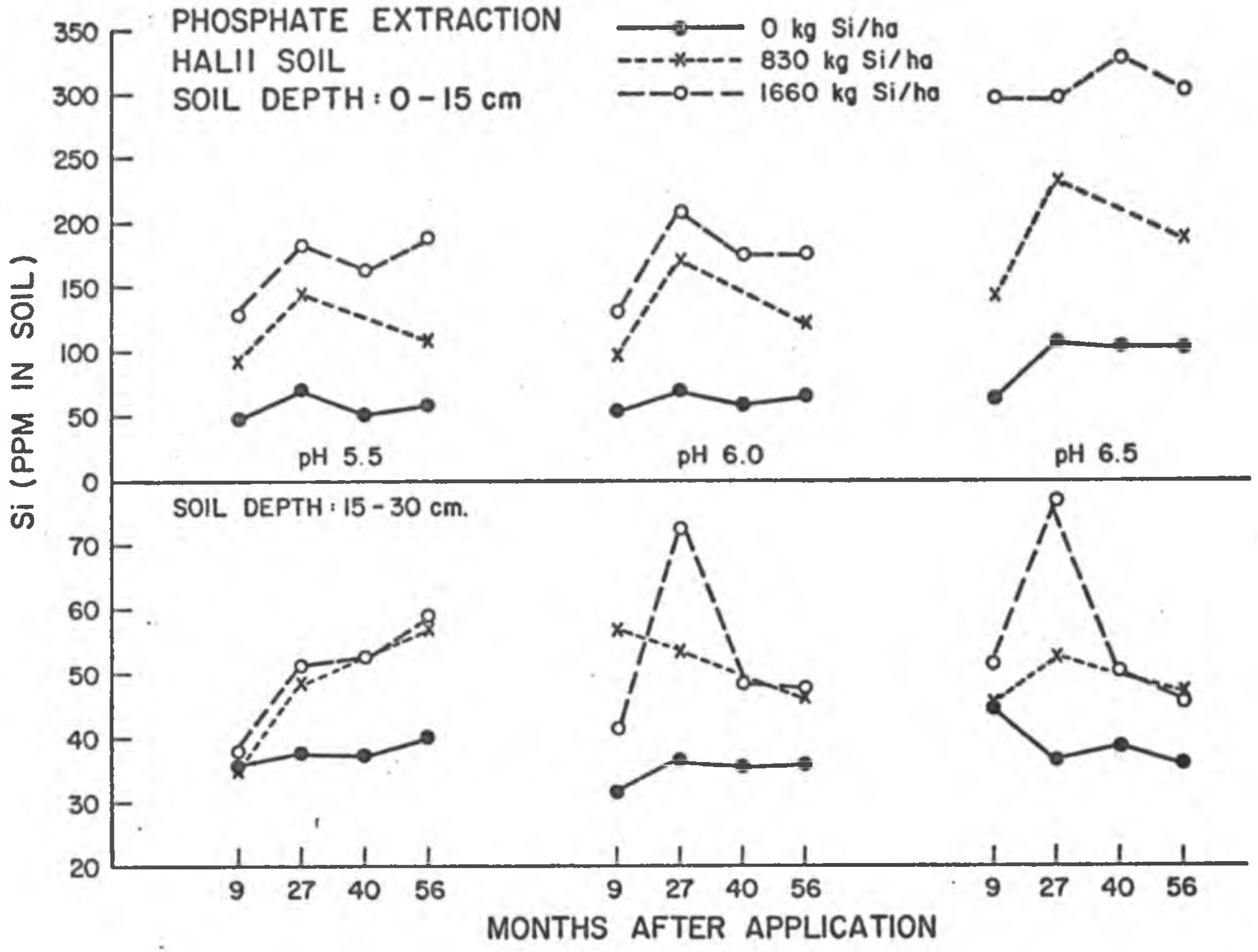

Figure 30. Changes in phosphate-extractable soil Si in the 0-15 and 15-30 cm depths with time as influenced by soil pH and applied Si

Table 19. Summary of F-tests of analysis of variance of phosphate-extractable soil Si of profile samples at 56 months (kikuyu grass sites)

Source of variation	d.f.	Depth (cm)		
		0-15	15-30	30-45
Whole plots:				
Replications	2			**
pH	2	**		*
Error (a)	4			
Subplots:				
Si	2	**	**	
Si x pH	4	*		
Error (b)	12			

* Significant at the 5% level

** Significant at the 1% level

but the zero Si treatment has the lowest value in all pH levels. The Si values in the surface layer are 2 to 3 times those in the 15 to 30 cm horizon (Appendix Tables 78 to 81).

Distribution of phosphate-extractable Si in the profile follows the same pattern shown for water-extractable Si (Figures 31, 32, and 33). Phosphate-extractable Si is concentrated in the 0 to 30 cm depth, and decreases to very low levels below 30 cm. This pattern is consistent at all sampling dates. Residual Si significantly affected extractable Si values only in the top two horizons, at 56 months (Table 19). Levels of extractable Si in the deeper layers were low, and no consistent pattern of Si treatments was apparent.

The distribution of water- and phosphate-extractable Si in the soil profile provides no evidence of leaching of applied Si below 30 cm, during five years cropping even though the experimental site received 1070 cm of rain in that period. Roy (1969) studied Si leaching with some Hawaiian soils in 4-inch soil columns, and found that, in the Gibbsihumox soil, most of the Si applied as $CaSiO_3$ was recovered in the top 2 inches of the column after 70 cm distilled water was percolated through the soil. He also reported that this soil had a high adsorption capacity for Si. In another study related to Si displacement under saturated flow, Roy (1969) concluded that Si movement was greatly affected by pH and the nature of anions present in the displacing solution. He showed that $CaCl_2$ was more effective than water in displacing Si in the

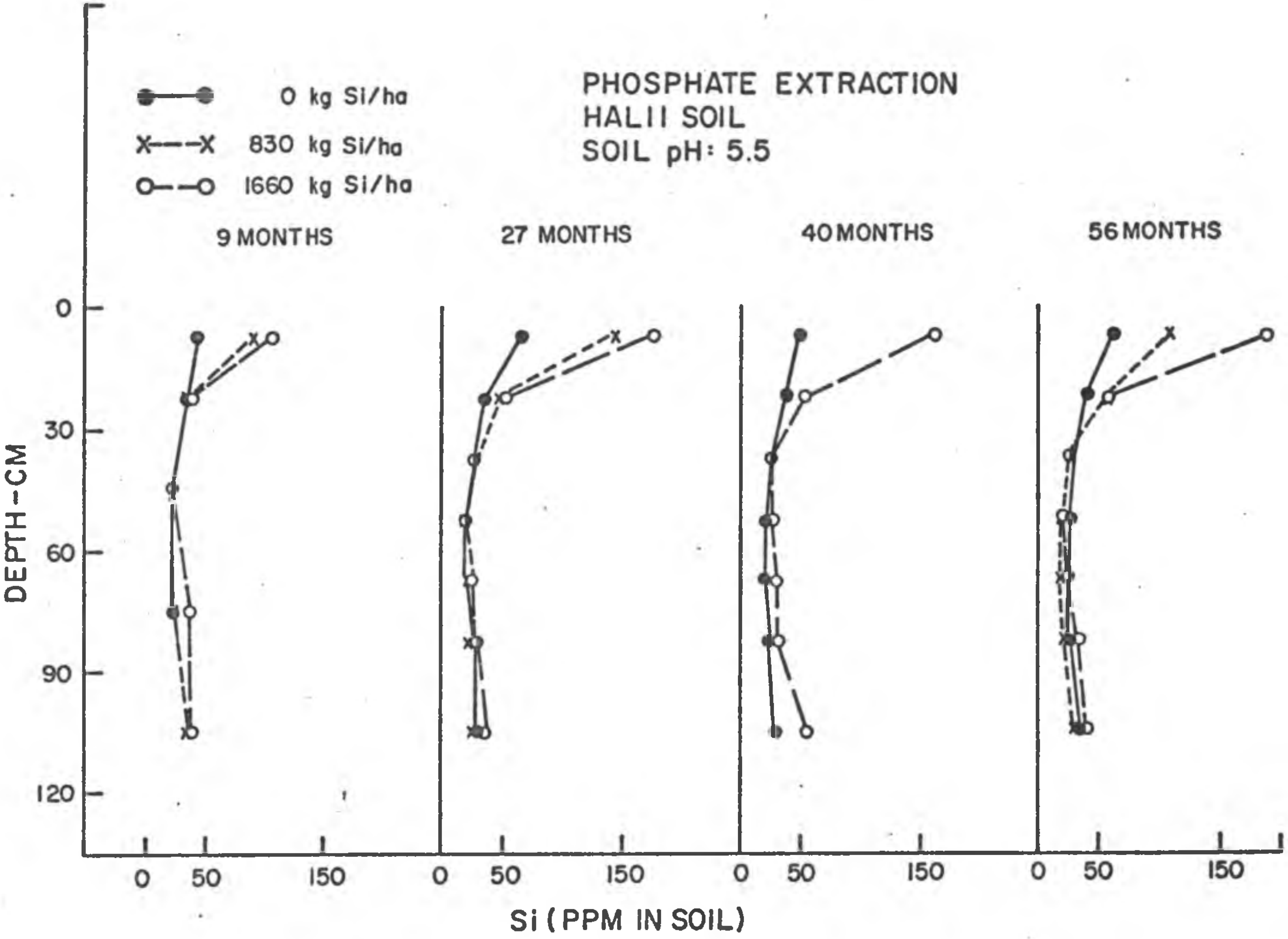

Figure 31. Influence of applied Si on phosphate-extractable soil Si distribution in profiles at pH 5.5 at 4 sampling dates

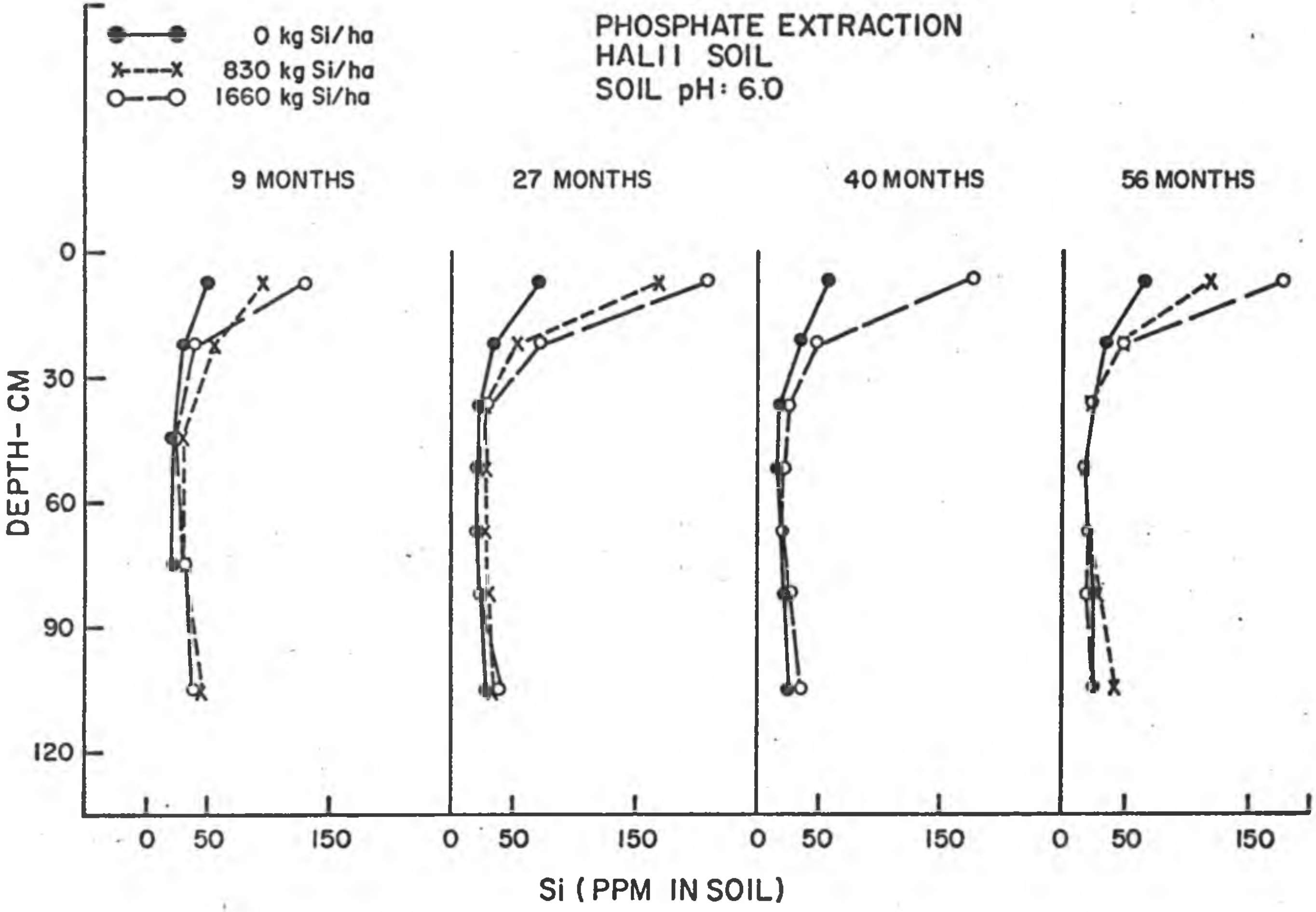

Figure 32. Influence of applied Si on phosphate-extractable soil Si distribution in profiles at pH 6.0 at 4 sampling dates

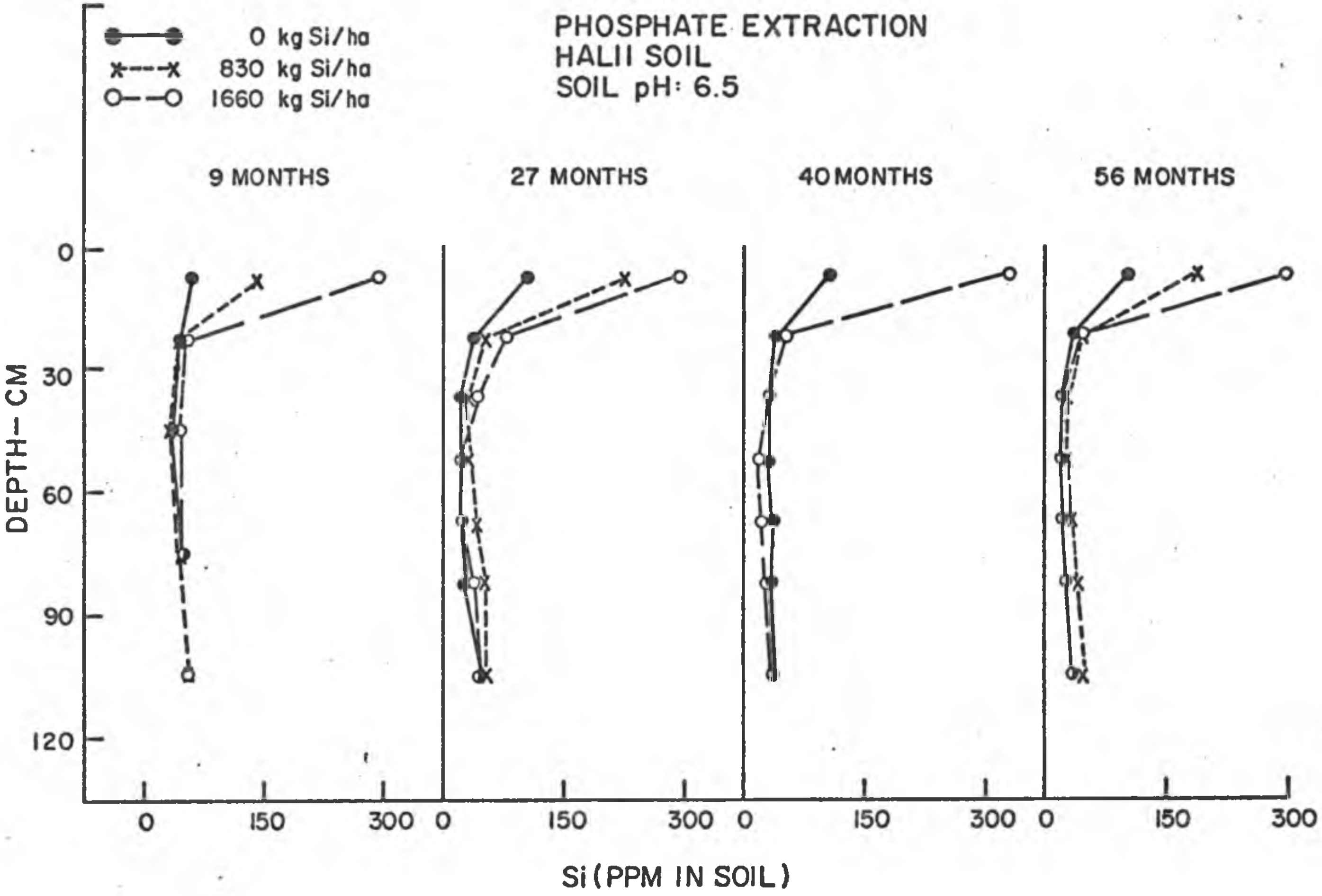

Figure 33. Influence of applied Si on phosphate-extractable soil Si distribution in profiles at pH 6.5 at 4 sampling dates

Gibbsihumox soil. Hagihara (1971) reported a 3% loss of applied silicate, when 95 inches of water were percolated through a 12-inch column of a similar Gibbsihumox soil. He found that most of the Si recovered was present in the top two inches, below which levels increased very slightly. He attributed this phenomenon to the restricted movement and high adsorption of the applied Si. Although the situation in the field with growing plants is more complex, these controlled studies in the laboratory partially support our findings of restricted Si movement in the profile.

Recovery of Applied Si After Five Years of Cropping

An attempt has been made in this section to account for the applied Si recovered by plant uptake during five years of cropping, and that remaining in the soil to a depth of 120 cm at the end of the experiment. Uptake of Si by the sugarcane plant and ratoon crops, corn, and seven harvests of kikuyu grass is summarized in Table 20 for the three pH levels at 280 kg P/ha. It is evident that considerably more Si was taken up by plants in the applied Si treatments at pH 5.5 than at pH 6.5. In the zero Si plots, however, there was little difference in the total Si taken up at pH 5.5 and 6.5 (120 kg versus 118 kg Si/ha). The uptake of Si from calcium silicate was calculated as Si taken up in the 830 and 1660 kg Si treatments minus Si taken up in the zero Si treatment at each pH. The assumption that the amount of Si extracted by plants in the zero Si plots was a measure of native Si

Table 20. Uptake of Si by several crops grown with 280 kg P/ha

Crop	pH 5.5			pH 6.0			pH 6.5		
	Applied Si (kg/ha)								
	0	830	1660	0	830	1660	0	830	1660
Sugarcane (P)	24.5*	68.5	92.1	22.9	57.2	70.3	28.7	49.9	81.3
Sugarcane (R)	25.1	63.8	123.0	21.6	50.1	88.1	29.2	62.4	79.5
Corn	15.4	49.6	55.3	10.7	35.9	49.2	11.4	26.6	33.7
Kikuyu grass (7 harvests)	60.3	115.0	164.0	57.8	83.3	147.0	49.7	104.0	125.0
Total Si uptake	125.0	297.0	434.0	113.0	226.0	354.0	118.0	243.0	320.0
Uptake of applied Si	--	172.0	309.0	--	113.0	241.0	--	125.0	202.0

* Expressed as kg Si/ha

taken up within each pH may not be completely valid, but is the best estimate available under the experimental conditions. The total amount of applied Si recovered by plants ranged from 113 to 172 kg/ha in the 830 Si treatments and 202 to 309 kg/ha in the 1660 Si treatments (Table 21). This means that Si removed by plants during the five years accounted for only 12 to 21% of the applied Si, with the remaining portion still retained by the soil.

Total quantities of applied Si that remain in the soil at the end of the experiment were estimated by exhaustive extraction of Si with phosphate solution as outlined earlier. The amounts of Si recovered from the soil to a depth of 120 cm were combined to include any Si moved from the surface horizon to lower layers. The fraction of Si that originated from calcium silicate was assumed to be the difference between Si values of treatments with added Si and zero Si, calculated for each pH. Total amounts of applied Si recovered ranged from 120 to 232 kg/ha in the 830 Si treatments, and 231 to 413 kg/ha in the 1660 Si treatments (Table 21). Silicon values were higher at pH 6.5 than at pH 5.5. This means that 14 to 28% of the applied Si was recovered by exhaustive phosphate extraction from the profile, with the highest recovery from the 1660 Si treatment at pH 6.5. The relative amounts of applied Si recovered by plants decreased with increasing soil pH, while that extracted from soil increased with increasing pH (Figure 34). This is in agreement with the

Table 21. Balance sheet of Si recovered during five years of cropping

Applied Si (kg/ha)	pH 5.5		pH 6.0		pH 6.5	
	830	1660	830	1660	830	1660
Plant uptake (kg/ha)	172	309	113	241	125	202
Phos.-ext. soil Si (kg/ha)	120	305	194	231	232	413
Total appl. Si recovered (kg/ha)	292	614	307	472	357	615
%	35	37	37	28	43	37
Applied Si unaccounted for (kg/ha)	538	1046	523	1188	473	1045
%	65	63	63	72	57	63

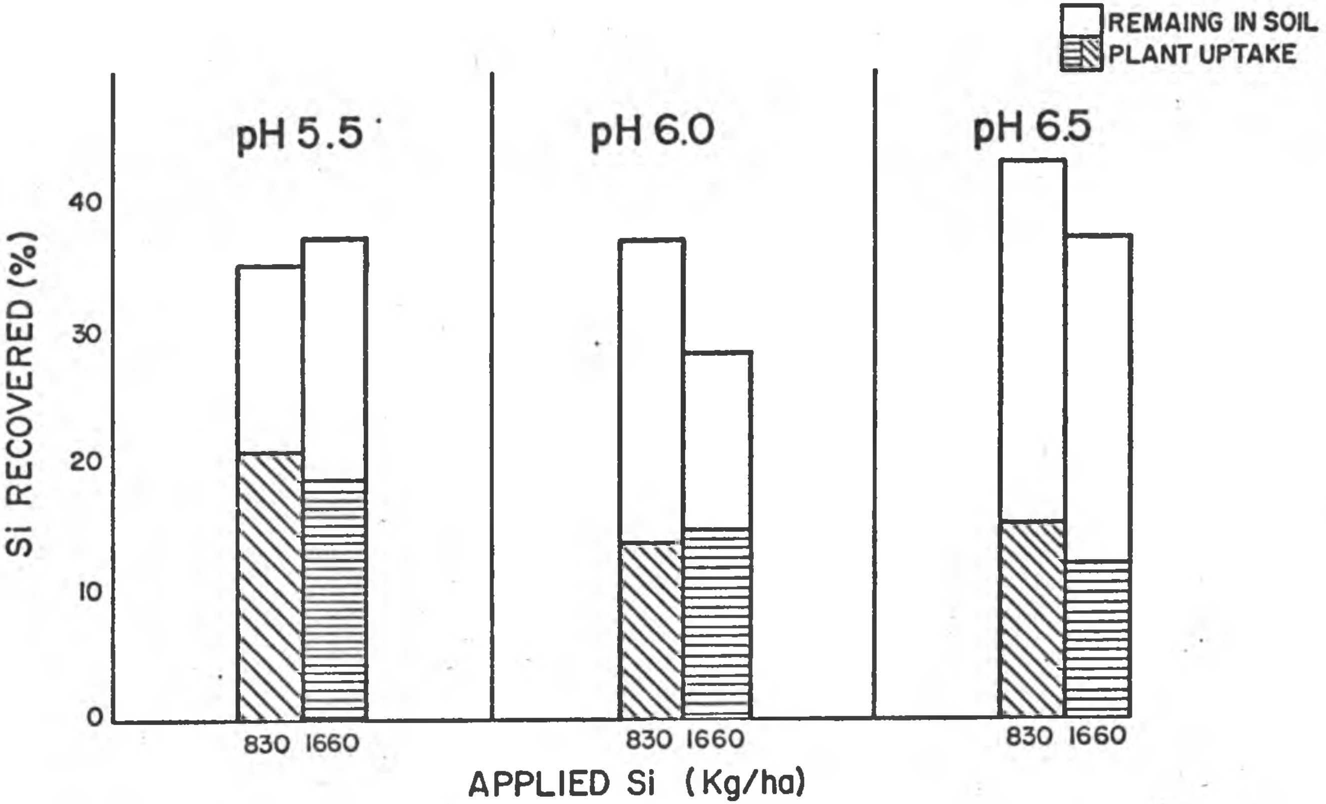

Figure 34. Recovery of applied Si by phosphate extraction and plant uptake at 3 pH levels at the end of 56 months

concept of greater Si solubility at lower pH values which was reflected in the increased uptake by plants at pH 5.5 than at pH 6.5.

The total amount of applied Si recovered by both plant uptake and soil extraction from the 830 Si treatment was higher at pH 6.5 than at pH 5.5 (357 kg/ha versus 292 kg/ha), which was due largely to the relatively larger amount of phosphate-extractable Si removed from the soil (Table 21). In the 1660 Si treatment, the values at both pH 5.5 and 6.5 were the same (615 kg/ha). The fact that the differential uptake of Si at pH 5.5 and 6.5 was counterbalanced by Si extracted from the soil at the highest level of applied Si provides strong evidence against any possibility of Si leaching beyond the 120 cm depth, due to low soil pH. The total recovery of Si ranged from 28 to 43%, which means that 57 to 72% of the Si applied five years ago still exists in the soil in some adsorbed or precipitated form not readily extracted by phosphate solution. Other possible methods for recovering additional amounts of applied Si from the soil include extraction with NaOH (Jackson, 1965) or total Si analysis (Kilmer, 1965) of the soil. These methods are not very promising since the amount of Si applied is very small compared to the total Si in the soil, and thus differentiation between the high background of native soil Si and applied Si would be very difficult.

Soil P

Modified Truog-extractable P (Residual P level 280 kg P) was higher with residual Si treatments than with the zero Si treatment in the 0 to 15 cm layer at all sampling dates (Figure 35, Appendix Tables 82 to 84). This influence of Si on extractable P in the 15 to 30 cm horizon was measurable in the 9-, 27-, and 40-month samples. Figure 35 shows that extractable P in the 0 to 15 cm depth increased sharply from 9 to 27 months and then decreased towards the end of the experiment. This trend was also observed in the 15 to 30 cm depth, but the magnitude of change was small. The effect of Si on P availability was very striking in the 0 to 15 and 15 to 30 cm horizons (Figures 35 and 36) at 40 months and analysis of variance showed this influence to be highly significant (Table 22). The P values were significantly higher with 1660 Si than with zero Si in both 0 to 15 cm (52 ppm vs. 33 ppm P) and 15 to 30 cm layers (10 ppm vs. 7 ppm P). Below 30 cm, in all sampling dates, no effect of Si on extractable P was detected (Figure 36, Appendix Tables 82 to 84). It should be pointed out that in the 9-month samples P analysis was conducted in the 0 to 30 cm horizon only (Roy, 1969). The effect of Si on P availability may be explained as due to: (1) partial saturation of sorption sites by Si thus decreasing P sorption which results in greater P solubility, and (2) inactivation of Fe and Al by the formation of insoluble compounds with Si applied as $CaSiO_3$. Iron and aluminum are known to

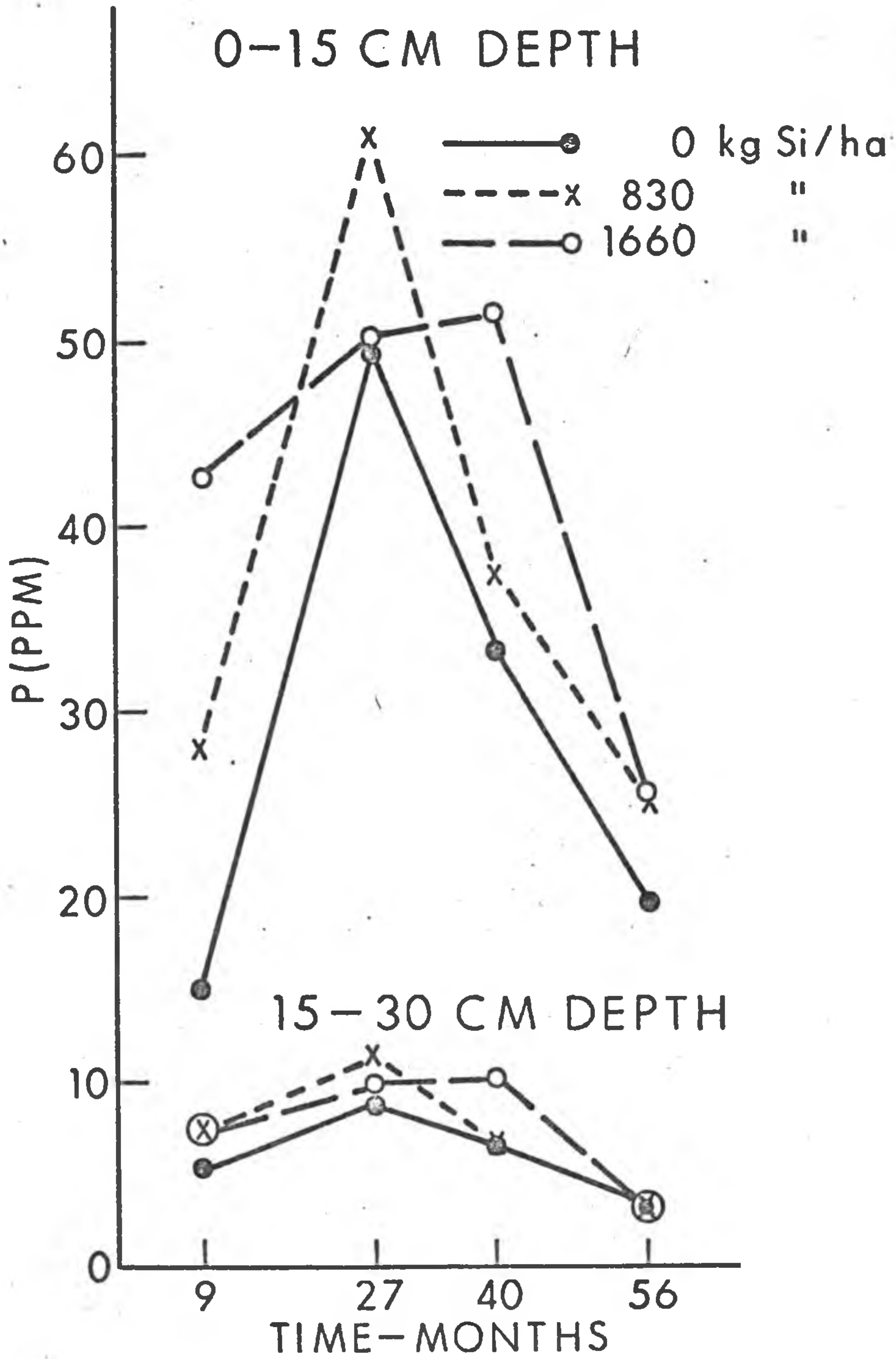

Figure 35. Changes in modified Truog-extractable soil P in the 0-15 and 15-30 cm depths with time as influenced by applied Si

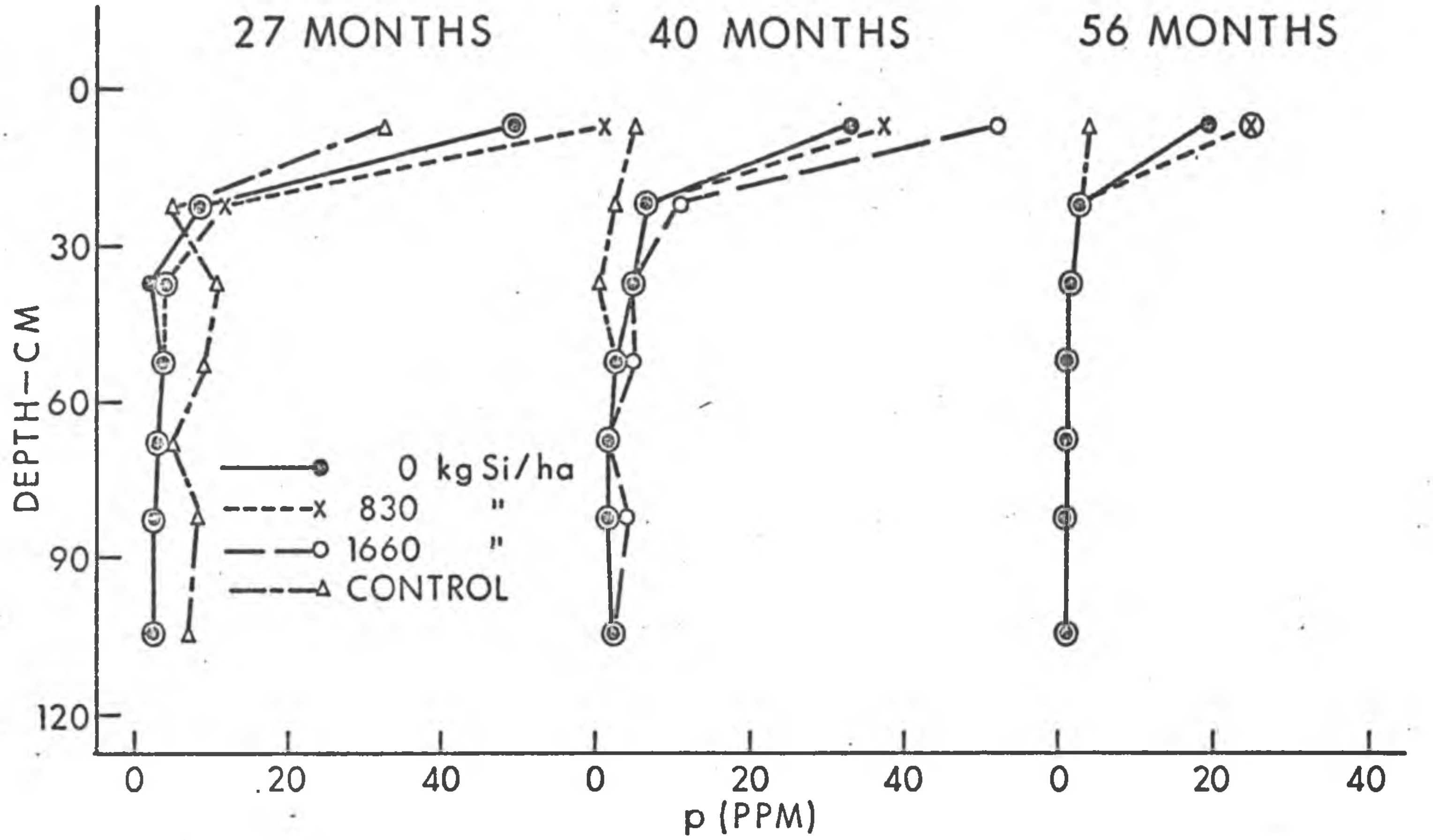

Figure 36. Influence of applied Si on modified Truog-extractable P distribution in profiles at 3 sampling dates

Table 22. Summary of F-tests of analysis of variance of modified Truog-extractable soil P, soil pH and $BaCl_2$-extractable soil Al of profile samples at 27, 40 and 56 months[a]

Source of variation	d.f.	Mod. Truog-ext. P		Soil pH				$BaCl_2$-ext. Al	
		40 months		27 months		56 months		56 months	
		Depth (cm)							
		0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
Whole plots:									
Replications	2								
pH	2			**	*	**	*	**	
Error (a)	4								
Subplots:									
Si	2	**	**		*				*
Si x pH	4		*					*	
Error (b)	12								

[a] Samples collected after corn (27 months) and after kikuyu grass (40 and 56 months)

* Significant at the 5% level

** Significant at the 1% level

form insoluble compounds with P, but Si competition reduces this formation making more P available.

No significant effect of residual soil pH on extractable P was observed throughout the experiment. However, slightly higher P values were observed at pH 6.5 than at pH 5.5 in the 0 to 30 cm horizon at 40- and 56-months (Appendix Tables 82 to 84).

The P data plotted in Figure 36 indicate that P values tended to decrease with time in the 0 to 30 cm horizon and were lowest at the end of the experiment. The following two factors may partially explain this decrease in extractable P with time: (1) The removal of P by continuous cropping decreased labile P in the soil, and (2) slow fixation of added P by Fe and Al compounds in the soil with time. There is no evidence of P movement to lower layers during the five years of cropping (Figure 36). Most of the P was extracted from the surface layer and very little was detected in the 15 to 30 cm horizon. Amounts of extractable P below 30 cm were negligible (less than 2 ppm in the soil). This supports earlier findings of immobilization and restricted movement of applied P in the highly weathered soils of Hawaii (DeDatta _et al_. 1963; Fox _et_ _al_, 1968a; Roy, 1969).

Soil pH

An increase in soil pH in the 0 to 15 and 15 to 30 cm depths with increased treatment pH was observed throughout the period of the experiment (Figure 37). It should be noticed that pH values decreased at 40 months and then increased at 56 months. The increase in soil pH in these horizons due to residual pH was significant for the 27- and 56-month samples (Table 22). Soil pH at 40 months followed trends similar to those at 27 and 56 months (Figure 37, Appendix Tables 86 to 87), but no statistical analyses were performed since replicates were composited for pH determinations. Residual Si increased soil pH in the 15 to 30 cm depths significantly in the 27-month samples where pH of the 1660 Si treatment (5.1) was significantly higher than pH of the zero and 830 Si treatments (4.9 and 4.8, respectively).

The curves plotted in Figure 38 indicate that the pH differential between pH 5.5, 6.0 and 6.5 is clear to a depth of 30 cm. Below 30 cm the pattern is variable although the pH values of treated plots are generally higher than those of the control plot where no liming materials were added. At 27 months the differential between pH 5.5 and 6.5 is visible to a depth of 75 cm while it extends to 90 cm at 40 months. Fifty-six months after the initial pH adjustments were made, pH values were consistently higher at pH 6.5 than at pH 5.5 or 6.0 to a depth of 120 cm.

It is apparent from the above results that the effect of surface applied lime ($CaCO_3$/$CaSiO_3$) on subsoil pH increases with time as shown in Figure 36 for the 56 months samples. The experimental site received about 1070 cm of rain during

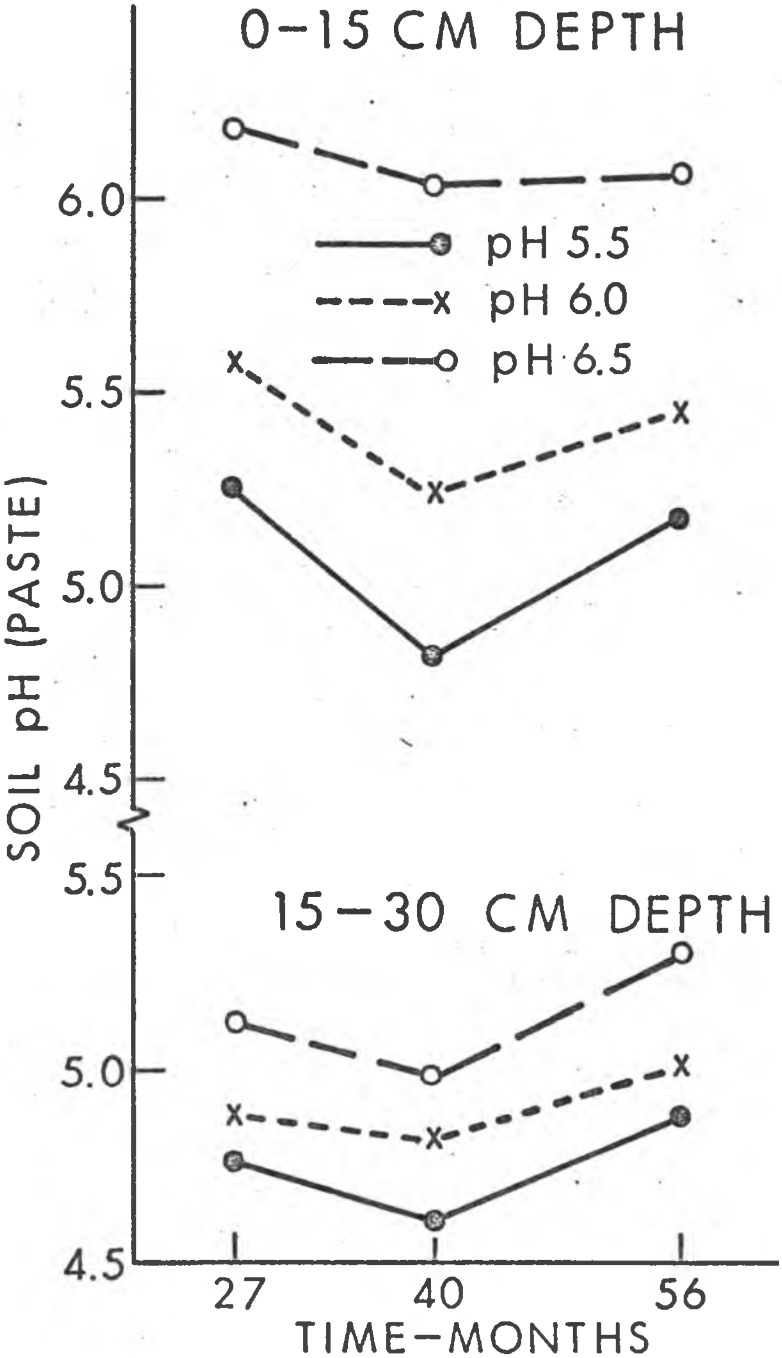

Figure 37. Changes in actual soil pH in the 0-15 and 15-30 cm depths with time after initial pH adjustments

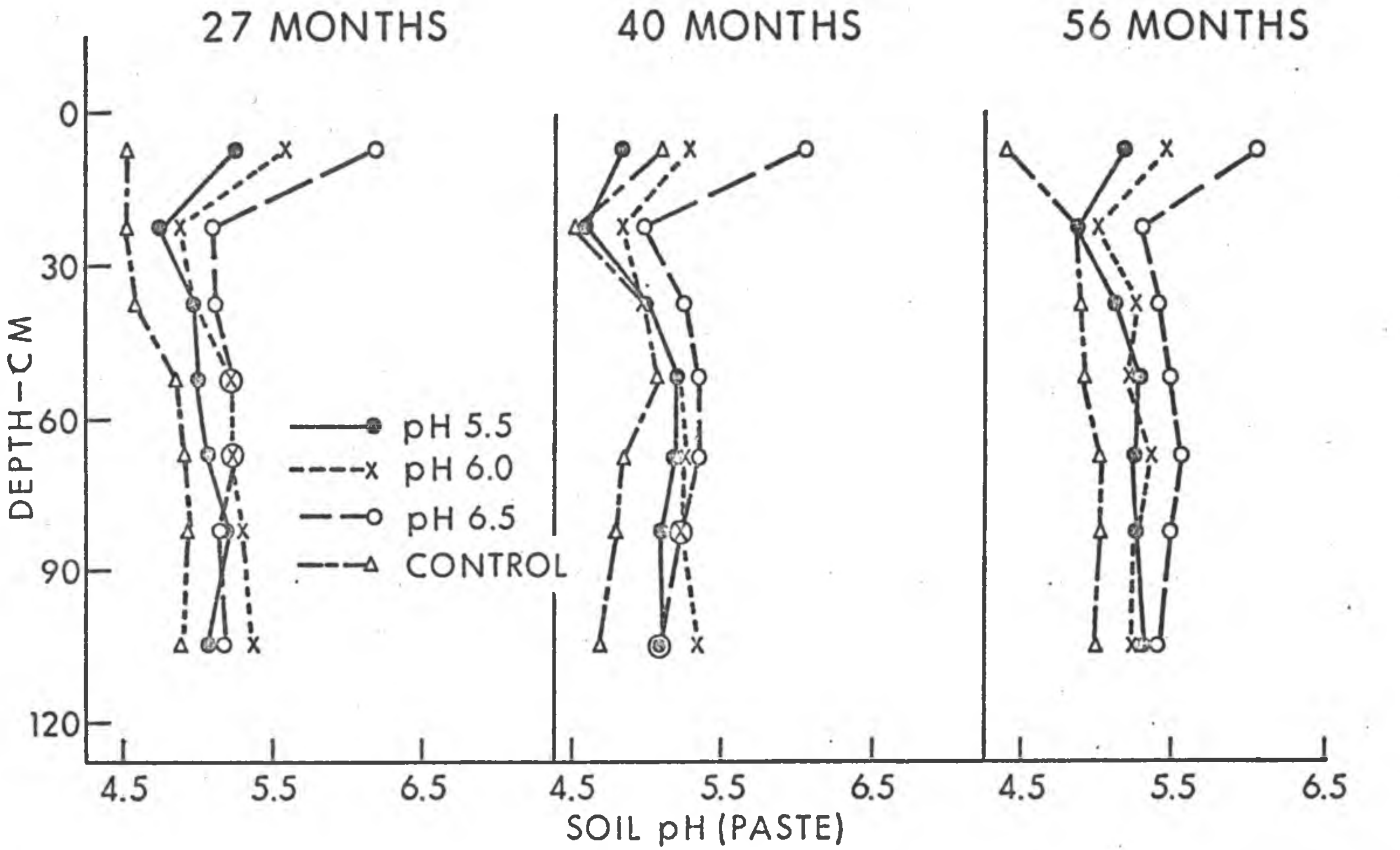

Figure 38. Variation in actual soil pH with depth at three sampling dates after initial pH adjustments

the 56 months cropping period and cations such as Ca from the liming materials were very likely leached into the subsoil resulting in increased pH. Mahilum et al (1970) reported leaching of Ca in a hydrandept which increased pH of the lower horizons.

It must be noted that pH values decreased sharply in the 15 to 30 cm depth and then increased slowly in the lower horizons (Figure 38, Appendix Tables 85 to 87). This phenomenon was observed at all pH levels throughout the experiment. Apparently more of the liming materials reacted with the surface soil and less moved to lower layers. Also, the high density of plant roots in the 15 to 30 cm horizon removed substantial amounts of cations, including Ca, and in addition roots produce carbonic acid which increases soil acidity. This low pH in the 15 to 30 cm depth greatly increased Al solubility which will be discussed in the following section.

Soil Al

Barium chloride-extractable soil Al decreased with increasing soil pH and the differential was very noticeable in the 0 to 15 and 15 to 30 cm depths at all sampling dates (Figure 39, Appendix Tables 88 to 90). Extractable soil Al increased with time at pH 5.5 and 6.0 in the 0 to 15 cm depth while values at pH 6.5 decreased to less than 1 ppm at the end of 56 months. In the 15 to 30 cm depth extractable Al decreased with time at pH 5.5 while it increased at pH 6.0 and 6.5.

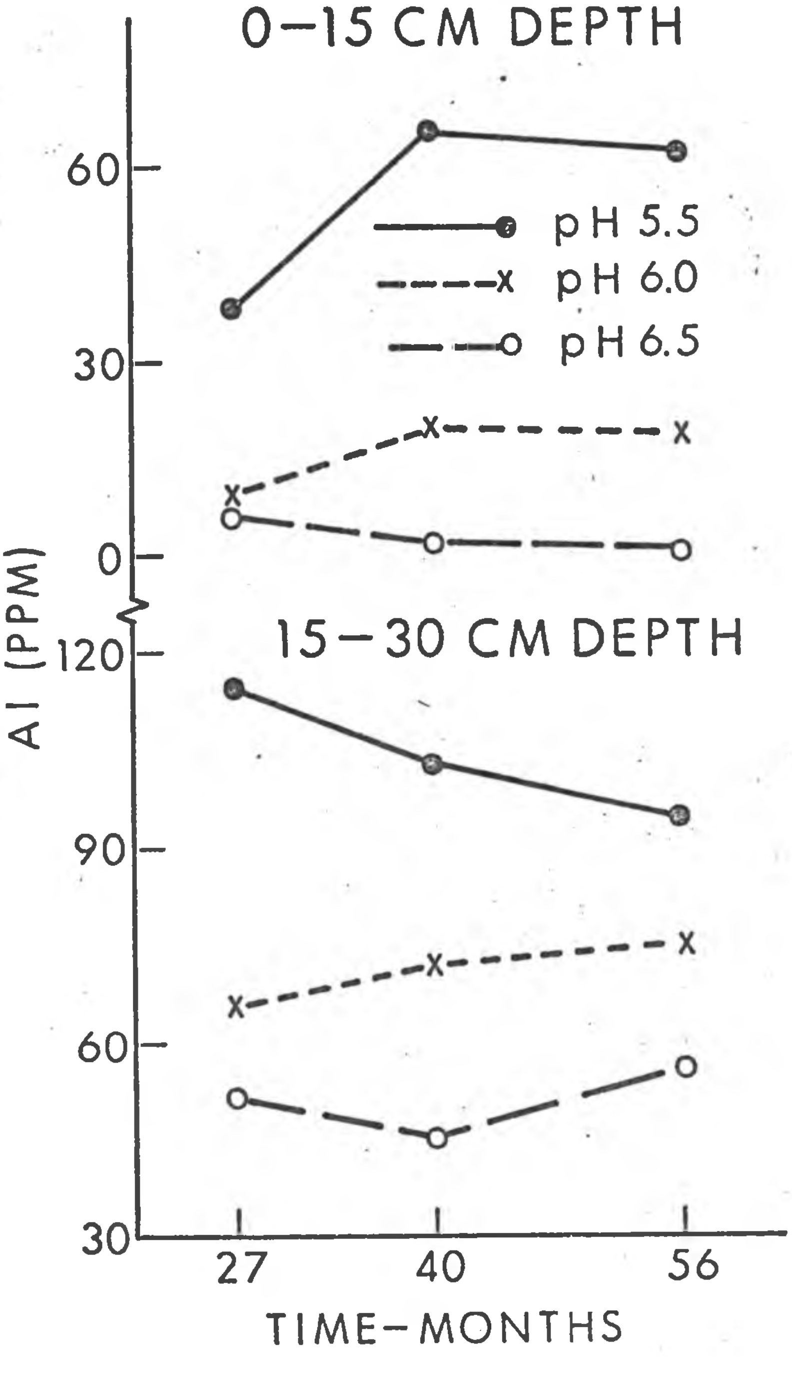

Figure 39. Changes in $BaCl_2$-extractable soil Al in the 0-15 and 15-30 cm depths with time as influenced by soil pH .

Soil Al increased very sharply for all pH levels in the 15 to 30 cm horizon where Al concentrations ranged from 35 to 126 ppm compared to a range of 1 to 92 ppm in the 0 to 15 cm horizon (Figure 40, Appendix Tables 88 to 90). As mentioned earlier, soil pH values in the 15 to 30 cm layer were the lowest in the profile. On the other hand, in the control plot where no lime had been applied, extractable Al values in the 15 to 30 cm horizon were about one-third of those in the 0 to 15 cm layer (Figure 40). It is possible that due to the absence of liming material or very low Ca in the 15 to 30 cm horizon in the treated plots, Al activity remained high resulting in higher extractable Al values than in the surface layer. High concentrations of extractable Al may have been detrimental to root growth in this region, but this phenomenon was not investigated.

Increased soil pH reduced extractable Al to a depth of 45 cm (Figure 40). Concentrations of Al in lower horizons of limed plots as well as of control plot were less than 5 ppm in the soil in spite of the fact that pH ranged from 4.7 to 5.4. The subsoil consists of a high percentage of iron oxide concretions and the weathered material in this part of the profile does not have appreciable quantities of extractable Al.

Residual Si treatments had no significant effects on soil Al in the 0 to 15 cm layer, but had a significant effect on Al in the 15 to 30 cm horizon in samples collected at the

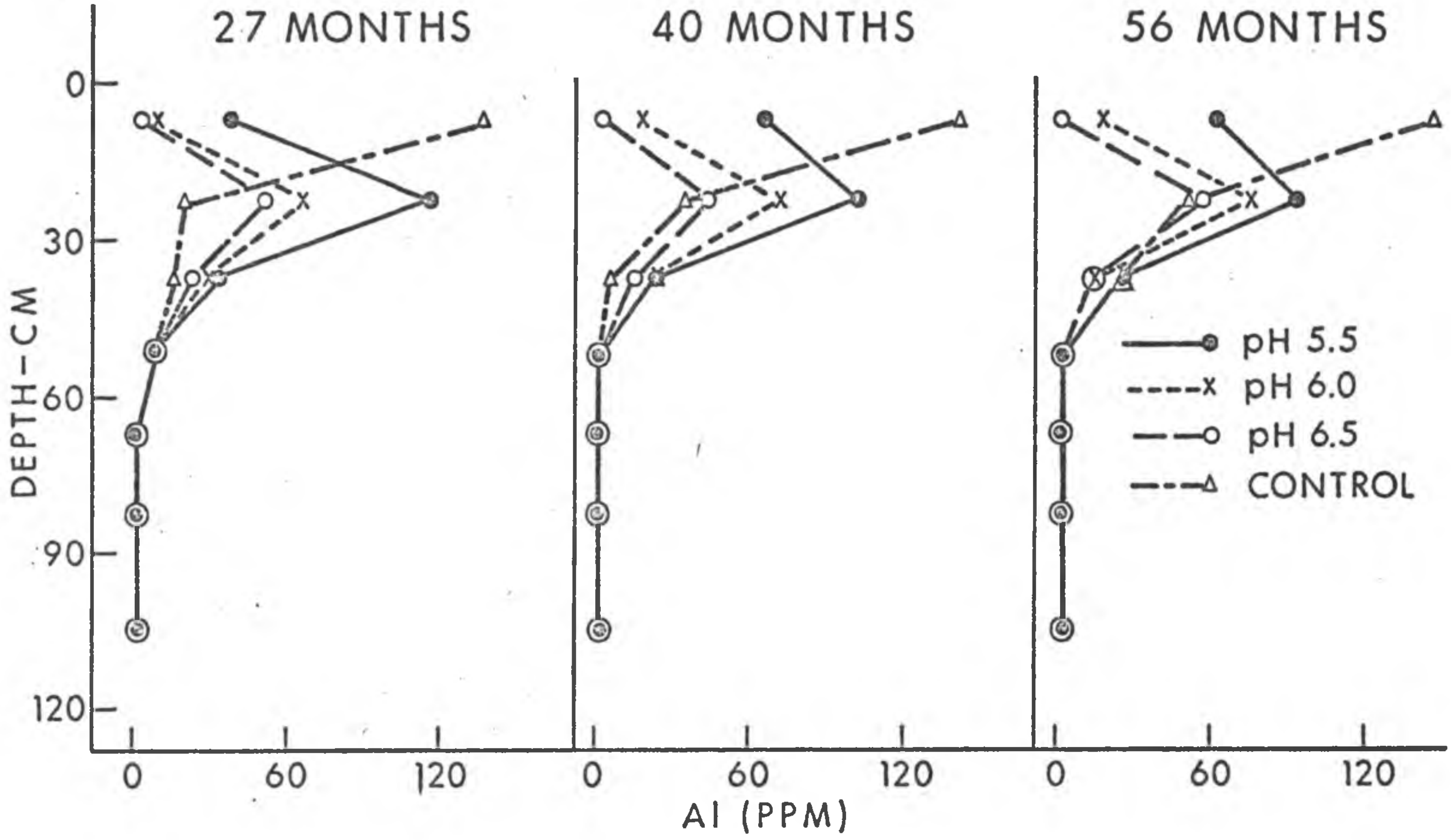

Figure 40. Influence of soil pH on $BaCl_2$-extractable soil Al distribution in profiles at 3 sampling dates

end of the experiment (56 months) (Figure 41, Table 22). Aluminum values in the 830 kg Si treatments were significantly lower than those from zero Si (60 ppm vs. 94 ppm Al in soil, respectively) (Figure 41, Appendix Table 90). It should be noted that the effect of Si on soil Al was more pronounced at pH 5.5 and 6.0 than at pH 6.5 and this extended to a depth of 45 cm. Below 45 cm there was very little Al that could be extracted with unbuffered $BaCl_2$ solution.

The decrease in extractable Al due to silicate applications may be due to the formation of insoluble aluminosilicates in the soil or to precipitation of Si on hydrated Al oxides. The effect of $CaCO_3$ is mainly precipitation of Al as oxides or hydroxides due to increased soil pH. These results show that Al toxicity in plants grown on highly weathered soils rich in Al may be effectively reduced by $CaCO_3/CaSiO_3$ applications, but that the liming material should be mixed with the top 30 cm layer instead of only 15 cm to insure greater reduction in Al solubility.

Conclusions

Water-extractable soil Si in the 0 to 15 cm layer increased significantly with increasing levels of residual Si in samples collected 27, 40 and 56 months after initial $CaSiO_3$ applications. In the 15 to 30 cm layer the effect of residual Si on water-extractable Si was significant at the 10% level at 27 months, at the 5% level at 40 months, and at

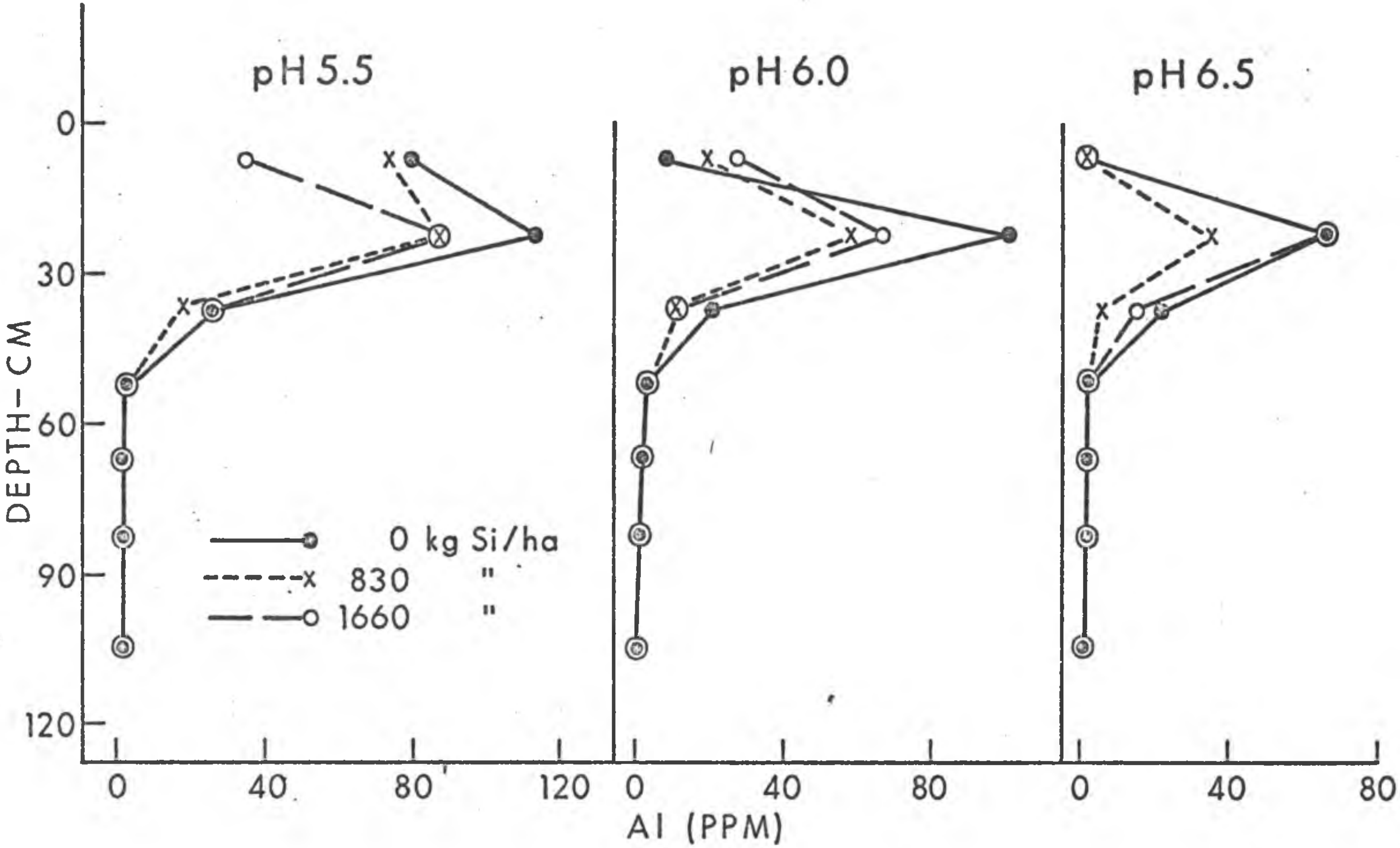

Figure 41. Influence of residual Si on $BaCl_2$-extractable Al distribution in profiles at 3 pH levels at 56 months

the 1% level at 56 months. This means that some Si moved to the 15 to 30 cm depth with time. More Si leached from the surface to the 15 to 30 cm depth at pH 5.5 and 6.0 than at pH 6.5 because Si solubility is higher at lower pH levels. Below 30 cm, Si levels were essentially the same for all Si treatments throughout the experiment which indicates that there was no substantial Si movement below 30 cm.

Distribution of phosphate extractable Si in the profile followed the same pattern as water-extractable Si. Residual Si significantly increased phosphate-extractable Si levels only in the top two horizons at 56 months. Levels of phosphate-extractable Si below the 30 cm depth were very low and no consistent pattern with Si treatments was apparent indicating applied Si did not leach below 30 cm. More Si was extracted with phosphate solution at pH 6.5 than at pH 5.5 and 6.0 in the 0 to 15 cm layer at the end of the experiment. This implies that less Si was removed by plant uptake or by leaching at pH 6.5 and that phosphate-extractable Si is an index of Si remaining in the soil in some fixed form and thus is a measure of the Si-supplying capacity of the soil.

Plant uptake by the sugarcane plant and ratoon crops, corn, and seven harvests of kikuyu grass accounted for 12 to 21% of the applied Si. Exhaustive phosphate extraction of profile samples taken at the end of five years recovered 14 to 28% of the applied Si. Total recovery of applied Si ranged from 28 to 43% which means that 57 to 72% of the applied Si remained in the soil in some form not readily displaced by phosphate solution.

Phosphorus solubility was markedly increased by Si treatments in the 0 to 15 cm horizon throughout the experiment, but in the 15 to 30 cm horizon this affect diminished toward the end of the experiment. The amounts of modified Truog-extractable P below 30 cm were negligible and Si treatments had no effect on P levels.

The pH differentials between pH 5.5, 6.0, and 6.5 were apparent to a depth of 30 cm below which the pattern was variable although pH values of treated plots were generally higher than those of the control plot where no liming materials had been added. Soil pH decreased sharply in the 15 to 30 cm depth and then increased slowly in the lower horizons. This phenomenon was observed during the entire cropping period. Increased soil pH reduced $BaCl_2$-extractable soil Al to the 45 cm depth and Al concentrations in the lower horizons were very low and unaffected by pH treatments. Barium chloride-extractable Al increased very sharply in the 15 to 30 cm horizon at all pH levels due to the low pH of this layer. This suggests the need to mix liming materials to a depth of 30 cm to insure greater reduction in Al solubility.

III. UPTAKE OF RESIDUAL SILICON FROM THE HALII SOIL BY RICE (*Oryza sativa* L.)

Soil profile studies (Section II) showed that five years after silicate application, the bulk of the applied Si remained in the top 30 cm of soil in a form not readily displaced by phosphate solutions. Whether this so-called "fixed" Si becomes available to plants slowly is not known. The objective of this study was to measure the amount of Si extracted by rice plants from a small volume of soil and compare this with the amount of Si removed by exhaustive phosphate extraction.

Materials and Methods

Soil profile samples collected after five years of cropping from kikuyu plots (Section II) were used. The three replicates of the Si x pH combination for 0 to 15 cm depths were composited. Eight grams of shredded filter paper were spread at the bottom of an 11 x 11 x 7 cm plastic container. Fifty grams of soil (oven dry basis) were evenly distributed on top of the filter paper, and 100 seeds of rice, variety IR-8, were scattered over the soil and 25 ml of Hoagland's solution added. Seeds were covered with 4 grams of shredded filter paper and enough distilled water was added to saturate the filter paper and bring the water content to 50% of the soil weight. Filter paper was used as a water reservoir and to reduce evaporation from the soil surface.

Experimental Procedure

The plastic containers containing soil and seeds were covered with plastic lids and transferred to a growth chamber with controlled light and temperature. The containers were kept under constant darkness until emergence. After emergence, the growth chamber was adjusted for a 16 hour light period and an 8 hour dark period, with $80 \pm 2^{\circ}$ F day temperature and $70 \pm 2^{\circ}$ F night temperature. The plants were watered with distilled water frequently and the containers weighed once a day to maintain a constant moisture. Additional applications of N, P, K, Ca, and Fe were made to insure continued growth (Table 23).

A randomized complete block design was used with three residual Si treatments (0, 830, and 1660 kg Si/ha), three pH levels (5.5, 6.0, and 6.5) and two soil depths (0 to 15 and 15 to 30 cm). The treatments were replicated three times. A control treatment with no soil was also included in each replication to allow for correction of Si impurities in the filter paper and seed Si. The containers within a replicate were rotated every two days to minimize temperature or light gradients in the chamber.

Harvest and Plant Analysis

After 10 weeks of growth (one replication was harvested after 8 weeks), plants were cut about 0.5 cm above the surface, rinsed in distilled water and dried in the oven at 70° F. The

Table 23. Source, rate and schedule of fertilizer application to rice

Element	Rate of application ppm soil									Source*
	Days after planting				Days after first harvest					
	Pre-planting	18	34	41	4	19	33	47	61	
N	238.00	95.0	95.0	190.0	238.00	238.0	95.0	95.0	190.0	KNO_3, $Ca(NO_3)_2 \cdot 4H_2O$, $(NH_4)_3PO_4$
P	62.00	25.0	25.0	50.0	62.00	62.0	25.0	25.0	50.0	$(NH_4)_3PO_4$
K	470.00	188.0	188.0	396.0	470.00	470.0	188.0	188.0	188.0	KNO_3
Ca	120.00	48.0	48.0	96.0	120.00	120.0	48.0	48.0	48.0	$Ca(NO_3)_2 \cdot 4H_2O$
Fe	2.20	0.9	0.9	0.9	2.20	0.9	0.9	0.9	0.9	$FeSO_4$, Fe-chelate
Mg	48.00				48.00					$MgSO_4 \cdot 7H_2O$
S	64.00				64.00					$MgSO_4 \cdot 7H_2O$
B	2.86				2.86					H_3BO_3
Mn	1.31				1.31					$MnCl_2 \cdot 4H_2O$
Cu	0.08				0.08					$CuSO_4 \cdot 5H_2O$
Zn	0.22				0.22					$ZnSO_4 \cdot 7H_2O$
Mo	0.18				0.18					$Na_2MoO_4 \cdot 2H_2O$
ml solution**	25	10	10	20	25	25	10	10	20	

* Chemicals used were A.R. grade

** Solution concentration used = 2 x ppm soil plant material was ground in a stainless steel Wiley mill and analysed for Si (see Appendix A for methods). A ratoon crop was grown for another 10 weeks and processed similarly for Si analysis. The fertilizer schedule for the ratoon crop is given in Table 23.

Results and Discussion

Results of the uptake of residual Si by rice in the growth chamber study will be discussed in the following order: (1) yield, (2) silicon uptake, and (3) comparison of silicon extracted by phosphate solution and by plants.

Yield

Dry matter yields of plant and ratoon crops of rice were not influenced by residual Si treatments (Appendix Table 92). It is likely that residual Si levels in the soil were not high to affect plant growth directly or indirectly. As mentioned previously there had been no response to residual Si treatments by the preceding crops of kikuyu grass and desmodium in the field (Appendix Tables 8 and 16). Response to Si applications by rice has been reported in the literature (Mitsui and Takatoh, 1963; Okuda and Takahashi, 1964). Dry matter yield was reduced by increasing soil pH in both plant and ratoon crops grown on soil collected from the 0 to 15 cm horizon (Appendix Table 92). Rice grown on soil of the 15 to 30 cm horizon showed no yield depression with increasing pH. It should be pointed out that in the surface soil, the reduction in plant growth at pH 6.5 became apparent when the seedlings emerged and the effect persisted through plant and ratoon crops.

Yield of the plant crop was about 3 times higher than that of the ratoon crop, but there was a small difference between plants grown on soil from the 0 to 15 and 15 to 30 cm horizons. Not all plants started growing after the plant crop was harvested and growth was slow; this resulted in lower dry matter production in the ratoon crop. It should be noted that growth chamber conditions were not ideal for maximum plant growth, and plants in both plant and ratoon crops were chlorotic, even though nutrient solution was applied every two weeks or so (Table 23).

Silicon Uptake by Rice

Whole-plant Si concentrations increased markedly with increasing residual Si treatments in both plant and ratoon crops grown on soil from the 0 to 15 cm depth (Appendix Table 92). Residual Si treatments increased Si concentrations in rice grown on soil from the 15 to 30 cm horizon only slightly, and the increase was not proportional to the applied Si treatments. Increasing soil pH increased Si concentrations in both plant and ratoon crops in the 0 to 15 cm horizon. This differential was more striking in the ratoon crop than in the plant crop (compare 0.19, 0.30, and 0.86% Si in the ratoon with 0.17, 0.19, and 0.35% Si in the plant crop at pH

5.5, 6.0 and 6.5, respectively). In the 15 to 30 cm horizon, whole-plant Si concentrations were not influenced by soil pH in the plant crop, but in the ratoon crop, Si concentration increased with increasing pH (0.15, 0.17, and 0.20% Si). The ratoon crop had higher Si concentrations than the plant crop, probably because plant growth was reduced in the ratoon. Whole-plant silicon concentrations ranged from 0.07 to 0.44% in the plant crop, and 0.12 to 1.18% in the ratoon crop. Thiagalingam (1971) reported that 0.36 to 0.77% Si in the whole-plant were inadequate for normal growth of rice. In the present study, the levels were generally low, with the exception of one value (1.18% Si in the 1660 Si treatment at pH 6.5 in the ratoon crop), which was exceptionally high, due to the very low dry weight.

Rice plants removed larger quantities of Si from soil which had received Si treatments than from untreated soil, and this trend was present in both plant and ratoon crops (Appendix Table 93). The Si differential between the 830 and 1660 Si treatments was relatively small and not always proportional to the amounts initially applied. Greater amounts of Si were removed at pH 6.5 than at pH 5.5 in both crops. Quantities of Si extracted by the plant crop were generally higher than those extracted by the ratoon crop, which is in contrast to Si concentration which was higher in the ratoon than in the plant crop. Within each crop, plants accumulated more Si from soil of the 0 to 15 cm depth than from soil of the 15 to 30 cm depth, and the magnitude of the difference was greater at pH 6.5 than at 5.5.

Total amounts of Si removed from the 0 to 30 cm depth by plant and ratoon crops combined were substantially greater at pH 6.5 than at pH 5.5 and 6.0 (compare 688 kg/ha at pH 6.5 with 406 and 443 kg/ha at pH 5.5 and 6.0, respectively) (Appendix Table 93). As discussed in Section II, more Si was taken up at pH 5.5 than at pH 6.5 by crops grown during five years of the field experiment (see Table 20 for uptake data). In the field, higher Si solubility at low soil pH was responsible for greater Si uptake at pH 5.5 than at pH 6.5. However, in the present study, plant uptake of Si was more closely related to phosphate-extractable Si levels, which reflect the amount of Si adsorbed by the soil complex (Appendix Table 93). Total Si uptake by rice plants increased with increasing levels of residual Si at all pH levels. However, the difference in Si uptake between the 830 and 1660 Si treatments at pH 6.0 and 6.5 was comparatively small.

The rate of Si uptake from soil by rice was estimated by calculating the amount of Si extracted per day per gram of oven dry soil and it was found that the rate of Si uptake decreased with time. It is clear from Figure 42 that Si uptake decreased sharply with time, and the differential between Si treatments and zero Si became small at the end of 20 weeks in the 0 to 15 cm depth. This pattern is similar to that attained with successive extraction with phosphate

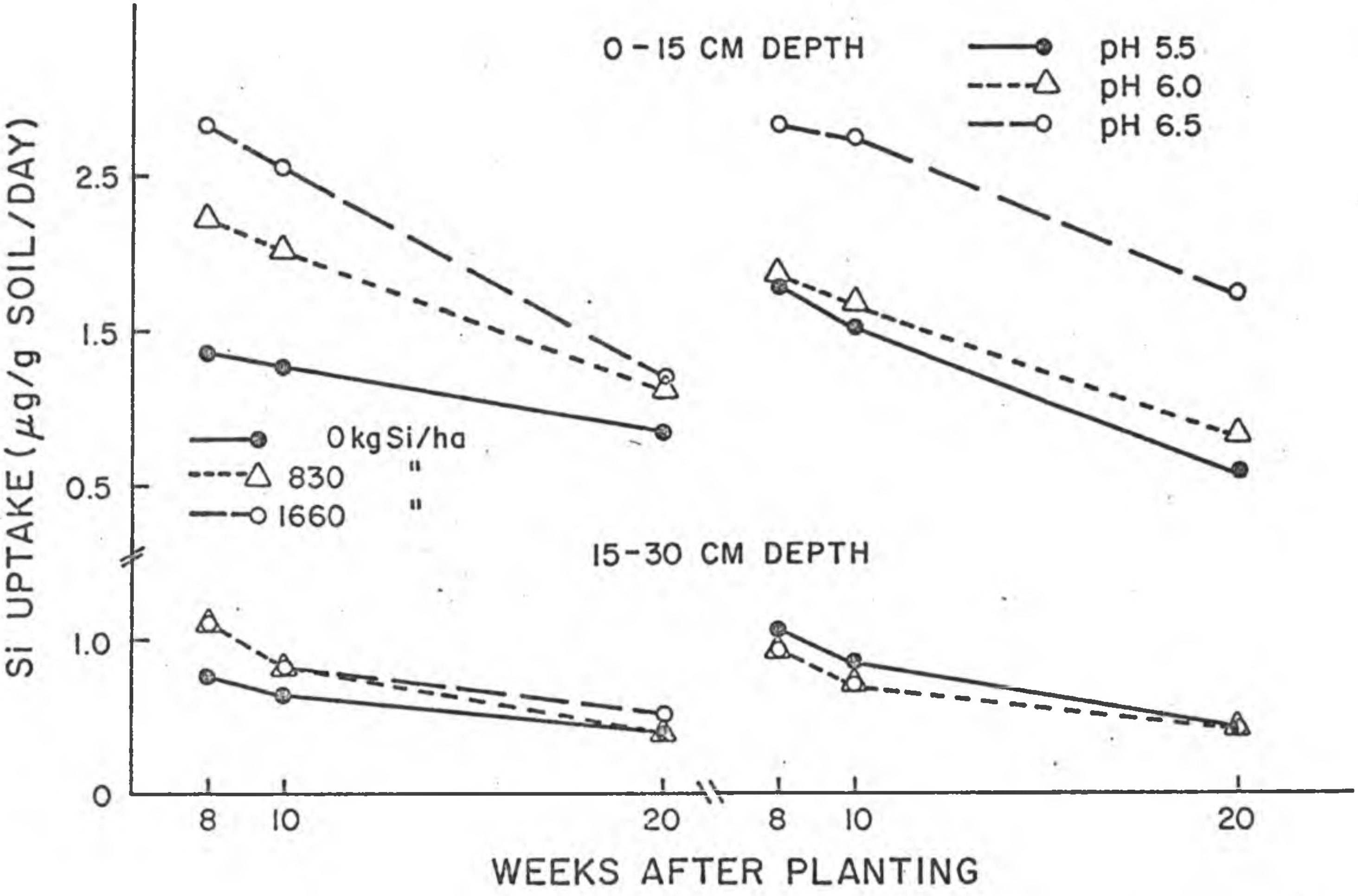

Figure 42. Changes in the rate of Si uptake by rice grown on soil from 0-15 and 15-30 cm depths for 20 weeks as influenced by residual Si and soil pH

solution (Figure 25). In the 15 to 30 cm horizon, although Si uptake decreased with time, the difference between the 1660 and zero Si treatments remained constant. Silicon uptake at various soil pH levels decreased with time, and the reduction was greater in the 0 to 15 cm depth. It should be noted that considerably more Si was extracted by rice at pH 6.5 than at pH 5.5 and 6.0, and this difference remained constant throughout the experiment. These results indicate that the plant crop harvested 8 to 10 weeks after planting (Replication 3 was harvested at 8 weeks, and replications 1 and 2 after 10 weeks) may have removed most of the easily available forms of Si from the soil, resulting in a decrease in the rate of Si release to the soil solution during ratoon growth. This could have caused the substantial reductions in uptake observed in the ratoon, but since dry matter yields of the ratoon crop were almost one-third of those in the plant crop, the reduced Si uptake in the ratoon also may have resulted from reduced yields.

Comparison of Silicon Extracted by Phosphate Solution and by Plants

Exhaustive phosphate extraction removed larger amounts of Si from the applied Si treatments than zero Si in the 0 to 15 cm layer (Figure 43, Appendix Table 93). More Si was extracted from this layer at pH 6.5 than at pH 5.5 and 6.0, which indicates higher Si retention at high pH during the five years duration of the field experiment. The quantities

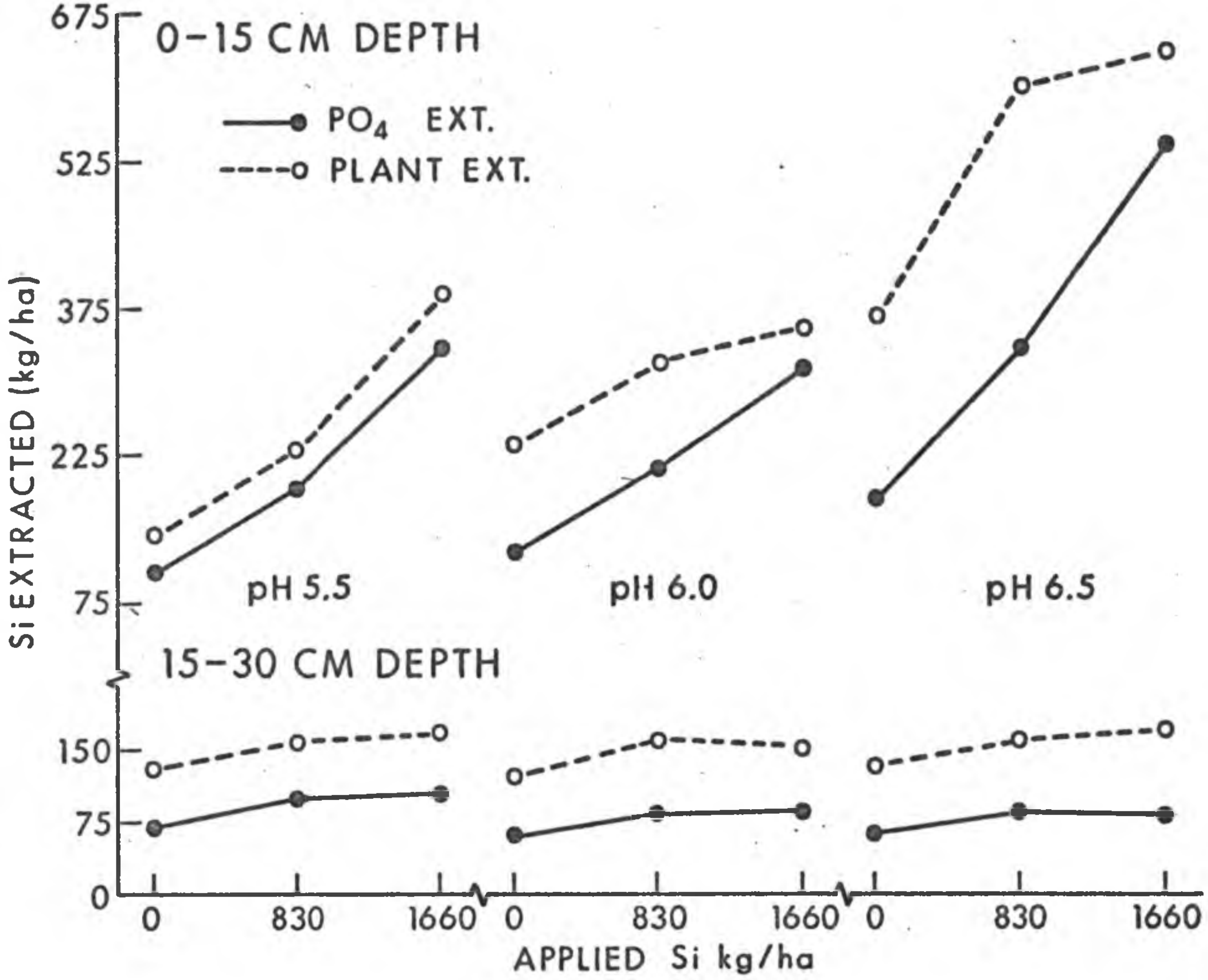

Figure 43. Influence of residual Si on soil Si extracted by phosphate solution and rice from 0-15 and 15-30 cm depths at 3 pH levels

of Si extracted in the 15 to 30 cm horizon were proportional to Si treatments, and the lowest amounts were obtained from the zero Si treatment at all pH levels. Silicon values in the surface layer were 2 to 3 times those in the 15 to 30 cm depth (For detailed discussion of phosphate-extractable Si, see Section II).

Silicon uptake by plant and ratoon crops of rice combined follows essentially the same pattern as phosphate-extractable Si (Figure 43). However, more Si was extracted by plants than by phosphate solution from Si treatments in both horizons.

Inspection of Figure 25 reveals that extraction with phosphate was exhaustive, and 13 successive extractions were required to reach a constant rate of Si release by the soil in the 0 to 15 cm horizon, and 9 extractions for the 15 to 30 cm horizon. In no case did extraction fail to remove some Si and the differential between zero and applied Si treatments persisted. It must be emphasized that an equilibration time of four hours was employed for each successive phosphate extraction which is considerably shorter than the periods of plant extraction. It may be recalled that the plant crop of rice was grown for 8 to 10 weeks and the ratoon for another 10 weeks. Growing plants constantly removed Si from the soil solution (although at a decreasing rate with time. See Figure 42), which allowed continued release of Si from soil to solution to maintain the equilibrium in the soil solution. Theoretically, plants should be able to constantly extract Si from the soil solution as long as soluble Si compounds are present. The rate of extraction should depend on the plant species and the solubility of Si compounds in soil. Therefore, more Si was extracted by rice than phosphate solution because the total extraction time for plants was longer and also because of possibly greater efficiency of Si removal by rice roots than by phosphate solution.

The recovery of applied Si from the 0 to 30 cm horizon by phosphate solution and plant uptake was calculated as Si extracted from the 830 and 1660 kg Si treatments minus Si extracted from the zero treatment at each pH. The total amount of Si recovered by plant uptake ranged from 109 to 252 kg/ha in the 830 Si treatments and from 141 to 297 kg/ha in the 1660 Si treatments (Appendix Table 93). This means that Si removed by rice plants accounted for 8.3 to 30.4% of applied Si. Total amounts of Si recovered by phosphate extraction ranged from 114 to 170 kg/ha in the 830 Si treatments and 219 to 376 kg/ha in the 1660 Si treatments which means that 13 to 23% of the applied Si was removed by phosphate solution from the 0 to 30 cm horizon.

It is apparent from Figure 44 that relatively more Si was removed by plant uptake than by phosphate extraction in the 830 Si treatments at pH 6.0 and 6.5. In the 1660 Si treatment, however, phosphate solution extracted considerably more Si than was taken up by rice plants. At pH 5.5, the difference between the two methods was small. Rice plants

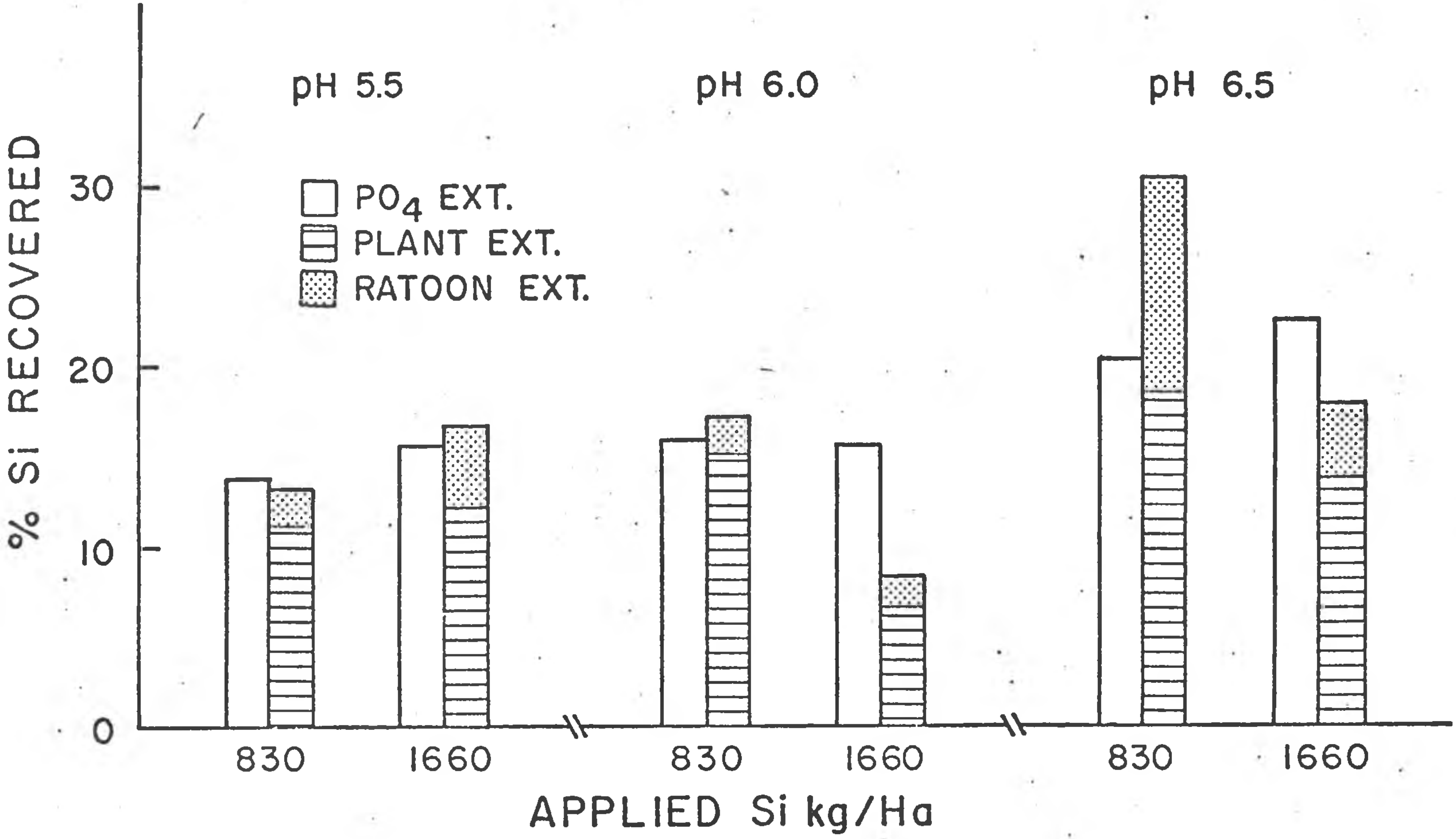

Figure 44. Recovery of applied Si by phosphate extraction and rice uptake at 3 pH levels

extracted proportionately more native Si than did phosphate solution which resulted in comparable amounts of added Si being recovered by the two methods. It may be pointed out that the ratoon crop contributed a comparatively small amount of Si to the total Si extracted by rice (Figure 44). Although the absolute amounts of Si removed by rice plants were higher than those extracted by phosphate solution in this study (Figure 43), the efficiency of the plant extraction technique for a plant and ratoon crop of rice in recovering Si that originated from applied Si was no better than phosphate extraction, especially at the highest levels of Si applied.

It may be recalled from Section II that plant uptake during five years of cropping in the field and exhaustive phosphate extraction of soil samples taken to a depth of 120 cm, collected at the end of the experiment accounted for only 28 to 43% of the applied Si (Table 21). Substituting plant uptake values for phosphate extractable Si in Table 21, we still account for only 28 to 45% of the Si applied five years earlier. This means that 55 to 72% of the applied Si is still retained by the soil in forms that the techniques employed could not recover.

Conclusions

Plant and ratoon crops of rice did not respond to residual Si applied five years ago. Dry matter yield decreased with increasing soil pH in both plant and ratoon crops grown on the surface horizon only. Yield of the ratoon crop was about one-third of plant crop yield in plants grown on soil from both horizons.

Uptake of Si by both plant and ratoon crops increased considerably with increasing levels of residual Si. However, the amounts of Si extracted by the plant crop were generally higher than those extracted by the ratoon crop. Within each crop plants extracted more Si when grown on the 0 to 15 cm horizon, than on the 15 to 30 cm horizon. Total amounts of Si removed by plant and ratoon crops combined were substantially greater at pH 6.5 than at 5.5 and 6.0 which is in contrast to the field data where crops grown for five years extracted more Si at pH 5.5 than at pH 6.5. Apparently, Si extraction by rice plants was closely related to phosphate-extractable Si levels which reflect the amount of Si fixed by the soil rather than the solubility of soil Si. The rate of Si uptake from soil by rice plants decreased with time which may be due to the reduced rate of soil Si release and/or reduced yields in the ratoon crop.

More Si was extracted by plant and ratoon crops of rice combined than by phosphate solution because the total extraction time for rice was longer and also because of possibly greater efficiency of Si removal by rice roots than by phosphate solution. Silicon uptake by rice accounted for 8 to 30% of applied Si and exhaustive phosphate extraction recovered 13 to 23% of applied Si. Rice plants extracted proportionately more native Si than did phosphate solution which resulted in comparable amounts of added Si being recovered by the two methods. The results of this study show that 55 to 72% of Si applied five years ago is still retained by the soil in a form that these techniques could not measure.

IV. STUDY OF SOIL ALUMINUM EXTRACTION METHODS IN RELATION TO PLANT ALUMINUM UPTAKE AND YIELD

Presence of large amounts of extractable Al in some Hawaiian soils induces extreme P deficiencies through fixation and/or precipitation of applied P, and inhibits plant growth. Although various extracting solutions with a wide range of pH values have been employed to assess the availability of soil Al to plants, little work has been conducted on the methodology of Al extraction in tropical soils in relation to plant Al uptake. The purpose of this study was to evaluate various extraction methods to find a measure of soil Al that is closely related to plant Al uptake and yield in several crops grown on tropical soils.

Materials and Methods

Description of Soils

The soils used for the aluminum uptake study were developed under a wide range of climatic conditions and differed in mineralogical composition. These soils have been described by Cline *et al* (1955), USDA (1972), and McCall (1973). Some of their important characteristics are as follows:

Akaka Soil: This soil is a Typic Hydrandept that is derived from volcanic ash under a rainfall of 300 to 700 cm a year. The soil is wet in its natural condition, and irreversably dehydrates on drying. The clays are highly hydrated oxides, with allophane being the most dominant mineral present. The organic content of the soil is high, but the inorganic fraction of the soil is highly leached, and is depleted of bases and Si. The soil has 22 to 30% Al_2O_3, 26 to 37% Fe_2O_3 (Sherman et al, 1964), and the silica-sesquioxide ratio is generally below 0.5 in the upper part of the profile. Surface soil pH ranges from 3.7 to 4.7. The soil has extremely high P and Si fixing capacities and may respond to applications of these nutrients (Roy, 1969).

Halii Soil: Halii soil is a Typic Gibbsihumox developed from basic igneous rocks and volcanic ash with rainfall ranging from 250 to 510 cm a year. The soil is made up of 20% or more gravel-sized aggregates that are 30% or more gibbsite, as well as smooth ironstone pebbles. Iron and aluminum oxides are the main constituents of the upper part of the soil, which has been depleted of bases and Si. Surface soil pH ranges from 3.5 to 4.5. The soil has a high P fixing capacity, and responds to phosphate and silicate applications.

Wahiawa Soil: Wahiawa soil is classified as Tropeptic Eutrustox. The soil is developed from residuum and old alluvium derived from basic igneous rocks in areas with rainfall of 90 to 150 cm annually. It is dominated by halloysite, and Mn compounds are common throughout the soil. Base saturation is 50% or more in the oxic horizon, and soil pH ranges from 5.5 to 6.5 in the surface layers. The soil has a high P fixing capacity and responds to high phosphate applications.

Lualualei Soil: Lualualei soil is a Typic Chromustert developed in alluvium in areas with rainfall from 45 to 75 cm a year. It contains montmorillonite-type clays which are very plastic and sticky when wet and which crack upon drying. Surface soil pH is 7.0 to 8.0. The soil is well supplied with available P, and is high in bases, especially exchangeable Mg.

Kawaihae Soil: Kawaihae soil is an Ustollic Camborthid developed from volcanic ash over aa lava in areas of very low rainfall (10 to 50 cm). The soil is very coarse-textured and the solum has a high content of unweathered primary minerals. The soil contains oxides of Fe and Al and some kaolinite. Soil pH varies from 6.5 to 7.5 in the top layers. A typical characteristic of the soil is an accumulation of $CaCO_3$, either as a definite soil horizon or as coatings on rock fragments at a depth of about 50 cm.

Soil Collection and Preparation

Akaka soil was collected from Hilo, the island of Hawaii, and Halii soil from the Kauai Branch Station, Kapaa, Kauai. Wahiawa soil was collected from Kawailoa ridge and Lualualei soil from Nanakuli, both on Oahu and Kawaihae soil from the island of Hawaii. All bulk samples were collected from the top 15 cm layer, and all except the Akaka soil were air dried and passed through a 0.25 inch mesh sieve for use in the greenhouse experiments. For laboratory analysis, soils were passed through a 2 mm sieve, and stored in polyethylene bags.

Experimental Procedures

One gallon cans lined with polyethylene were filled with 2.3 kg soil (oven dry basis), except for the Akaka soil, where 2.3 kg field moist soil was used for all experiments. Constant volume in all pots was achieved by mixing acid washed silica sand with soils of higher bulk densities. Reagent grade $CaCO_3$ or $CaSiO_3$ (99% pure) from the Hawaiian Cement Corporation was used as the liming material. A blanket application of nutrient elements (Table 24) was made with and without the liming treatments, and P was banded 5 cm below the surface to minimize fixation by soil and to reduce P effects on Al solubility in soil. Soils were equilibrated before planting and were maintained at field capacity throughout the growth period. Home and garden insecticide was sprayed to control aphids. After harvest, plant tops were washed in 0.01% detergent solution, rinsed in distilled water and dried in the oven at 70° C. Soil samples were collected from below the P band (the top 7 cm was not disturbed to avoid P contamination) for laboratory analysis. Soil samples were stored moist in polyethylene bags for chemical analysis. Plant roots were washed with tap water to remove soil and organic matter, then washed for 30 seconds in 0.01% detergent solution. This was followed with three rinses with distilled water in beakers. Roots were

Table 24. Source and rate of fertilizer used in greenhouse experiments

Element	Rate of application ppm soil	Source*
N	200	urea
P**	100	$Ca(H_2PO_4)_2 \cdot 2H_2O$
K	200	KCl
Ca	75	$Ca(H_2PO_4)_2 \cdot 2H_2O$
Mg	50	$MgSO_4 \cdot 7H_2O$
Zn	10	$ZnSO_4 \cdot 7H_2O$
Mn	3	$MnSO_4 \cdot H_2O$
B	1	H_3BO_3

* Chemicals used were A.R. grade

** P banded 5 cm. below the soil surface then placed in nylon netting and held in a waring blender with distilled water for 2 fifteen-second rinses. Roots were dried in the oven at 70° C. Plant material was ground in a stainless steel Wiley mill and stored in plastic vials for chemical analysis.

Experiment 1. Effect of Soil Mineralogy on Aluminum Uptake by Corn (*Zea mays* L.)

The effects of soil mineralogy and pH on Al uptake by corn plants were studied with five soils (described earlier) and replicated three times in a randomized complete block design. A blanket application of nutrient elements was made (Table 24), and soils were equilibrated for three weeks at field capacity. Ten seeds of a sweet corn variety (H-68) were planted in each can about one-fourth of an inch deep, and one week after germination, plants were thinned to four plants per can. Plants were harvested after five weeks, and tops and roots were processed separately for chemical analysis.

Experiment 2. Effect of pH Differentials on Aluminum Uptake by Corn in Akaka and Halii Soils

The following calcium treatments were added to Akaka and Halii soils:

Akaka	0, 8, 16 and 32 meq. Ca/100 gm soil as $CaSiO_3$;
Halii	0, 2, 8, and 16 meq. Ca/100 gm soil as $CaSiO_3$,
	0 and 16 meq. Ca/100 gm soil as $CaCO_3$.

The experiment was replicated three times, using a randomized complete block design. Liming treatments were thoroughly mixed with 2.3 kg of soil, blanket application of nutrients added, and soils equilibrated for three weeks at field capacity. Corn variety H-68 was grown for five weeks as described in Experiment 1. After harvest, plant material and soil samples were secured for chemical analysis.

<u>Experiment 3</u>. <u>Effect of pH Differentials on Aluminum Uptake by desmodium (Desmodium aparines) in Akaka and Halii Soils</u>

The following calcium treatments were added to Akaka and Halii soils:

Akaka 0, 8, 16 and 32 meq. Ca/100 gm soil as $CaSiO_3$;
Halii 0, 2, 8, and 16 meq. Ca/100 gm soil as $CaSiO_3$,
0 and 16 meq. Ca/100 gm soil as $CaCO_3$.

A randomized complete block design was used with three replications. Liming treatments were thoroughly mixed with 2.3 kg soil, a blanket application of nutrients (Table 24) was added, and the soils equilibrated at field capacity for 16 weeks before planting. Five cuttings of desmodium, which were previously grown in a perlite-sand mixture in a mist chamber, were planted in each plot. After ten days, the plants were thinned to three per pot, and four weeks after planting, the plants were cut to a uniform height. This cutting was discarded because of possible carry-over effects from the previous growth.

Plants were harvested 10 weeks after the first cutting, and tops and roots were processed separately for chemical analysis.

Experiment 4. Effect of pH Differentials on Aluminum Uptake by Louisiana White Clover (*Trifolium repens* L.) in Akaka and Halii Soils

The treatments applied to both soils were 0, 8, and 16 meq. Ca per 100 gm soil as $CaSiO_3$. Treatments were thoroughly mixed with the soil, fertilizer nutrients applied, and the soils were equilibrated at field capacity for 17 weeks. Fifty seeds of clover were planted in each can just below the soil surface. Plants were thinned to 20 per can after 2 weeks, and to 6 after 5 weeks. After 13 weeks of growth, plants were harvested, and tops and roots were processed separately for chemical analysis.

Soil Analysis

Soil Aluminum Extraction

The objective of this study was to compare several extraction methods designed to measure extractable Al in soils, and to relate it to Al concentrations in plant tissues and to plant growth. Six extracting solutions which have been used in Hawaii and elsewhere were selected (Table 25). With the exception of 0.01*M* $CaCl_2$ and water, each extracting solution was evaluated at three equilibrium times as follows:

Table 25. Soil Al extraction methods used

Extracting solution	Soil-solution ratio	Equilibrium time	References for extractants
1N KCl	1:10	A. Immediate extraction B. 1.5 hours shaking C. Overnight equilibrium	Chapman and Pratt (1961), McLean (1965)
1N $BaCl_2$	1:10	A. Immediate extraction B. 1.5 hours shaking C. Overnight equilibrium	Yuan and Fiskell (1959)
1N NH_4OAc, pH 4.8	1:10	A. Immediate extraction B. 1.5 hours shaking C. Overnight equilibrium	McLean *et al* (1959)
1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8	1:10	A. Immediate extraction B. 1.5 hours shaking C. Overnight equilibrium	Plucknett and Sherman (1963)
0.01M $CaCl_2$	1:2	16 hours shaking	Hoyt and Nyborg (1971)
H_2O	1:4	16 hours shaking	

Immediate Mixing and Extraction: Ten grams of soil were mixed with 50 ml of solution and filtered immediately through a buchner funnel with suction. The soil was washed five times, using a 10 ml portion of extracting solution each time, and the final volume made to 100 ml. Solutions were stored in plastic vials for analysis.

One and One-Half Hour Shaking: Ten grams of soil were shaken with 100 ml of extracting solution for 1.5 hours, and filtered through Whatman No. 50 filter paper. Solutions were stored in plastic vials for analysis.

Overnight Equilibration: Ten grams of soil were mixed with 50 ml of extracting solution, and allowed to equilibrate overnight. The soil solution was then filtered through a buchner funnel with suction, and washed five times with 10 ml portions of extracting solution. The final volume was made to 100 ml. Solutions were stored in plastic vials for analysis.

The extraction procedures used for $CaCl_2$ and water are described below.

Extraction with 0.01M $CaCl_2$: A 25-gram soil sample was shaken with 50 ml of 0.01M $CaCl_2$ solution for 16 hours and the extract filtered through Whatman No. 50 filter paper. Extracts were stored in plastic vials for analysis.

Extraction with Water: A 25-gram soil sample was shaken with 100 ml of distilled water for 16 hours, and the extract filtered through Whatman No. 50 filter paper. Extracts were stored in plastic vials for analysis.

Aluminum in the soil extracts was determined by the Aluminon method as described by McLean (1965) as follows:

Transfer a suitable aliquot of soil extract to a 100 ml beaker. Dilute to about 25 ml and add 2 ml 1% thioglycolic acid. Mix and add 10 ml aluminon reagent (NH_4-aurine tricarboxylate, $C_{22}N_3O_9$) and mix again. Adjust the pH of the solution to 4.2, with 1:1 NH_4OH or 1:1 HCl and transfer the mixture to a 50 ml volumetric flask with 2 to 3 small distilled water washings, and bring the volume to just below the neck with distilled water. Heat in a boiling water bath for 16 minutes, cool for 2 hours and make to volume. Shake vigorously and read optical density at 537.5 mµ on a spectrophotometer.

Exchangeable Calcium and Magnesium Extraction

A 25-gram soil sample was shaken for 30 minutes with 250 ml of 1N NH_4OAc solution adjusted to pH 7.0 and allowed to equilibrate overnight. The soil solution was then extracted with suction on a buchner funnel. The soil was washed 5 times, using a 50 ml portion of extracting solution each time. The final volume was made to 500 ml. Calcium and magnesium in the extract were determined with a Perkin-Elmer Atomic

Absorption Spectrophotometer, using the addition of 0.5% lanthanum oxide solution to reduce interference by P.

In addition, Ca and Mg were also determined in the 1N KCl extract.

Soil pH

Soil pH was determined in a saturated soil paste with distilled water after 30 minutes of equilibration. A Coleman pH meter with glass electrodes was used for these measurements.

Plant Analysis

Ground, oven dried plant samples were analyzed for Al, P, Ca, and Si. Methods of digestion, fusion and analysis are described in Appendix A.

All soil and plant data are expressed on the oven dry basis

Results and Discussion

The results will be discussed in the following order: (1) influence of soil mineralogy on dry matter yield, and Al concentrations in corn; (2) influence of pH differentials in Akaka and Halii soils on dry matter yield and plant composition of different crops; (3) influence of soil mineralogy and pH on extractable soil Ca and Mg in Experiments 1, 2, 3, and 4; (4) influence of soil mineralogy and pH on Al extracted by various methods; (5) relationship between soil Al and plant

Al; (6) relationship between soil Al and dry matter yield; (7) influence of soil Ca and Mg on soil-plant relationships; and (8) interference in color development in the aluminon method with $BaCl_2$ extracts.

Influence of Soil Mineralogy on Corn (Experiment 1)

Yield

Combined dry matter yield of tops and roots of corn grown in five unlimed soils increased in the order Akaka < Halii < Wahiawa < Kawaihae < Lualualei (Appendix Table 94). Top and root weights in Akaka soil were significantly lower than those in the other soils, and plant and root weights in Halii and Wahiawa soils were significantly lower than those in Lualualei soil (Appendix Table 94). It is interesting to note that yield in these soils is inversely related to the weathering intensity and rainfall under which these soils developed. Apparently in the high rainfall areas, cations are leached from soils and they become acidic, which promotes Al solubility and induces Ca deficiency. This is illustrated by the extractable Al and Ca data (see Appendix Table 94 for soil Ca, and Appendix Table 98 for soil Al data). Aluminum values were highest in Akaka soil and lowest in Kawaihae and Lualualei soils, while the reverse was true for soil Ca. The low yields in Akaka soil may be due to the high amounts of extractable Al being toxic to plant growth. High yields in Lualualei and Kawaihae soils may be largely due to low extractable Al, high extractable Ca and Mg (and possibly other cations not analyzed) combined with favorable pH for micronutrient availability.

Plant Al

Plant Al concentrations of corn tops ranged from 16 to 128 ppm and in roots from 775 to 2975 ppm; the highest concentrations were found in plants grown in Akaka soil (Appendix Table 94). Aluminum concentration of tops grown in Akaka soil was significantly higher than those in the other four soils, while the difference between plant Al in these four soils was small and nonsignificant. Top and root Al concentration did not vary directly with pH.

Influence of pH differentials in Akaka and Halii Soils on Yield and Composition of Several Crops

Corn (Experiment 2)

Yield: Dry matter yield of corn tops and roots increased in Akaka soil as soil pH increased to 5.2 (Figure 45, Appendix Table 95). Further increase in pH resulted in yield reductions. The effect of soil pH on top and root weights, however, was not significant. In Halii soil increasing pH had no significant effect on dry matter yield (Figure 45, Appendix Table 95). The increase in dry matter yield in Akaka soil to pH 5.2 may be due to increased levels of Ca and reduction in soluble Al. The yield decrease at pH 5.7 and 6.3 may be attributed to over-liming which created nutrient imbalance affecting growth.

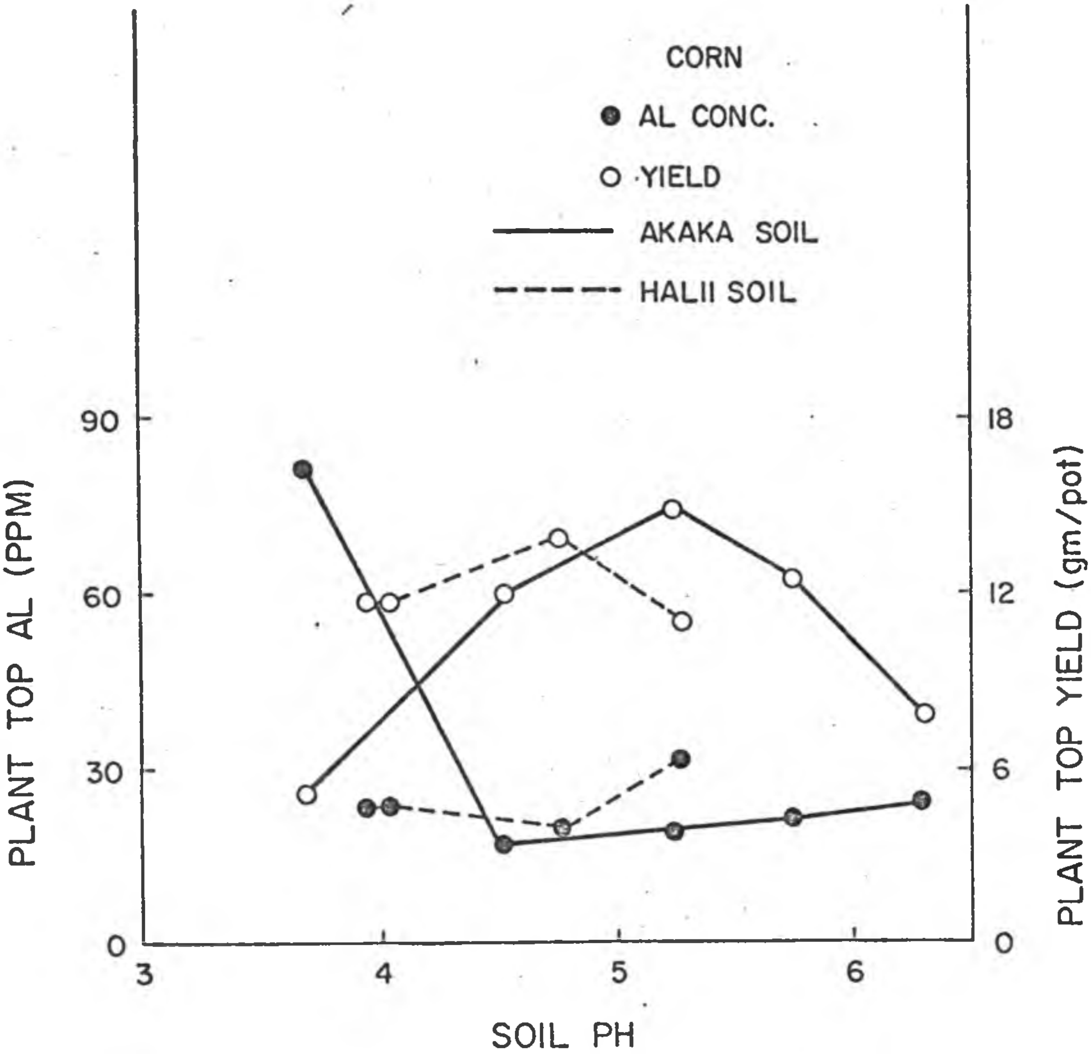

Figure 45. Influence of soil pH on dry matter yield and plant Al of corn grown on Akaka and Halii soils (Experiment 2)

Plant Al: In Akaka soil, Al concentrations in tops decreased sharply with the first increment of $CaSiO_3$, which raised soil pH from 3.7 to 4.5. Further increase in pH resulted in slightly higher Al values (Figure 45). In Halii soil, the Al content of tops increased slightly with increasing soil pH. In both soils, the effect of pH on plant Al concentration was not significant (see Appendix Table 95 for data). Aluminum concentration of corn roots decreased with increasing soil pH in Akaka and Halii soils although the decrease in Halii soil, where pH was adjusted with $CaSiO_3$, was not consistent (Appendix Table 95). Aluminum concentrations in corn roots were much higher than Al concentrations in tops which indicate that translocation of Al to upper parts of the plant was low. Similar results were reported by Plucknett *et al* (1963), who observed large accumulations of Al in *Leucaena* roots, but very little Al in the tops.

Plant P, Ca, and Si: Phosphorus concentrations in corn tops were not influenced by soil pH in either soil. Phosphorus concentrations ranged from 0.08 to 0.11 per cent in the tops, and no difference was observed between the two soils. Thiagalingam (1971) reported 0.15 to 0.18 per cent P in corn tops grown in Halii soil, and the concentrations in our experiment seem low. This is due to the fact that 100 ppm P was supplied in the present experiment while 500 ppm P was supplied by Thiagalingam (1971). The critical P level in corn leaf tissue, below which deficiency may occur, is suggested as 0.2 per cent (Chapman, 1967). Akaka and Halii soils have high P fixing capacities and very likely most of the P applied was immobilized in the soil, thus leaving little P available to plants.

Plant top Ca increased with increasing $CaSiO_3$ applications in both Akaka and Halii soils, and the levels were higher in Halii than in Akaka soil (Appendix Table 95). It should be noted that, at the same level of applied Ca in Halii soil, more Ca was taken up from $CaCO_3$ than $CaSiO_3$. Apparently, $CaCO_3$ is more reactive in the soil than $CaSiO_3$, supplying more available Ca to plants.

Silicon concentrations in the plant tops increased with $CaSiO_3$ applications in both soils. In Halii soil, where pH was raised with $CaCO_3$, plant Si decreased with pH, which agrees with the concept of lower Si solubility at higher soil pH discussed earlier in section I under soil Si.

Desmodium (Experiment 3)

Yield: Dry matter of desmodium tops increased with increasing soil pH in Akaka soil, although the effect was nonsignificant (Figure 46). The effect of pH on root weight was small and nonsignificant, but it tended to increase with pH (Appendix Table 96). In Halii soil, increasing pH had no consistent effect on dry matter yield of plant tops (Figure 46) or roots (Appendix Table 96). In contrast to the present results, desmodium grown on a similar Gibbsihumox soil produced

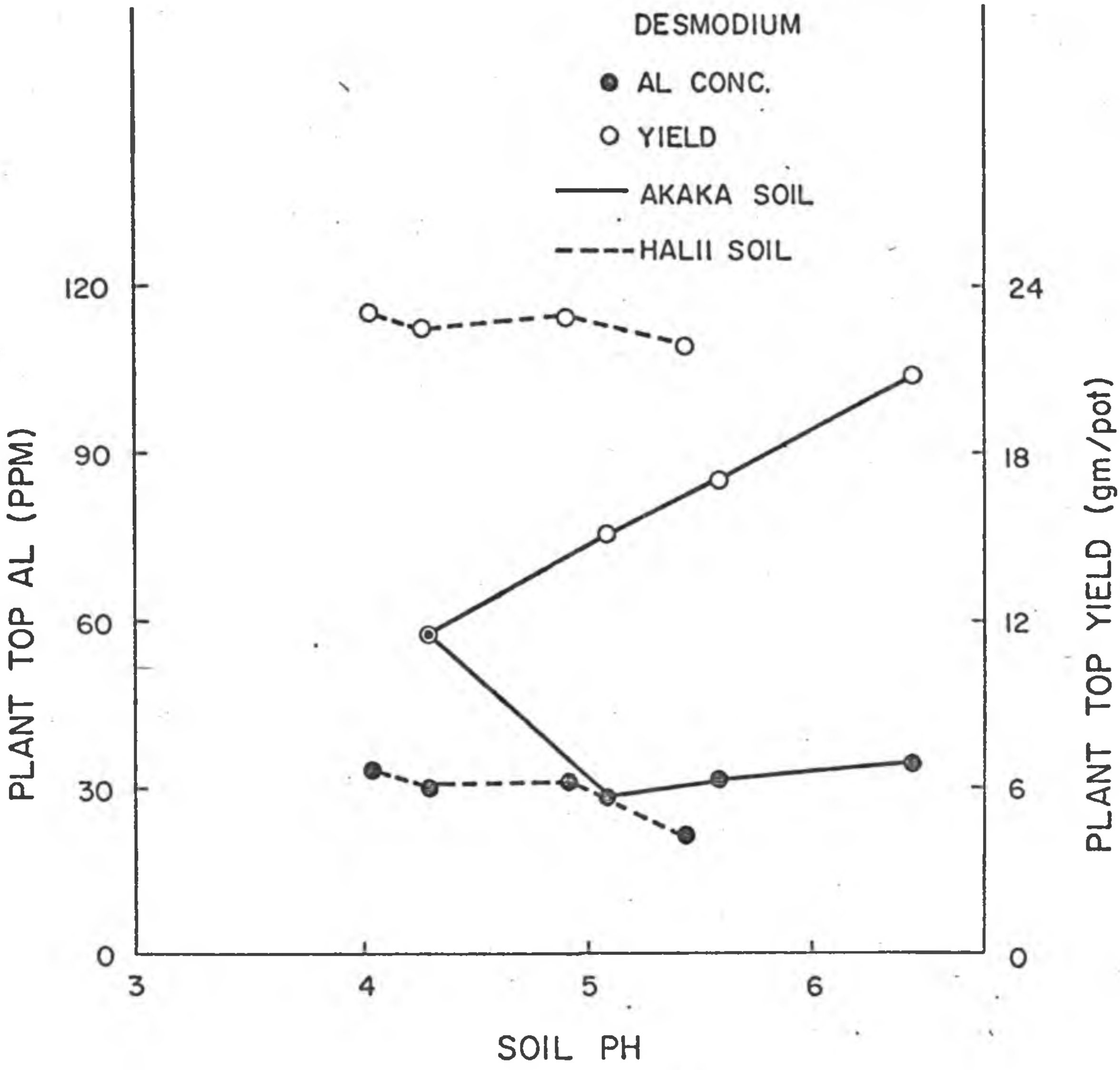

Figure 46. Influence of soil pH on dry matter yield and plant Al of desmodium grown on Akaka and Halii soils (Experiment 3)

a significant yield increase with application of 2.2 tons $CaSiO_3$/ha, according to Thiagalingam (1971).

Plant Al: Aluminum concentrations in tops of desmodium grown in Akaka soil decreased significantly as soil pH increased from 4.3 to 5.1, and Al values at pH above 5.1 were not significantly different (Figure 46, Appendix Table 96). The effect of pH on plant top Al in desmodium grown on Halii soil was nonsignificant, although there was a slight decreasing trend with increased pH (Figure 46). Root Al contents increased with the first $CaSiO_3$ addition in both soils, and then decreased with further additions. This effect of pH on root Al was significant only in Akaka soil (Appendix Table 96). Much higher concentrations of Al were found in roots than in tops (21 to 57 ppm in tops versus 1500 to 4800 ppm in the roots).

Plant P, Ca and Si: Phosphorus contents of desmodium tops decreased slightly with pH in Akaka soil, but no trend was observed in P values of plants grown on Halii soil (Appendix Table 96). Plant P in desmodium tops ranged from 0.11 to 0.16%. Thiagalingam (1971) reported P contents in desmodium grown on Halii and Paaloa soils ranged from 0.17 to 0.36%. Phosphorus levels in the present experiment are low by comparison since only 100 ppm P was applied.

Plant Ca and Si in Akaka and Halii soils increased with $CaSiO_3$ applications (Appendix Table 96). There was a sharp increase in both elements with the first increment of $CaSiO_3$

and little additional change with subsequent additions.

Louisiana White Clover (Experiment 4)

Yield: Dry matter yield of white clover tops and roots increased significantly with increased soil pH in both Akaka and Halii soils (Figure 47, Appendix Table 97). In Akaka soil, top weight at 8 meq. Ca was significantly higher than at zero Ca, while in Halii soil, only the top weight at 16 meq. Ca was significantly higher than the zero Ca. In both Akaka and Halii soils, the root weights of applied Ca treatments were significantly higher than those of zero Ca.

Plant Al: Aluminum concentrations in white clover tops (Figure 47) and roots (Appendix Table 97) decreased sharply as pH increased to 5.3 and decreased gradually as pH increased above 5.3. The reduction in top Al as soil pH increased was significant in Akaka soil, but not in Halii soil, although the reduction was marked. The reverse of this was true for root Al, where the reduction in Al with pH was significant in Halii soil, but nonsignificant in Akaka soil. Aluminum values in clover tops ranged from 23 to 144 ppm and from 470 to 3720 ppm in clover roots.

Dry matter yield and Al concentrations of plant tops were significantly ($P < .01$) correlated in all experiments (Appendix Table 102), and r values were in the order: white clover > corn (experiment 2) > corn (experiment 1) > desmodium. This shows that reduction of Al toxicity by increased soil

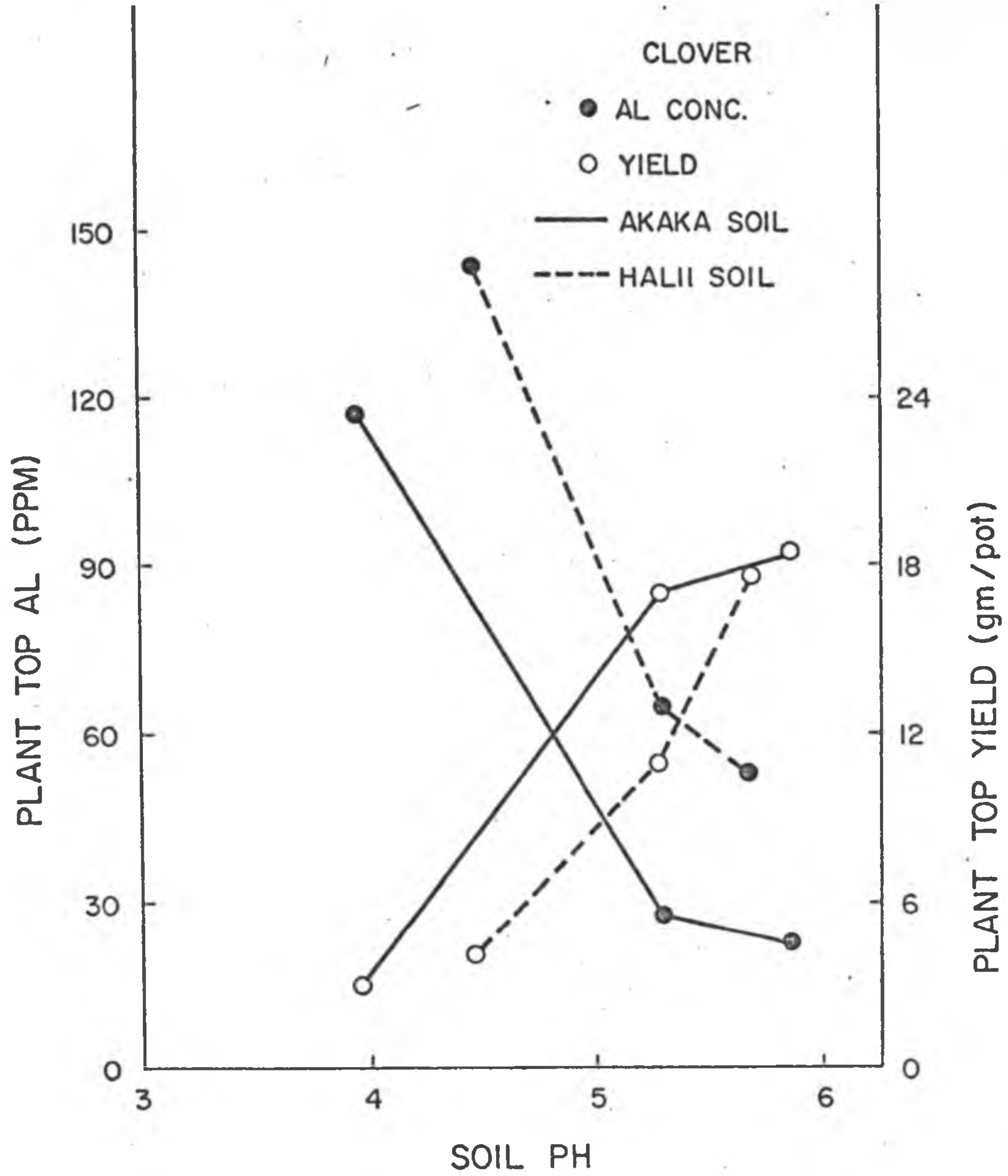

Figure 47. Influence of soil pH on dry matter yield and plant Al of white clover grown on Akaka and Halii soils (Experiment 4)

pH stimulated growth, but the extent of this effect varied in plant species.

In summary, it may be stated that yield response of corn, desmodium and white clover to $CaSiO_3$ applications was evident in Akaka soil. The yield increase with $CaSiO_3$ was only observed in white clover on Halii soil, which may indicate some soil-plant interactions in Halii soil that are responsible for the differential behavior of plant species. Aluminum contents of corn, desmodium and white clover tops decreased with increasing soil pH in Akaka soil, while this effect was marked in white clover only in Halii soil. Concentrations of Al in white clover tops were the highest, followed by corn and desmodium. Apparently plant species differ in their ability to translocate Al from roots to tops.

Influence of Soil Mineralogy and pH on extractable Soil Ca and Mg

Soil Ca and Mg extracted with 1N NH_4OAc adjusted to pH 7.0 after harvest, from soils of varying mineralogy generally increased with increasing soil pH (Experiment 1, Appendix Table 94). Extractable Ca ranged from 94 to 11500 ppm and the highest concentrations were found in Lualualei soil, and the lowest in Akaka soil. Extractable soil Mg concentrations ranged from 71 to 3050 ppm. It may be pointed out that soil Mg was higher in Akaka than in Halii soil, although pH was lower in Akaka than in Halii soil. Comparison of corn yield and soil Ca data in this experiment indicates dry matter production was highest in soil with high Ca which may imply that low dry matter production in Akaka soil was due to Ca deficiency rather than Al toxicity. Calcium and Mg levels in these soils are also related to the weathering intensity and amount of rainfall in the area. For example, Lualualei and Kawaihae soils which have developed in low rainfall areas and are not highly weathered have high levels of extractable Ca and Mg whereas Akaka and Halii soils which developed in high rainfall areas and are intensely weathered have low levels of extractable Ca and Mg.

Extractable Ca in Akaka and Halii soils limed to various pH levels in Experiments 2, 3, 4 increased with $CaSiO_3$ and $CaCO_3$ applications (Appendix Tables 95, 96, and 97, respectively). Extractable Mg in limed Akaka soil generally increased with $CaCiO_3$ additions in Experiments 2 and 4 and decreased with $CaSiO_3$ in Experiment 3 (Appendix Tables 95, 96, and 97). Extractable soil Mg in limed Halii soil was not affected by $CaSiO_3$ additions in Experiment 2, increased with $CaSiO_3$ in Experiment 3, and decreased with $CaSiO_3$ in Experiment 4.

Soil Ca and Mg were also extracted with 1$\underline{N}$ KCl (1.5 hours shaking) in soil samples collected after harvest in Experiments 1, 2, and 4 and Ca and Mg values in these extracts followed the same pattern as those extracted by 1$\underline{N}$ NH_4OAc, pH 7, discussed above (for KCl-extractable Ca and Mg data see Appendix Table 102). However, Ca and Mg concentrations in the KCl extracts were generally slightly lower than those in the NH_4OAc, pH 7.0 extracts.

Influence of Soil Mineralogy and pH on Al Extracted by Various Methods

Aluminum was extracted by 14 extraction methods from soil samples collected after harvest in experiments 1, 2, 3, and 4 (For data, see Appendix Tables 98-100). Six extracting solutions were used, and, with the exception of $0.01\underline{M}$ $CaCl_2$ and H_2O, each solution was evaluated at three equilibration times as described in the Materials and Methods section (Table 25). Simple correlation coefficients calculated with data from all experiments indicated high correlation among the Al values obtained by extraction at the three different times (Appendix Table 101; $r = 0.89$ to 0.98; $n = 96$). However, the correlation between Al extracted by shaking for 1.5 hours and that extracted after overnight equilibration was the highest ($r = 0.94$ to 0.98). Mean Al values of data combined for four experiments show that in $1\underline{N}$ KCl and $1\underline{N}$ $BaCl_2$ solutions more Al was extracted by shaking for 1.5 hours and after overnight equilibration than was extracted after immediate mixing (Appendix Table 100, last line). The difference in Al extracted by 1.5 hours shaking and that extracted after overnight equilibration was negligible, which suggests that both methods reached the same state of equilibrium. In $1\underline{N}$ NH_4OAc and $1\underline{N}$ $NH_4OAc + 0.2\underline{N}$ $BaCl_2$, both adjusted to pH 4.8, extractable Al increased with increasing time of equilibration (Appendix Table 100, last line).

Correlation between soil Al extracted by various methods was high (r = 0.70 to 0.98), except for 0.01M $CaCl_2$ (r = 0.60 to 0.71), although all r values were highly significant (Appendix Table 101).

The amounts of Al extracted by various methods decreased in the order, 1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8 $>$ 1N NH_4OAc, pH 4.8 $>$ 1N $BaCl_2 \geqslant$ 1N KCl $\geqslant H_2O \geqslant$ 0.01M $CaCl_2$ (Figure 48, Appendix Tables 98 to 100). Aluminum extracted from different soils was in the order of Akaka $>$ Halii $>$ Wahiawa $\geqslant$ Lualualei = Kawaihae (Appendix Table 98, Experiment 1), which is related to the degree of weathering and amount of rainfall for the soil. The sources of Al in Akaka and Halii soils are hydrated aluminum oxides, allophane and gibbsite. Both soils contain a high percentage of amorphous mineral colloid rich in Al. Aluminum in the extracts is derived mainly from dissolution of these compounds, and this fraction is not exchangeable according to the classical definition of exchangeable Al (Ayers et al, 1965). The highly buffered 1N NH_4OAc and 1N NH_4OAc + 0.2N $BaCl_2$ used in this study were able to dissolve Al from crystalline as well as amorphous materials resulting in high levels of extractable Al. Unbuffered salts such as $BaCl_2$ and KCl are less effective in dissolving Al from crystalline and amorphous materials while 0.01M $CaCl_2$ and H_2O are unable to extract much Al from soil. Wahiawa, Kawaihae and Lualualei soils contain mostly iron oxides, halloysite, kaolin, and montmorillonite and thus have low levels of extractable Al. However, appreciable amounts of

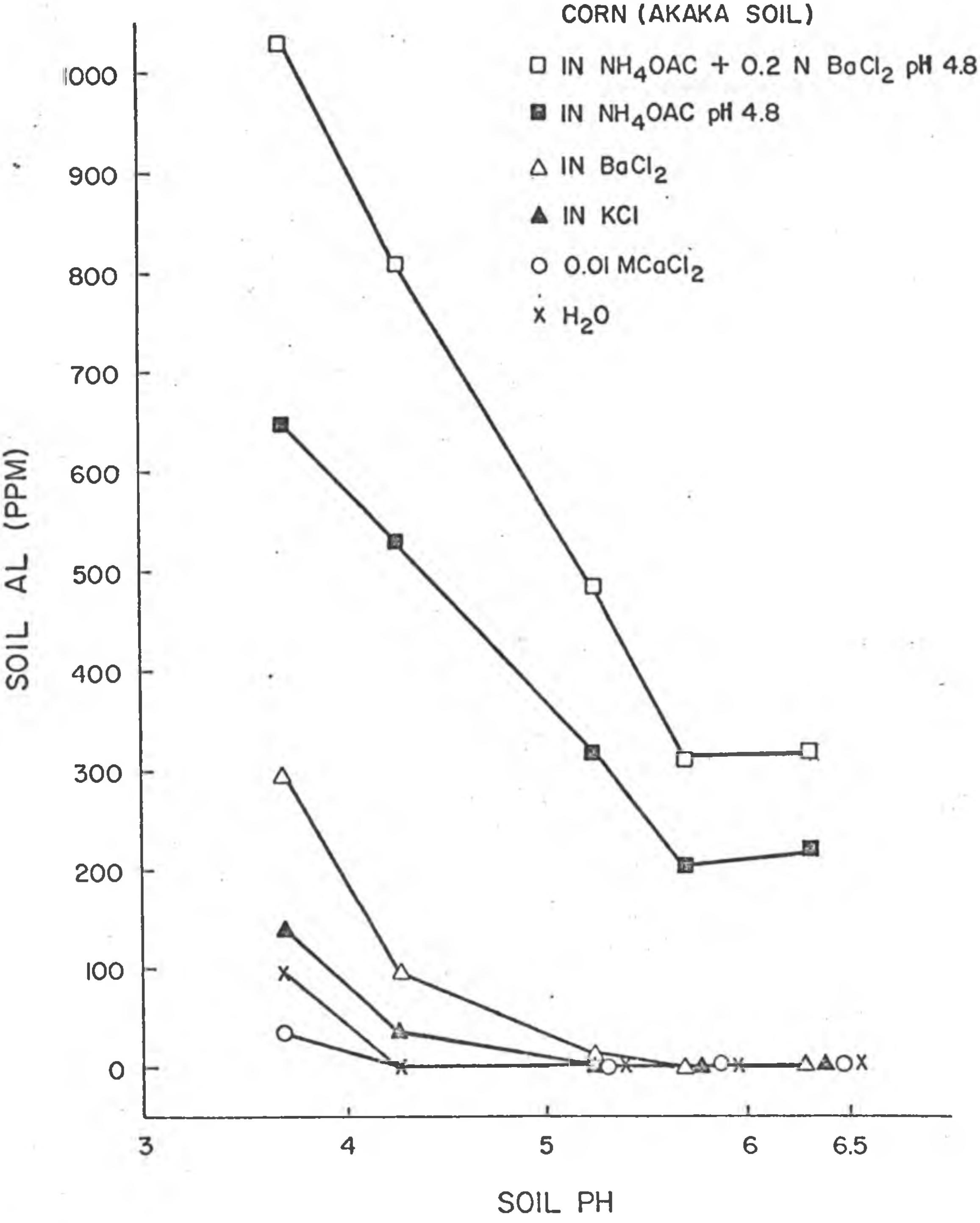

Figure 48. Influence of soil pH on Al extracted by various solutions from Akaka soil after corn (Experiment 2)

Al were extracted from these soils by the buffered salts adjusted to pH 4.8, which are known to dissolve crystalline minerals. In addition to soil composition, Al solubility is also a function of soil pH; i.e., the lower the pH, the higher the Al solubility. This relationship is well illustrated by Akaka soil, which has the lowest pH and highest Al, and by Lualualei, which has the highest pH and lowest Al.

Decreases in extractable Al with $CaSiO_3$ or $CaCO_3$ applied to Akaka and Halii soils (Experiments 2, 3, and 4) were caused by an increase in soil pH, which resulted in the formation of less soluble hydroxide forms of Al (Appendix Tables 98 to 100). This is illustrated in Figure 48, where Al extracted from Akaka soil limed with $CaSiO_3$ (Experiment 2, after corn) decreased with increasing soil pH. It should be noted that buffered NH_4OAc, with or without $BaCl_2$, extracted appreciable amounts of Al at soil pH above 5.0. Since buffered solutions at pH 4.8 control pH of the suspension, the limed samples were extracted at about pH 4.8. This lowering of pH to 4.8 dissolved recently precipitated forms of Al, and other insoluble Al compounds that resulted in appreciable amounts of Al in the extract when soil pH was above 5.0. With $BaCl_2$, KCl, $CaCl_2$, and H_2O, on the other hand, the soil itself determined pH of the extraction; hence, less Al was extracted at soil pH above 5.0. This is substantiated by the findings of Pratt and Bair (1961) in which freshly precipitated $Al(OH)_3$ had a relatively high solubility in NH_4OAc at pH 4.8 compared to that in KCl.

Relationship between Soil Al and Plant Al

The objective of this study was to compare various Al extraction methods to find a measure of soil Al that would best predict plant Al uptake and yield response in crops. Aluminum extracted by 14 methods from soil samples collected after harvest of experiments 1, 2, 3 and 4 was correlated with plant top Al concentrations of corn, desmodium and white clover, using a quadratic equation (see Appendix Tables 94 to 97 for plant Al data and 98 to 100 for soil Al data). Plant Al was treated as a dependent variable and soil Al and soil Al squared as independent variables.

In Experiment 1, where corn was grown on five unlimed soils of varying mineralogy, Al extracted with 1N KCl (1.5 hours shaking) and H_2O were best correlated with Al concentrations in corn tops (R = 0.99; Table 26). Aluminum extracted by all methods was significantly ($p < 0.01$) correlated with plant Al in this experiment (R = 0.80 to 0.99). It appears that in soils where Al is present in different forms and pH varies greatly, 1N KCl- (1.5 hours shaking) and H_2O-extractable Al are more closely related to the forms of Al taken up by plants than is Al extracted with other methods.

Experiments 2, 3, and 4 were conducted to study the soil Al and plant Al relationship in soils with constant mineralogy where an Al differential was induced by varying pH with liming materials. In Experiment 2, in which corn was grown on limed

Table 26. Relationship of soil Al extracted by various methods with plant top Al of corn, desmodium and white clover in greenhouse experiments

Extracting solution	Equilibration time	Experiment number[a]									
		1	2		3		4		1,2,3,4	Average rank	'Average' 'R'
		5 soils	Akaka	Halii	Akaka	Halii	Akaka	Halii			
					R^b						
1N KCl	A^c	0.92	0.76	0.56^{ns}	0.85	0.83	0.90	0.95	0.61	1	0.82
	B	0.99	0.69*	0.53^{ns}	0.71	0.87	0.98	0.78	0.62	4	0.79
	C	0.93	0.75	0.53^{ns}	0.85	0.85	0.91	0.86	0.62	2	0.81
1N $BaCl_2$	A	0.88	0.84	0.41^{ns}	0.86	0.87	0.88	0.68	0.68	8	0.77
	B	0.81	0.76	0.37^{ns}	0.82	0.84	0.92	0.76*	0.68	11	0.76
	C	0.92	0.75	0.39^{ns}	0.83	0.88	0.95	0.87	0.65	3	0.80
1N NH_4OAc, pH 4.8	A	0.92	0.65*	0.33^{ns}	0.88	0.85	0.98	0.81	0.54	7	0.77
	B	0.80	0.68*	0.30^{ns}	0.86	0.85	0.90	0.83	0.64	13	0.75
	C	0.80	0.83	0.40^{ns}	0.84	0.79	0.94	0.83	0.51	9	0.78
1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8	A	0.96	0.96	0.34^{ns}	0.60	0.69	0.94	0.88	0.58	6	0.80
	B	0.84	0.88	0.27^{ns}	0.86	0.83	0.92	0.75*	0.58	10	0.76
	C	0.88	0.69*	0.32^{ns}	0.76	0.81	0.94	0.86	0.52	12	0.75
0.01M $CaCl_2$	16 hours shaking	0.96	0.77	0.49^{ns}	0.85	0.76	0.97	0.76*	0.40	5	0.79
H_2O	16 hours shaking	0.99	0.98	0.50^{ns}	--	--	0.89	0.50^{ns}	--	--	--

[a] Experiment 1, corn in five unlimed soils. Experiments 2,3,and 4, corn, desmodium and white clover, respectively, each in limed Akaka and Halii soils.

[b] $Y = a + b_1X + b_2X^2$, where X = soil Al

[c] A = Immediate mixing and extraction
B = One and a half hour shaking and filtration
C = Overnight equilibration and extraction

ns, * Nonsignificant, and significant at the 5% level, respectively. Values without asterisks are significant at the 1% level.

Akaka soil, Al extracted with water and with 1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8 (immediate extraction) were most closely related to plant Al (R = 0.98 and 0.96, respectively) (Table 26). Multiple R values ranged from 0.65 to 0.98. In limed Halii soil in this experiment R values ranged from 0.27 to 0.56 and were nonsignificant. Aluminum extracted with 1N KCl (immediate extraction) was the most closely related to plant Al. The cause of this poor relationship which is evident in Figure 45 is that plant Al increased as pH increased above 4.8 while soil Al decreased consistently with increasing soil pH (Appendix Table 98). In Experiment 3, where desmodium was grown on limed Akaka soil, R values for all methods were highly significant and ranged from 0.71 to 0.88 with 1N NH_4OAc, pH 4.8 having the highest R value (Table 26). When desmodium was grown on limed Halii soil, Al extracted with 1N $BaCl_2$ and 1N KCl was best correlated with plant Al (R = 0.88 and 0.87, respectively) and the R values ranged from 0.69 to 0.88. Aluminum in white clover grown on limed Akaka soil was best correlated with soil Al extracted with 1N KCl (1.5 hours shaking) and 1N NH_4OAc, pH 4.8 (immediate extraction) (R = 0.98, Table 26). With Halii soil in Experiment 4, soil Al extracted with 1N KCl (immediate extraction) was more closely related to plant Al concentrations in white clover than that extracted with other methods (R = 0.95). The range of R values was from 0.50 to 0.95 (Table 26).

It appears from these studies that no one method for extracting Al was best correlated with plant Al in all crops. Soil and plant data for all four experiments were combined in one regression analysis and Al extracted with 1N $BaCl_2$ (both immediate extraction and 1.5 hours shaking procedures) was found to have the highest correlation with plant Al (R = 0.68; Table 26, column 10) followed by 1N $BaCl_2$, overnight equilibration (R = 0.65). This does not agree with the regression analysis of individual sets of data in which R values for 1N KCl generally had the best correlation.

Combining data for all crops and soils in one relationship appears to produce a generalized relationship applicable to the range of conditions tested, but it is very subject to interactions between soils and crops. Since the objective of this study was to identify a procedure which extracted the particular form of Al that was taken up by plants, or at least was closely related to it, it becomes necessary to evaluate these methods under the particular conditions of soil Al solubility and the characteristic Al uptake of a plant species. Therefore another approach employed was to rank individual values in each of the 7 sets of comparisons by assigning number one to the highest R value in each set and ranking the R values successively. The ranks thus given were averaged across sets to summarize the performance of extraction methods in relation to plant Al uptake. This analysis revealed that 1N KCl, immediate extraction and 1N KCl, overnight equilibration, were ranked 1 and 2, respectively, which means that soil Al extracted with these two methods was generally better correlated with plant Al uptake of the individual species in the various soil conditions (Table 26, column 11). Buffered solutions generally had relatively poor correlation between soil and plant Al for the specific conditions tested.

The overall relationship between soil and plant Al was also evaluated by calculating an 'average R' value (arithmatic average of the R values) for the 7 sets of correlations (Table 26, columns 3 to 9) for each method. The range of 'average R' values was 0.75 to 0.82 with 1N KCl, immediate extraction, and 1N KCl, overnight equilibration, having the highest values (R = 0.82 and 0.81, respectively. See Table 26, column 12). The relatively narrow range of 'average R' values indicates that all extraction methods were generally comparable in their ability to extract the form of soil Al taken up by the plants tested.

Results of the ranking and 'average R' value techniques are similar in that both indicate that Al extracted with unbuffered solutions was better correlated with plant Al than that extracted with buffered solutions. Also, both showed 1N KCl to be slightly superior to 1N $BaCl_2$. These two techniques offer a more reliable evaluation of extraction methods than regression analysis of combined data because evaluation of each set of data is independent of soil-plant interactions.

Inspection of Table 26 (columns 3 to 9) shows that R values were not uniformly high, and in some cases were non-significant which means that extractable soil Al levels did not explain variation in plant Al concentrations of various crops to the same degree. This may be attributed to species differences in ability to translocate Al from roots to shoots. Clarkson (1969) reported that a large proportion of Al in barley roots was associated with the cell wall as an amorphous precipitate of $Al((OH)_3)_n$, which was brought about by hydrolysis of Al ions at the root surface. He suggested that plant species differ in their ability to produce hydroxyl ions at the root surface to precipitate incoming Al. Gangwar (1967) also showed that plants differ in their capacity to transfer Al to the above-ground parts. He reported that net translocation of Al in Kiami clover was twice that of corn. This differential capacity of plants to translocate Al agrees with our results in that white clover had higher concentrations of Al in the tops than corn or desmodium grown on the same soil. This suggests that plant roots have a mechanism to control Al translocation to the top, and thus Al extracted from soil is not completely reflected by Al in the tops.

Relationship between Soil Al and Dry Matter Yield

The relationship between soil Al extracted by 14 methods and plant top yields of corn, desmodium and white clover was determined using multiple regression analysis with plant yield as the dependent variable and soil Al and its square as independent variables. In Experiment 1 where corn was grown on five unlimed soils R values for 1N NH_4OAc, pH 4.8 (both 1.5 hours and overnight equilibration procedures) were the highest of the methods studied (R = 0.84, Table 27). Correlation coefficients ranged from 0.74 to 0.84 and were all significant at the 1% level.

In Experiment 2 where corn was grown on limed Akaka soil, R values for 1N NH_4OAc + 0.2N $BaCl_2$ and H_2O were the highest (R = 0.81 and 0.80, respectively; Table 27). Correlation coefficients ranged from 0.66 to 0.81. In the case of Halii soil, although the relationship between soil Al and corn yield was nonsignificant, 1N KCl, overnight equilibration, had the highest R value (0.35). Similar results were obtained in Experiment 3 where R values for the relationship between soil Al and desmodium yield on Akaka and Halii soils were generally nonsignificant. In the Halii soil, highly significant R values were obtained only for the buffered solutions. Apparently desmodium was relatively tolerant to Al. In the case of white clover grown on limed Akaka soil (Experiment 4), R values for all methods were similar (R = 0.91 to 0.96) and highly significant. The relationship with 1N NH_4OAc, pH 4.8, immediate extraction, had the highest R value. In Halii soil Al extracted with 1N $BaCl_2$, 1.5 hours shaking, and buffered solutions were more closely related to white clover yield than that extracted with other methods (Table 27).

Table 27. Relationship of soil Al extracted by various methods with yield of corn, desmodium and white clover in greenhouse experiments

Extracting solution	Equilibration time	Experiment number[a] 1	2		3		4		1,2,3,4	Average rank	'Average' 'R'
		5 soils	Akaka	Halii	Akaka	Halii	Akaka	Halii			
					R[b]						
1$\underline{N}$ KCl	A[c]	0.78	0.68*	0.28^{ns}	0.36^{ns}	0.44^{ns}	0.95	0.76*	0.43	6	0.61
	B	0.77	0.72	0.32^{ns}	0.16^{ns}	0.37^{ns}	0.94	0.75*	0.42	8	0.57
	C	0.76	0.66*	0.35^{ns}	0.47^{ns}	0.34^{ns}	0.95	0.75*	0.41	6	0.61
1$\underline{N}$ $BaCl_2$	A	0.79	0.72	0.20^{ns}	0.39^{ns}	0.48*	0.91	0.78*	0.48	6	0.61
	B	0.80	0.67*	0.17^{ns}	0.56^{ns}	0.42^{ns}	0.94	0.83	0.46	5	0.63
	C	0.79	0.67*	0.21^{ns}	0.38^{ns}	0.37^{ns}	0.94	0.77*	0.44	7	0.59
1$\underline{N}$ NH_4OAc, pH 4.8	A	0.77	0.67*	0.27^{ns}	0.40^{ns}	0.56*	0.96	0.83	0.47	4	0.64
	B	0.84	0.74	0.28^{ns}	0.37^{ns}	0.65	0.93	0.77*	0.51	3	0.65
	C	0.84	0.72	0.29^{ns}	0.43^{ns}	0.66	0.95	0.82	0.48	1	0.67
1$\underline{N}$ NH_4OAc + 0.2$\underline{N}$ $BaCl_2$, pH 4.8	A	0.80	0.81	0.19^{ns}	0.42^{ns}	0.34^{ns}	0.93	0.81	0.46	6	0.61
	B	0.82	0.78	0.24^{ns}	0.41^{ns}	0.66	0.93	0.80	0.48	2	0.66
	C	0.83	0.71	0.26^{ns}	0.45^{ns}	0.65	0.92	0.83	0.51	2	0.66
0.01$\underline{M}$ $CaCl_2$	16 hours shaking	0.76	0.76	0.31^{ns}	0.39^{ns}	0.25^{ns}	0.94	0.71*	0.31	7	0.59
H_2O	16 hours shaking	0.74	0.80	0.30^{ns}	--	--	0.94	0.41^{ns}	--	--	--

[a] Experiment 1, corn in five unlimed soils. Experiments 2,3,and 4, corn, desmodium and white clover, respectively, each in limed Akaka and Halii soils.

[b] $Y = a + b_1X + b_2X^2$, where X = soil Al

[c] A = Immediate mixing and extraction
B = One and a half hour shaking and filtration
C = Overnight equilibration and extraction

ns, * Nonsignificant, and significant at the 5% level, respectively. Values without asterisks are significant at the 1% level.

When data from all experiments are combined in a regression analysis, relatively low R values (0.31 to 0.51) are obtained and 1N NH_4OAc, 1.5 hours shaking, and 1N NH_4OAc + 0.2N $BaCl_2$, overnight equilibration, have the highest R values (Table 27, column 10). Evaluation of the methods by ranking in the individual sets of data shows that Al extracted with buffered solutions (both 1.5 hours and overnight equilibration procedures) were best correlated with yield (Table 27, column 11). The results obtained by ranking were further substantiated by the 'average R' values for the relationship between soil Al and plant yield over the four experiments were 1N NH_4OAc, overnight equilibration, had the highest 'average R' value closely followed by 1N NH_4OAc + 0.2N $BaCl_2$, 1.5 hours and overnight equilibration (Table 27, column 12). It should be pointed out that R values for the soil Al-yield relationship in Experiments 2 and 3 were generally low which may imply that levels of extractable soil Al did not affect plant growth on these soils. For example, the lack of yield response to increased soil pH in Halii soil in Experiments 2 and 3 may be due to high Ca levels in the untreated soil which were reflected in plant Ca levels in the zero $CaSiO_3$ treatments (see Appendix Tables 95 and 96 for soil and plant Ca data). Therefore additions of $CaSiO_3$ did not influence corn and desmodium yields.

From the results of soil Al-plant Al and soil Al-yield relationships it is clear that Al extracted with one method is not best correlated with plant Al and yield. Aluminum extracted with unbuffered solutions, especially 1N KCl, is more closely related to plant Al whereas Al extracted with buffered solutions, especially 1N NH_4OAc, pH 4.8, is more closely related to plant yield than that extracted with other methods. Thus the selection of an extraction method depends on the objective of the study. However, it should be recalled that buffered solutions dissolve recently precipitated forms of Al and other insoluble Al compounds at soil pH above 5.0 where Al solubility is generally very low. Also, R values for the soil Al-yield relationships were generally lower than those for soil Al-plant Al relationships suggesting that while soil Al has a strong influence on plant Al, it has considerably less effect on yield.

Relationship of Al/Ca + Mg Ratio with Plant Al and Yield

Possible antagonism between Al and Ca uptake has been reported in alfalfa, snapbean, and barley (Schmehl *et al*, 1952; Ragland and Coleman, 1959; Johnson and Jackson, 1964). Gangwar (1967) showed that Al depressed sorption of Ca in excised pineapple and Kaimi clover roots. Zandstra (1972) suggested that Al toxicity in plants was in effect an induced Ca deficiency. He proposed that an appropriate measure of Al^{+3} toxicity effects is the $(Ca)^{1/2}/(Al)^{1/3}$ ratio in solution which could be estimated from the corresponding ratio of exchangeable ions.

In the present study, $(Al)^{1/3}/(Ca + Mg)^{1/2}$ ratios were calculated in Experiments 1, 2, and 4 by employing 1N KCl-, and 1N $BaCl_2$-extractable Al (1.5 hours shaking procedure) and 1N NH_4OAc, pH 7.0, extractable Ca and Mg expressed as moles per gram soil. The inclusion of Mg in the ratio was based on the fact that Ca and Mg are complementary ions and substitute for each other in exchange reactions. The objective of the study was to determine the effect of relative activities of these ions in solution on plant growth and Al concentrations in three plant species. Multiple regression analysis was performed using the ratio with plant Al and yield in Experiments 1, 2, and 4. Results of Experiment 1 where corn was grown in five unlimed soils, indicate that lower R values were obtained between the Al/Ca + Mg ratio and plant Al than between soil and plant Al alone (Table 28). Similar results were obtained in Experiment 2 where corn was grown on limed Akaka and Halii soils. In Experiment 4, however, correlation coefficients for the relationship between the ratio and clover top Al were higher than those obtained between soil and plant Al alone (Table 28).

Dry matter yield of corn in Experiment 1 and clover in Experiment 4 were more closely related to the Al/Ca + Mg ratio than to extractable soil Al alone and the increase in R was evident in ratios calculated with both KCl- and $BaCl_2$-extractable Al. In Experiment 2 a reduction in R value was obtained with the Al/Ca + Mg ratio from that of $BaCl_2$-extractable Al.

Table 28. Comparison of soil Al with Al/Ca + Mg ratio in relation to plant Al and yield (Experiments 1, 2 and 4)

Soil Al vs plant Al

Extracting solution[b]	Experiment number							
	1		2		4		1, 2, 4	
	Soil Al vs Plant Al	Ratio[a] vs Plant Al	Soil Al vs Plant Al	Ratio vs Plant Al	Soil Al vs Plant Al	Ratio vs Plant Al	Soil Al vs Plant Al	Ratio vs Plant Al
				R^c				
1$\underline{N}$ KCl	0.99	0.81	0.51*	0.46*	0.72	0.84	0.65	0.64
1$\underline{N}$ $BaCl_2$	0.81	0.78	0.69	0.46*	0.72	0.81	0.69	0.64

Soil Al vs yield

Extracting solution	Soil Al vs yield	Ratio vs yield	Soil Al vs yield	Ratio vs yield	Soil Al vs yield	Ratio vs yield	Soil Al vs yield	Ratio vs yield
1$\underline{N}$ KCl	0.76	0.84	0.49*	0.49*	0.81	0.85	0.57	0.61
1$\underline{N}$ $BaCl_2$	0.80	0.84	0.55	0.45*	0.81	0.86	0.60	0.63

[a] Ratio $=(Al)^{1/3}/(Ca+Mg)^{1/2}$, concentrations expressed as moles/g soil

[b] Al extracted by 1$\underline{N}$ KCl and 1$\underline{N}$ $BaCl_2$ (1.5 hours shaking), Ca and Mg displaced by 1$\underline{N}$ NH_4OAc, pH 7.0

[c] $Y = a + b_1X_1 + b_2X^2$, where X_1 = soil Al or Al/Ca+Mg ratio

* Significant at the 5% level. Values without asterisks are significant at the 1% level.

No change in R value was observed when the ratio was calculated with KCl-extractable Al and correlated with corn yield.

When regression analysis was performed on pooled data from all three experiments, slightly lower R values between Al/Ca + Mg ratio and plant Al than between soil and plant Al were obtained. However, the Al/Ca + Mg ratio was more closely related to yield than was soil Al when the pooled data of three experiments was analyzed. This increase in R values occurred with ratios calculated from both KCl- and $BaCl_2$-extractable Al. This suggests that yield response to $CaSiO_3$ applications in crops grown on high Al, low Ca soils may be due to the increased Ca supply as well as the reduction in soil Al levels with increased pH.

Interference of Color Development of Aluminon Reagent in $BaCl_2$ Extracts

Differential amounts of 1N $BaCl_2$ used for blank determinations in $BaCl_2$-extractable Al analysis produced varying intensities of the deep red color developed with aluminon (NH_4 - aurine tricarboxylate, $C_{22}N_3O_9$). Apparently $BaCl_2$ reacts with aluminon to form color compounds as does Al. It should be pointed out that the nature of the complex formed with aluminon which gives rise to the deep red lake, is not known (McLean, 1965). In the present study an attempt was made to minimize errors introduced in the Al analysis by the use of $BaCl_2$ solution. The method of Al determination using aluminon has been described earlier (see Materials and Methods).

A series of standard curves for increasing amounts of 1N $BaCl_2$ solution was constructed with solutions containing 0 to 50 µg Al (Figure 49). It is apparent that adding aliquots of 1N $BaCl_2$ to Al standards up to a volume of 8 ml increased optical density and the effect was greatest at higher Al concentrations. Figure 50 illustrates a standard curve where optical density was plotted for Al standards which contained 5, 8, 10, and 20 ml of 1N $BaCl_2$ solution. Data points are individual levels of $BaCl_2$ added. It is evident from Figure 50 that there was a slight increase in optical density with the addition of 8, 10, and 20 ml of $BaCl_2$ solution compared to addition of 5 ml, but there was no difference between the 8, 10, and 20 ml aliquots.

Based on the above results it is recommended that in soil extracts where the aliquot required for Al determination is less than 10 ml, additional 1N $BaCl_2$ should be added to give a constant total quantity of 10 ml $BaCl_2$ in all extracts. Practically, a constant volume of 10 ml $BaCl_2$ is more convenient and is recommended since there is no difference in optical density between 8 and 10 ml $BaCl_2$. This will eliminate errors in color development introduced by $BaCl_2$ when Al is determined with the aluminon method. In soil extracts with low Al concentrations, aliquots larger than 10 ml are

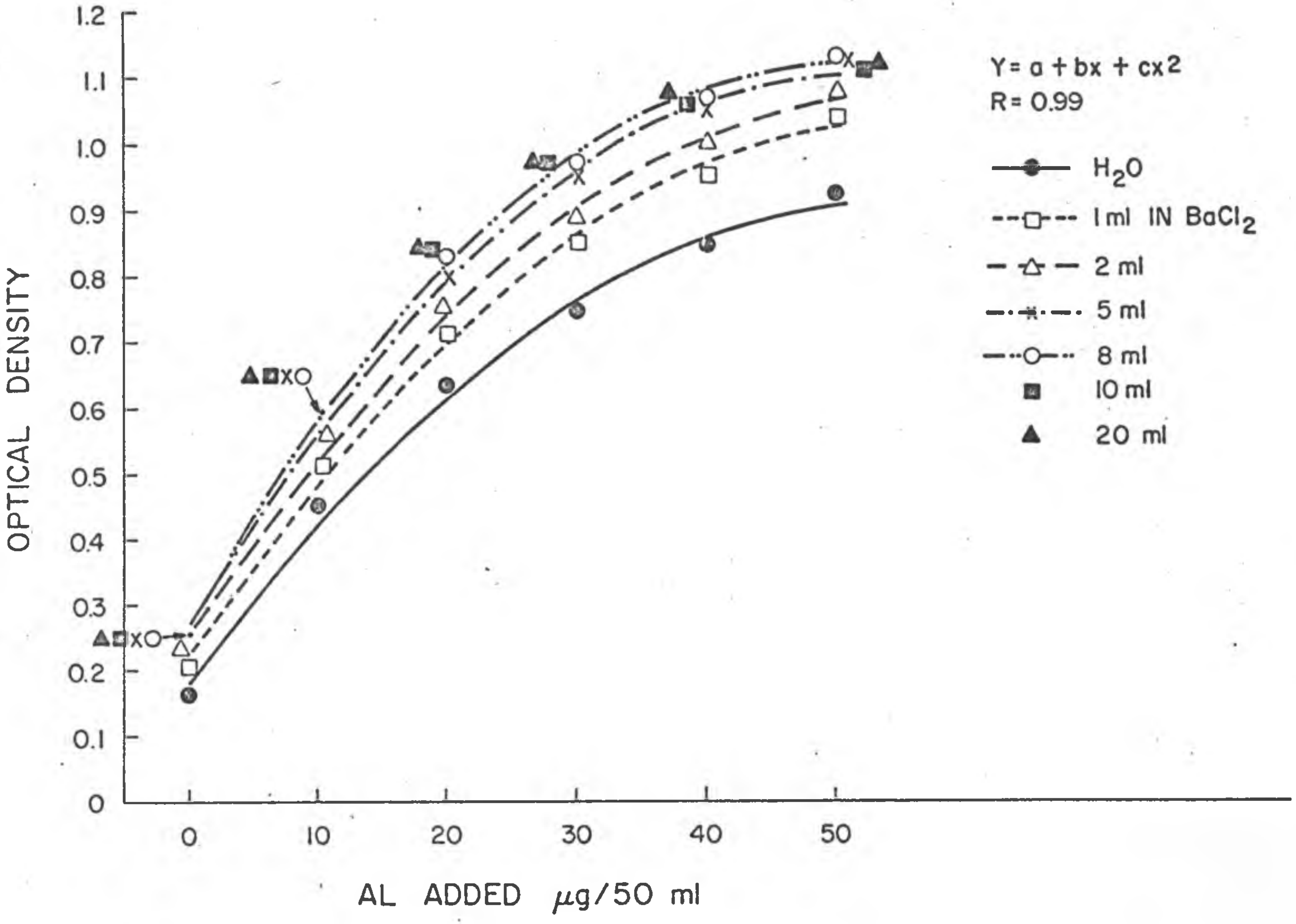

Figure 49. Influence of increasing amounts of 1N BaCl$_2$ in Al standards on color development in the aluminon method

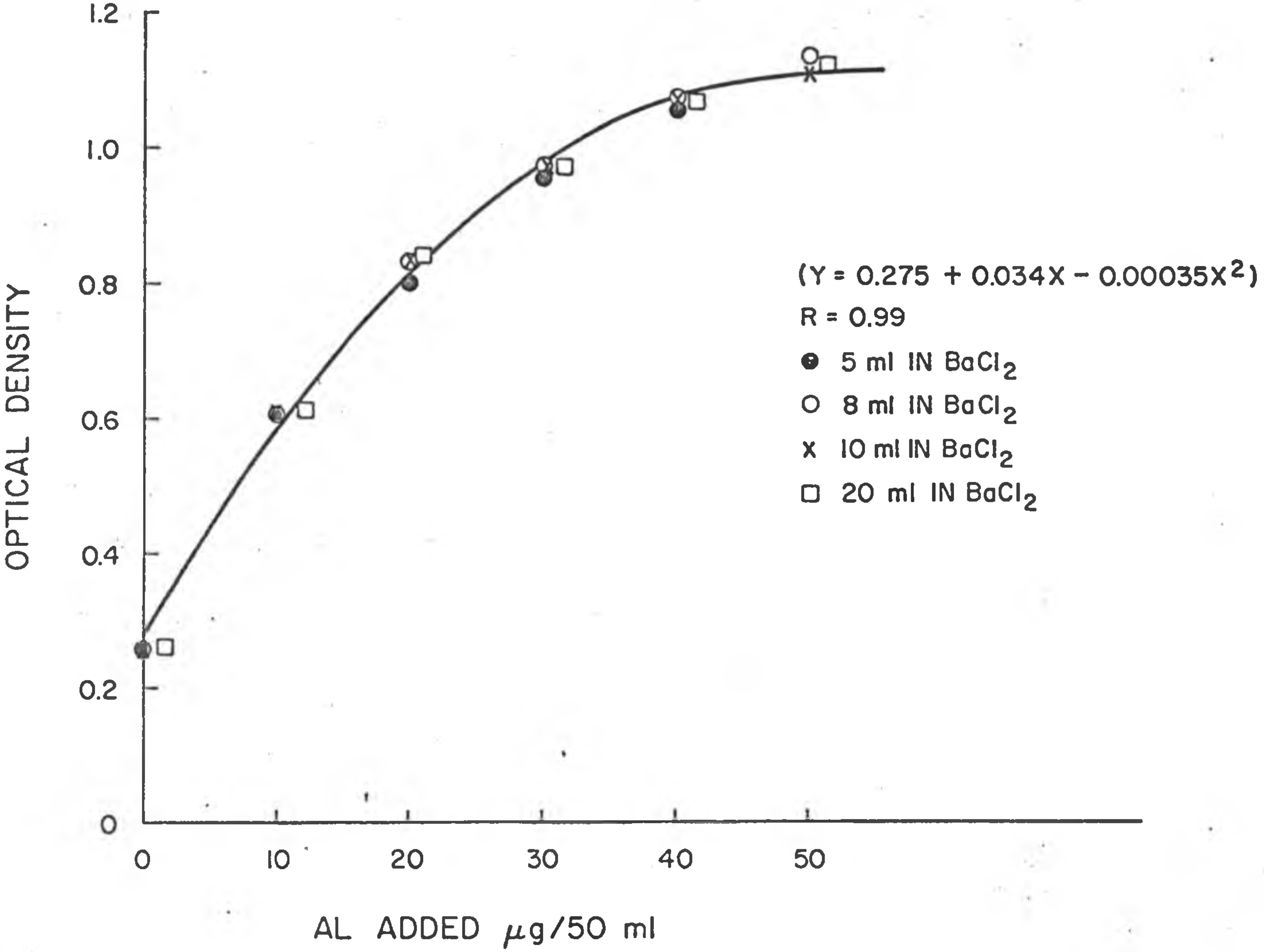

Figure 50. Standard curve for aluminon method with 5-20 mls of 1N $BaCl_2$ added to Al standards

required for analysis and no corrections for $BaCl_2$ are necessary.

Conclusions

Dry matter yield of corn grown in pots on five unlimed soils of different mineralogy and pH increased with increasing pH and soil Ca and decreased with increasing rainfall in the area where these soils developed. Aluminum concentrations of corn tops grown on Akaka soil were significantly higher than those on Halii, Wahiawa, Lualualei and Kawaihae soils while the differences between these soils were small and nonsignificant. The yield response of corn, desmodium and Louisiana white clover to $CaSiO_3$ was evident in Akaka soil. A yield increase with $CaSiO_3$ in Halii soil was observed only in white clover which may indicate soil-plant interactions in Halii soil are responsible for the differential behavior of plant species. Aluminum concentrations in tops of all three species decreased with increasing soil pH in Akaka soil while this pattern was observed only with clover in Halii soil. Aluminum concentrations in white clover tops were the highest followed by corn and desmodium which suggests that plant species differ in their ability to translocate Al from roots to tops.

Soil Al was extracted with 14 methods using 6 extracting solutions from soil samples collected after harvest. Combined Al data for all experiments indicated that in 1N KCl and 1N $BaCl_2$ solutions more Al was extracted by shaking for 1.5 hours and after overnight equilibration than was extracted by immediate extraction. With 1N NH_4OAc and 1N NH_4OAc + 0.2N $BaCl_2$, both adjusted to pH 4.8, extractable Al increased with increasing period of equilibration. The amount of Al extracted by various solutions decreased in the order: 1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8 > 1N NH_4OAc, pH 4.8 > 1N $BaCl_2$ ≥ 1N KCl ≥ H_2O ≥ 0.01M $CaCl_2$. Aluminum extracted from various soils was in the order Akaka > Halii > Wahiawa ≥ Lualualei = Kawaihae which is related to the degree of weathering and amount of rainfall affecting the soil.

Extractable Al in Akaka and Halii soils decreased with $CaSiO_3$ and $CaCO_3$ applications due to the pH increase which caused the formation of less soluble hydroxide forms of Al. Buffered solutions of 1N NH_4OAc and 1N NH_4OAc + 0.2N $BaCl_2$, extracted appreciable amounts of Al at soil pH above 5.0 because extraction was accomplished at about pH 4.8 which allowed extraction of recently precipitated forms of Al and otherwise insoluble Al compounds.

Results of ranking technique and 'mean R' values show that Al extracted with unbuffered solutions especially 1N KCl is more closely related to plant Al whereas Al extracted with buffered solutions, especially 1N NH_4OAc, pH 4.8, is more closely related to plant yield than that extracted with other methods. However, R values for the soil Al-plant yield relationships were generally lower than those for soil Al-plant Al relationships. This suggests that while soil Al has a strong influence on plant Al, it has considerably less effect on yield.

Ratios of $(Al)^{1/3}/(Ca + Mg)^{1/2}$ in soil extracts did not improve existing soil-plant Al relationships which may imply that ratios of Al and Ca + Mg activity in the soil solution had no effect on uptake of Al by plants. However, the $(Al)^{1/3}/(Ca + Mg)^{1/2}$ ratio was more highly correlated with dry matter yield than was soil Al. This increase in R values occurred with ratios calculated from both 1N KCl-and 1N $BaCl_2$-extractable Al. This suggests that yield increases were due to increased Ca + Mg levels as well as reduced Al concentrations in soil.

The errors due to variable color intensity with 1N $BaCl_2$ in the aluminon method can be eliminated by adding sufficient $BaCl_2$ solution to samples to give a constant volume of 10 ml $BaCl_2$ where smaller aliquots are used for analysis. Laboratory studies showed that addition of more than 8 ml $BaCl_2$ to samples had no effect on color development in the aluminon method.

SUMMARY AND CONCLUSIONS

The influence of residual Si, P and soil pH on the yield and nutrient uptake of kikuyu grass and desmodium was investigated in a 3 x 3 x 3 factorial experiment installed on a Gibbsihumox at the Kauai Branch Station. The fate of applied Si during and after five years of cropping was determined by plant uptake, exhaustive extraction of profile samples with phosphate solution and by water extraction. Residual Si in the 0 to 15 and 15 to 30 cm horizons at the end of the experiment was also extracted by rice grown in a growth chamber. A study of soil Al extraction methods in relation to Al concentrations in plant tissues and growth of corn, desmodium, and Louisiana white clover grown on some Hawaiian soils were also conducted.

The combined yields of seven harvests of kikuyu grass and desmodium increased significantly with increasing residual P levels, but were not significantly affected by residual Si or soil pH. The relative yield differential between the three Si treatments decreased sharply with time and at the end of 56 months yield from 1660 Si was only 2.5% higher than that with zero Si whereas yield from 830 Si was less than yield with zero Si. The decline in the relative yield response to P applications with time was small which indicates a high efficiency of P applied 56 months earlier. However, it should be pointed out that two supplemental additions of

P were made 21 and 27 months after the initial treatments.

Silicon concentrations in the whole-plant increased significantly with increasing residual Si in the last harvest in both species as did index-tissue Si concentrations in the last harvest and total Si uptake of all harvests combined. Although residual Si produced highly significant increases in water-extractable soil Si, the levels at the end of the experiment were lower than those set by Fox et al (1967b) as deficient for sugarcane growth. The lack of yield response to residual Si may be due to Si becoming strongly adsorbed with time leaving little Si available for plant growth. Supplemental applications may be necessary to maintain the growth response to Si.

Modified Truog-extractable soil P was significantly higher at 1660 Si than at zero Si at 56 months and also at 9, 21, and 40 months. The amount of Si sorbed at 0.2 ppm P in solution was significantly reduced by residual Si and P treatments at 56 months. However, P was about 7 times more effective than residual Si in reducing P requirements which contradicts the work of Roy et al (1971) who reported that in soil samples collected 9 months after the initial application, Si was more efficient than P in decreasing P requirements. Apparently, Si became more strongly adsorbed with time than P and therefore was less effective in reducing P sorption. Sorbed P was shown to be a better indicator of plant P needs than modified Truog-extractable P.

Multiple regression analysis showed that in addition to the treatments applied five years ago, the soil factors important to plant growth in both species were P sorbed, modified Truog-extractable P and $BaCl_2$-extractable Al. Plant variables which appeared to be important for crop production included P, K, and Mg and possibly also Mn, Zn, Al and Ca.

Water- and phosphate-extractable soil Si in soil profiles at the end of five years increased significantly with residual Si only in the top two layers. More Si leached from the surface layer to the 15 to 30 cm horizon at pH 5.5 than at pH 6.5 due to greater Si solubility at lower soil pH. Levels of extractable Si below 30 cm were very low and showed no consistent pattern of Si treatments which indicates that there was no substantial leaching of applied Si below 30 cm. Phosphate-extractable Si levels in the 0 to 15 cm horizon were higher at pH 6.5 than at pH 5.5 and 6.0 at the end of the experiment implying that less Si was removed by plant uptake or by leaching at pH 6.5. Phosphate-extractable Si appears to be an index of the capacity of soil to supply Si.

Plant uptake by the sugarcane plant and ratoon crops, corn, and seven harvests of kikuyu grass accounted for 12 to 21% of the applied Si. Exhaustive phosphate extraction of profile samples taken after five years recovered 14 to 28%

of the applied Si. Total recovery of applied Si ranged from 28 to 43% which means that 57 to 72% of the applied Si remained in the soil in some form not readily displaced by phosphate solution.

Uptake of Si by plant and ratoon crops of rice grown on soil from 0 to 15 and 15 to 30 cm horizons increased considerably with increasing levels of residual Si. Total amounts of Si removed by plant and ratoon crops combined were substantially greater at pH 6.5 than at pH 5.5 and 6.0 which is in contrast to the field data where crops extracted more Si at pH 5.5 than at pH 6.5. Apparently, Si extraction by rice plants was closely related to phosphate-extractable Si levels which reflect the amount of Si fixed by the soil rather than the solubility of soil Si. The rate of Si uptake from soil by rice decreased with time possibly due to the reduced rate of soil Si release and/or reduced yields in the ratoon crop.

More Si was extracted by plant and ratoon crops of rice combined than by phosphate solution because the total extraction time for rice was longer and also because of possibly greater efficiency of Si removal by rice roots. Rice extracted proportionately more native Si than did phosphate solution which resulted in comparable amounts of added Si being recovered by the two methods, i.e., 8 to 30% for rice and 13 to 23% for exhaustive phosphate extraction.

The results of this study show that 55 to 72% of Si applied five years ago is still retained by the soil in a form that these techniques could not measure.

An evaluation of 14 methods for extraction of soil Al using 6 extracting solutions showed that amount of Al extracted by the various solutions decreased in the order: 1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8 > 1N NH_4OAc, pH 4.8 > 1N $BaCl_2 \geqslant$ 1N KCl $\geqslant$ $H_2O \geqslant$ 0.01M $CaCl_2$. Aluminum extracted from the five soils tested was in the order Akaka > Halii > Wahiawa > Lualualai = Kawaihae which is related to the degree of weathering and the amount of rainfall affecting the soil.

Extractable Al in Akaka and Halii soils decreased with $CaSiO_3$ and $CaCO_3$ applications due to an increase in pH which caused the formation of less soluble hydroxides of Al. Buffered solutions of 1N NH_4OAc and 1N NH_4OAc + 0.2N $BaCl_2$, extracted appreciable amounts of Al when soil pH was above 5.0 because extraction was performed at about pH 4.8 which allowed removal of recently precipitated forms of Al and otherwise insoluble Al compounds.

From the results of soil Al-plant Al and soil Al-yield relationships it is clear that Al extracted with one method is not best correlated with plant Al and yield. Aluminum extracted with unbuffered solutions, especially 1N KCl, is more closely related to plant Al whereas Al extracted with buffered solutions, especially 1N NH_4OAc, pH 4.8, is more closely related to plant yield than that extracted with other methods. Thus the selection of an extraction method depends on the objective of the study. However, it should be recalled that buffered solutions dissolve recently precipitated forms of Al and other insoluble Al compounds at soil pH above 5.0 where Al solubility is generally very low. Also, R values for the soil Al-yield relationships were generally lower than those for soil Al-plant Al relationships suggesting that while soil Al has a strong influence on plant Al, it has considerably less effect on yield.

Ratios of $(Al)^{1/3}/(Ca + Mg)^{1/2}$ in soil extracts did not improve existing soil-plant Al relationships but did improve soil Al-yield relationships. This suggests that yield increases in these soils were due to increased Ca and Mg as well as reduced soil Al concentrations.

The errors due to variable color intensity with 1N $BaCl_2$ in the aluminon method can be eliminated by adding sufficient 1N $BaCl_2$ solution to samples to give a constant volume of 10 mls $BaCl_2$ where smaller aliquots are used for Al analysis.

APPENDIX A

Plant Analytical Methods

Digestion Procedures

Lithium Tetraborate Fusion

A modification of the lithium tetraborate method of Suhr and Ingamells (1966) was used for fusion of ashed plant material for Si determination. A 0.5 gram sample of the ground plant material was weighed into a platinum crucible and ashed overnight at 550° C in a muffle furnace. The cooled ash was thoroughly mixed with 0.5 gram lithium tetraborate and the material transferred to a carbon crucible. The mixture was fused for 20 minutes at 950° C in a muffle furnace. The crucible was removed, swirled and the hot melt poured into a 400-ml beaker containing 100 mls of 0.5N nitric acid. The mixture was stirred with a magnetic stirrer to dissolve the melt and the solution stored in a plastic vial for Si determination.

Nitric-Perchloric Acid Digestion

Plant P, K, Ca, Mg, Al, Mn and Zn were determined in the nitric-perchloric acid digest (Jackson, 1958). A 0.5 gram sample of the ground plant material was transferred to a 100 ml Kjeldahl flask and 15 mls of 2:1 nitric-perchloric acid mixture added. The mix was predigested overnight in the Kjeldahl flask covered with an inverted beaker. Digestion was carried out on a MicroKjeldahl digestion rack at low temperature for 30 minutes and then at high temperature to the white fuming stage. Digestion was continued at low temperature for another 15 minutes to complete the dehydration of Si. After cooling the material was transferred to a 50 ml volumetric flask and made to volume with distilled water.

Chemical Methods

Plant Silicon

Plant silicon was determined by the Silico-Molybdate Blue method of Kilmer (1965).

A suitable aliquot was pipetted into a 50 ml volumetric flask, diluted to about 35 mls with distilled water and 1 ml of ammonium molybdate solution added. After 30 minutes, 3 ml 10% oxalic acid was added and within two minutes 1 ml reducing solution (1 amino, 2 napthal, 4 sulphonic acid) was added with mixing and the sample made to volume. After 30 minutes, optical density was measured with a Coleman Junior Spectrophotometer at 660 mμ.

Plant Phosphorus

Plant P was determined by the Vandate-Molybdate yellow method of Barton (1948) as follows:

A suitable aliquot of the nitric-perchloric digest was pipetted into a 50 ml volumetric flask and diluted to about 35 ml. Five ml Barton's reagent was added, the solution was mixed and made to volume with distilled water, then mixed and allowed to stand for 30 minutes for color development. Optical density was measured on a Coleman Junior Spectrophotometer at 430 mμ.

Plant Aluminum

Plant Al was determined by the aluminon method of Chenery (1948) as described by McLean (1965). A suitable aliquot of the nitric-perchloric acid digest was pipetted into a 100 ml beaker and diluted to about 20 ml. Two ml 1% thioglycolic acid and 10 ml aluminon reagent were added and pH was adjusted to 4.2 with 1:1 NH_4OH or 1:1 HCl. The solution was then transferred to a 50 ml volumetric flask with 2 to 3 small washings of distilled water. The flask was heated in a boiling water bath for 16 minutes, allowed to cool, then made to volume and mixed vigorously. The optical density was measured on a Coleman Junior Spectrophotometer at 537.5 mμ.

Plant Calcium and Magnesium

A suitable aliquot of nitric-perchloric acid digest was transferred to a 50 ml volumetric flask and lanthanum oxide added to give a concentration of 0.5% lanthanum in the diluted solution. The lanthanum is added to eliminate interference from Al, P or SO_4 ions. The Ca and Mg concentrations were determined with a Perkin-Elmer atomic absorption spectrophotometer model 303.

Plant Manganese and Zinc

Plant Mn and Zn concentrations were read directly on a portion of the nitric-perchloric acid digest with the Perkin-Elmer Atomic absorption spectrophotometer model 303.

Plant Potassium

Potassium in the solution used for Ca and Mg determination was measured on a Beckman D. U. flame photometer.

Soil Analytical Methods

Extraction Procedures

Water-extractable Silicon

Three grams of soil (oven dry basis) was shaken with 30 ml distilled water in a centrifuge tube for four hours. The suspension was centrifuged at 12,000 rpm and Si in the supernatent was determined with the Silico-molybdate blue method of Kilmer (1965) as described earlier.

Modified Truog-extractable Phosphorus

Soil P was extracted by the modified Truog method of Ayers and Hagihara (1952) as follows:

A 2.0 gram soil sample (oven dry basis) was shaken with 200 ml 0.02N H_2SO_4 containing 3.0 grams ammonium sulphate per liter for 30 minutes in a 500 ml Erlenmeyer flask. The suspension was filtered through Whatman No. 42 filter paper and P in the extract was determined by the method of Dickman and Bray (1940).

$BaCl_2$-Extractable Aluminum

Ten grams of soil were shaken with 100 ml 1N $BaCl_2$ for 1.5 hours and filtered through 2V filter paper. Aluminum in the extract was determined with the aluminon method of Chenery (1948) as described earlier for plant Al.

Chemical Methods

Soil Phosphorus

Soil P was determined with the Molybdenum Blue method of Dickman and Bray (1940) as described by Jackson (1958). A suitable aliquot of the modified Truog extract was transferred to a 50 ml volumetric flask and diluted to about 35 ml. Five ml ammonium molybdate solution was added and mixed, then 2 ml diluted stannous chloride was added with force, the solution made to volume and mixed. After 10 minutes, the optical density was measured on a Coleman Junior Spectrophotometer at 660 mμ.

APPENDIX B

Table 1. Influence of residual Si, P and soil pH on kikuyu grass yield (Harvest 1)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	6000	4846	3968	5740	5138	5952	6163	5821	5675				5887
830	5578	4862	5090	5009	5708	6846	5545	5822	5155	4049	4683	3919	6147
1660	5187	4943	5870	5139	6375	5236	4830	4716	5187				5057

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	4938	5610	5886	5478
830	5177	5854	5507	5513
1660	5333	5583	4911	5276
Ave.	5150	5682	5435	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	5968	5268	5198	5478
830	5377	5464	5697	5513
1660	5052	5345	5431	5276
Ave.	5466	5359	5442	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	5591	5296	5513	5466
280	4884	5740	5453	5359
1120	4976	6011	5339	5442
Ave.	5150	5682	5435	

Control plot 3757

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 2. Influence of residual Si, P and soil pH on kikuyu grass yield (Harvest 2)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5300	5122	5659	4992	5659	5545	5480	6130	6196				4862
830	5838	5464	5334	5789	5545	6374	5936	5594	5578	4732	5106	4814	4586
1660	5269	5399	6098	5366	5578	5545	5106	5871	5399				4488

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	5360	5399	5935	5565
830	5545	5903	5703	5717
1660	5589	5496	5459	5515
Ave.	5498	5599	5699	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	5257	5637	5800	5565
830	5854	5534	5762	5717
1660	5247	5616	5681	5515
Ave.	5453	5596	5748	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	5469	5382	5507	5453
280	5328	5594	5865	5596
1120	5697	5821	5724	4748
Ave.	5498	5599	5699	

Control plot 3171

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 3. Influence of residual Si, P and soil pH on kikuyugrass yield (Harvest 3)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	9274	7318	9529	8310	9204	9499	9090	9383	10082				6651
830	9282	9237	9334	7188	8570	9107	8082	9676	8196	7415	7399	8944	7041
1660	10505	9595	9432	8179	8830	9123	8310	8716	9383				6310

Si x pH††

Si (kg/ha)	pH 5.5	6.0	6.5	Ave.
0	8707	9004	9518	9076
830	9284	8288	8651	8741
1660	9844	8711	8803	9119
Ave.	9278	8668	8991	

Si x P††

Si (kg/ha)	P (kg/ha) 110	280	1120	Ave.
0	8891	8635	9703	9076
830	8184	9161	8879	8741
1660	8998	9047	9313	9119
Ave.	8691	8948	9298	

P x pH††

P (kg/ha)	pH 5.5	6.0	6.5	Ave.
110	9687	7892	8494	8691
280	8717	8868	9258	8948
1120	9432	9243	9220	9298
Ave.	9278	8668	8991	

Control plot 5269

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 4. Influence of residual Si, P and soil pH on kikuyugrass yield (Harvest 4)*

Si x P x pH[†]

Si (kg/ha)	pH 5.5 P (kg/ha) 110	pH 5.5 P (kg/ha) 280	pH 5.5 P (kg/ha) 1120	pH 6.0 P (kg/ha) 110	pH 6.0 P (kg/ha) 280	pH 6.0 P (kg/ha) 1120	pH 6.5 P (kg/ha) 110	pH 6.5 P (kg/ha) 280	pH 6.5 P (kg/ha) 1120	pH 5.0 P (kg/ha) 110	pH 5.0 P (kg/ha) 280	pH 5.0 P (kg/ha) 1120	pH 6.0 P (kg/ha) 0
0	3517	3778	4016	3048	2981	3510	2996	3622	3647				3092
830	3896	4046	3746	2933	2964	4000	3296	3767	3204	3453	3288	4024	2946
1660	3758	3680	4362	3179	3309	3408	3990	3795	3760				2897

Si x pH[††]

Si (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
0	3770	3180	3422	3457
830	3896	3299	3422	3539
1660	3933	3299	3848	3693
Ave.	3866	3259	3564	

Si x P[††]

Si (kg/ha)	P (kg/ha) 110	P (kg/ha) 280	P (kg/ha) 1120	Ave.
0	3187	3460	3724	3457
830	3375	3592	3650	3539
1660	3642	3595	3843	3693
Ave.	3401	3549	3739	

P x pH[††]

P (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
110	3724	3053	3427	3401
280	3835	3085	3728	3549
1120	4041	3639	3537	3739
Ave.	3866	3259	3564	

Control plot 2900

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 5. Influence of residual Si, P and soil pH on kikuyugrass yield (Harvest 5)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4944	4651	4813	4927	4586	5545	5431	4781	5838				4992
830	4716	5090	5236	4456	5106	5285	4407	5057	5594	5041	5041	5091	4716
1660	5334	5123	5155	5383	5367	5122	5611	5399	5578				4228

Si x pH††

Si (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
0	4803	5019	5350	5057
830	5014	4949	5019	4994
1660	5204	5291	5529	5341
Ave.	5007	5086	5299	

Si x P††

Si (kg/ha)	P (kg/ha) 110	280	1120	Ave.
0	5101	4673	5399	5057
830	4526	5084	5372	4994
1660	5442	5296	5285	5341
Ave.	5023	5018	5352	

P x pH††

P (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
110	4998	4922	5150	5023
280	4955	5020	5079	5018
1120	5068	5317	5670	5352
Ave.	5007	5086	5299	

Control plot 3025

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 6. Influence of residual Si, P and soil pH on kikuyugrass yield (Harvest 6)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4106	3475	4681	3568	4641	4544	4545	4194	5023				3527
830	4149	4874	4716	3698	3919	5170	4186	4818	4738	3926	3662	4336	2360
1660	4152	4863	4447	3926	4689	5308	4467	5068	4824				2644

Si x pH††

Si (kg/ha)	pH 5.5	6.0	6.5	Ave.
0	4057	4251	4587	4298
830	4580	4262	4581	4474
1660	4487	4641	4786	4638
Ave.	4375	4385	4651	

Si x P††

Si (kg/ha)	P (kg/ha) 110	280	1120	Ave.
0	4043	4103	4749	4298
830	4011	4537	4875	4474
1660	4182	4873	4860	4638
Ave.	4079^{a}	** 4504^{b}	4828^{b}	

P x pH††

P (kg/ha)	pH 5.5	6.0	6.5	Ave.
110	4106	3731	4399	4079
280	4401	4416	4693	4504
1120	4615	5007	4862	4828
Ave.	4375	4385	4651	

Control plot 46

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 7. Influence of residual Si, P and soil pH on kikuyugrass yield (Harvest 7)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3442	3834	5400	3287	3738	4787	2584	3771	4026				2698
830	3965	4034	4163	3283	3881	4988	3302	2523	3047	2376	3126	3841	2556
1660	3116	4641	4693	3201	3055	4667	2674	4371	4682				3109

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	4225	3937	3460	3874
830	4054	4050	2957	3687
1660	4150	3641	3909	3900
Ave.	4143	3876	3442	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	3104	3781	4738	3874
830	3516	3479	4066	3687
1660	2997	4022	4681	3900
Ave.	3206^{a}**	3761^{a}	4495^{b}	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	3508	3257	2853	3206
280	4170	3558	3555	3761
1120	4752	4814	3918	4495
Ave.	4143	3876	3442	3820

Control plot 1736

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 8. Influence of residual Si, P and soil pH on kikuyugrass yield (total of 7 harvests)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	36.6	33.0	38.1	33.9	35.9	39.4	36.2	37.7	40.5				31.7
830	37.4	37.6	37.6	32.3	35.7	41.8	34.7	37.2	35.5	31.0	32.3	35.0	30.3
1660	37.3	38.2	40.1	34.3	37.2	38.4	35.0	37.2	38.8				28.7

Si x pH††

Si (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
0	35.9	36.4	38.1	36.8
830	37.5	36.6	35.8	36.6
1660	38.5	36.6	37.0	37.4
Ave.	37.3	36.6	37.0	

Si x P††

Si (kg/ha)	P (kg/ha) 110	P (kg/ha) 280	P (kg/ha) 1120	Ave.
0	35.6	35.5	39.3	36.8
830	34.8	36.8	38.3	36.6
1660	35.5	37.5	39.1	37.4
Ave.	35.3^{a**}	36.6^{a}	38.9^{b}	

P x pH††

P (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
110	37.1	33.5	35.3	35.3
280	36.3	36.3	37.4	36.7
1120	38.6	39.9	38.3	38.9
Ave.	37.3	36.6	37.0	

Control plot 20.0

* Expressed as tons (metric)/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 9. Influence of residual Si, P and soil pH on desmodium yield (Harvest 1)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5594	5854	7041	7253	6244	6748	6846	6440	7009				5675
830	6065	7546	6212	6212	7984	6895	5691	6521	6425	6619	5561	5936	5301
1660	6066	6618	6813	6684	6846	6732	6521	6700	5285				6472

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	6163	6748	6765	6559
830	6608	7030	6212	6617
1660	6499	6754	6169	6474
Ave.	6423	6844	6382	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	6564	6179	6933	6559
830	5989	7350	6511	6617
1660	6424	6721	6277	6474
Ave.	6326	6750	6574	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	5908	6716	6353	6326
280	6673	7024	6554	6750
1120	6689	6792	6240	6574
Ave.	6423	6844	6382	

Control plot 3366

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 10. Influence of residual Si, P and soil pH on desmodium yield (Harvest 2)[*]

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1935	2146	2520	2342	2602	2537	1659	3529	2651				1252
830	2114	2406	2179	2131	2374	3041	2976	2716	2880	1366	2322	1919	1510
1660	1870	2374	2975	1480	2293	2862	2000	2260	2813				1821

Si x pH[††]

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	2200	2494	2613	2436
830	2233	2515	2857	2535
1660	2406	2212	2358	2325
Ave.	2280	2407	2609	

Si x P[††]

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	1979	2759	2569	2436
830	2407	2499	2700	2535
1660	1783	2309	2883	2325
Ave.	2056^{a**}	2522^{b}	2717^{b}	

P x pH[††]

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	1973	1984	2212	2056
280	2309	2423	2835	2522
1120	2558	2813	2781	2717
Ave.	2280	2407	2609	

Control plot 2098

[*] Expressed as kg/ha

[†] Means of 3 observations

[††] Means of 9 observations

[**] Means not followed by the same letter are significantly different at the 5% level

Table 11. Influence of residual Si, P and soil pH on desmodium yield (Harvest 3)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	7415	7285	7267	6082	7171	7955	7643	8229	7464				6066
830	7741	6732	6033	7269	7188	7497	7854	6179	6440	4635	7269	8456	5480
1660	7383	7009	7562	6212	7251	9529	7496	7529	8098				5025

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	7322	7069	7779	7390
830	6835	7318	6824	6992
1660	7318	7664	7708	7568
Ave.	7158	7350	7437	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	7047	7562	7562	7390
830	7621	6700	6657	6992
1660	7030	7263	8410	7568
Ave.	7233	7175	7453	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	7513	6521	7664	7233
280	7009	7203	7312	7175
1120	6954	8327	7334	7538
Ave.	7158	7530	7437	

Control plot 1464

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 12. Influence of residual Si, P and soil pH on desmodium yield (Harvest 4)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3642	4000	4217	3994	3684	4103	3956	4897	4921				3203
830	4010	3885	3942	4377	4357	4365	4362	4170	4493	3182	3763	3376	3120
1660	4154	3949	4352	3411	4113	4118	3670	4607	4514				3903

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	3953	3927	4591	4157
830	3946	4366	4342	4218
1660	4152	3881	4264	4099
Ave.	4017	4058	4399	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	3864	4194	4414	4157
830	4250	4137	4267	4218
1660	3745	4223	4328	4099
Ave.	3953	4185	4336	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	3935	3927	3996	3935
280	3945	4051	4558	4185
1120	4170	4195	4643	4336
Ave.	4017	4058	4399	

Control plot 1191

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

Table 13. Influence of residual Si, P and soil pH on desmodium yield (Harvest 5)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2049	2439	2098	2293	2293	2374	1707	2228	2553				2293
830	1675	2618	2520	2082	2082	2716	2732	2586	2781	2376	2098	2276	2781
1660	2260	2098	2780	2066	2732	2878	2325	1919	2342				2146

Si x pH††

Si (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
0	2195	2320	2163	2226
830	2271	2293	2700	2421
1660	2379	2559	2195	2378
Ave.	2282	2391	2353	

Si x P††

Si (kg/ha)	P (kg/ha) 110	P (kg/ha) 280	P (kg/ha) 1120	Ave.
0	2016	2320	2342	2226
830	2163	2429	2672	2421
1660	2217	2250	2667	2378
Ave.	2132^{a**}	2333^{a}	2560^{b}	

P x pH††

P (kg/ha)	pH 5.5	pH 6.0	pH 6.5	Ave.
110	1995	2147	2255	2132
280	2385	2369	2244	2333
1120	2466	2656	2559	2560
Ave.	2292	2391	2353	

Control plot 976

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 14. Influence of residual Si, P and soil pH on desmodium yield (Harvest 6)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1583	2115	2002	2702	2493	2429	2180	2412	3238				1475
830	2061	2201	2303	2112	2297	2511	2384	2292	2657	1136	1745	2032	1435
1660	2212	2140	2491	1918	2887	3314	2366	2430	2315				1835

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	1900	2541	2610	2350
830	2188	2307	2444	2313
1660	2281	2706	2370	2452
Ave.	2123	2518	2475	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	2155	2340	2556	2350
830	2186	2263	2490	2313
1660	2165	2486	2708	2453
Ave.	2169^{a**}	2363^{ab}	2585^{b}	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	1952	2244	2310	2169
280	2152	2559	2378	2363
1120	2262	2751	2737	2584
Ave.	2123	2518	2475	

Control plot 106

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 15. Influence of residual Si, P and soil pH on desmodium yield (Harvest 7)*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2053	2365	3291	2431	2765	2931	2071	3024	3633				1495
830	2305	2750	3466	2551	2599	4169	2505	3205	3700	1855	1951	2477	1588
1660	1927	3198	3423	1544	2913	3639	2634	3118	3050				1787

Si x pH††

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	2570	2709	2909	2729
830	2840	3106	3137	3028
1660	2849	2699	2934	2827
Ave.	2753	2838	2993	

Si x P††

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	2185	2718	3285	2729
830	2454	2851	3778	3028
1660	2035	3076	3370	2827
Ave.	2225^{a**}	2882^{b}	3478^{c}	

P x pH††

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	2095	2175	2403	2225
280	2771	2759	3116	2882
1120	3393	3580	3461	3478
Ave.	2753	2838	2993	

Control plot 411

* Expressed as kg/ha

† Means of 3 observations

†† Means of 9 observations

** Means not followed by the same letter are significantly different at the 5% level

Table 16. Influence of residual Si, P and soil pH on desmodium yield (total of 7 harvests)[*]

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	24.3	26.2	28.4	27.1	27.2	29.1	26.1	30.7	31.5				21.5
830	26.0	28.1	26.6	26.7	28.9	31.2	28.5	27.7	29.4	21.2	24.7	26.5	21.2
1660	25.9	27.4	30.4	23.3	29.0	33.1	27.0	28.6	28.4				23.0

Si x pH[††]

Si (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
0	26.3	27.8	29.4	27.8
830	26.9	28.9	28.5	28.1
1660	27.9	28.5	28.0	28.1
Ave.	27.0	28.4	28.6	

Si x P[††]

Si (kg/ha)	P (kg/ha)			Ave.
	110	280	1120	
0	25.8	28.0	29.7	27.8
830	27.1	28.2	29.1	28.1
1660	25.4	28.3	30.6	28.1
Ave.	26.1^{a**}	28.2^{b}	29.8^{c}	

P x pH[††]

P (kg/ha)	pH			Ave.
	5.5	6.0	6.5	
110	25.4	25.7	27.2	26.1
280	27.2	28.4	29.0	28.2
1120	28.5	31.1	29.8	29.8
Ave.	27.0	28.4	28.7	

Control plot 9.6

[*] Expressed as tons (metric)/ha

[†] Means of 3 observations

[††] Means of 9 observations

[**] Means not followed by the same letter are significantly different at the 5% level

Table 17. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 1)[*]

Kikuyugrass

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.119	0.216	0.229	0.133	0.167	0.253	0.285	0.116	0.178				0.225
830	0.248	0.347	0.322	0.359	0.233	0.311	0.201	0.243	0.278	0,390	0.359	0.370	0.261
1660	0.382	0.544	0.461	0.418	0.435	0.512	0.536	0.406	0.481				0.512

Control plot 0.386

Desmodium

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.088	0.118	0.115	0.074	0.064	0.134	0.116	0.079	0.086				0.107
830	0.206	0.200	0.157	0.148	0.123	0.182	0.116	0.130	0.127	0.223	0.187	0.218	0.214
1660	0.332	0.249	0.286	0.275	0.230	0.233	0.212	0.193	0.200				0.263

Control plot 0.248

[*] Expressed as % Si

[†] Three replicates composited for analysis

Table 18. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 2)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.223	0.294	0.207	0.165	0.165	0.359	0.149	0.136	0.178				0.280
830	0.399	0.447	0.392	0.328	0.263	0.367	0.274	0.349	0.379	0.474	0.304	0.461	0.374
1660	0.477	0.607	0.402	0.474	0.459	0.514	0.522	0.448	0.406				0.579

Control plot 0.346

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.158	0.164	0.231	0.138	0.094	0.239	0.196	0.156	0.143				0.176
830	0.331	0.367	0.292	0.259	0.287	0.290	0.215	0.186	0.153	0.380	0.300	0.332	0.322
1660	0.571	0.370	0.462	0.477	0.459	0.396	0.291	0.251	0.345				0.495

Control plot 0.241

* Expressed as % Si

† Three replicates composited for analysis

Table 19. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 3)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.175	0.136	0.119	0.136	0.123	0.191	0.144	0.120	0.146				0.260
830	0.246	0.259	0.238	0.243	0.185	0.272	0.228	0.257	0.278	0.379	0.235	0.281	0.317
1660	0.421	0.392	0.385	0.411	0.408	0.329	0.314	0.246	0.301				0.447

Control plot 0.241

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.061	0.08	0.075	0.055	0.038	0.081	0.089	0.06	0.06				0.092
830	0.130	0.113	0.085	0.103	0.082	0.122	0.087	0.072	0.081	0.160	0.105	0.105	0.184
1660	0.208	0.168	0.145	0.182	0.168	0.141	0.181	0.107	0.130				0.282

Control plot 0.164

* Expressed as % Si

† Three replicates composited for analysis

Table 20. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 4)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.168	0.146	0.209	0.156	0.201	0.186	0.175	0.130	0.180				0.290
830	0.209	0.304	0.284	0.296	0.247	0.261	0.225	0.296	0.293	0.363	0.234	0.277	0.343
1660	0.445	0.323	0.351	0.319	0.338	0.386	0.390	0.280	0.343				0.461

Control plot 0.293

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.116	0.132	0.126	0.129	0.111	0.164	0.170	0.119	0.149				0.146
830	0.217	0.179	0.170	0.185	0.178	0.261	0.136	0.113	0.162	0.272	0.209	0.276	0.248
1660	0.359	0.261	0.317	0.368	0.245	0.223	0.241	0.217	0.245				0.323

Control plot 0.241

* Expressed as % Si

† Three replicates composited for analysis

Table 21. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 5)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.165	0.149	0.148	0.153	0.159	0.220	0.183	0.132	0.200				0.208
830	0.241	0.269	0.245	0.324	0.244	0.230	0.252	0.274	0.283	0.326	0.245	0.258	0.266
1660	0.346	0.364	0.357	0.332	0.316	0.340	0.395	0.305	0.354				0.368

Control plot 0.234

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.176	0.244	0.143	0.184	0.138	0.290	0.205	0.181	0.201				0.327
830	0.387	0.296	0.238	0.360	0.250	0.370	0.275	0.238	0.222	0.614	0.436	0.362	0.626
1660	0.530	0.318	0.386	0.836	0.512	0.527	0.501	0.321	0.470				0.803

Control plot 0.307

* Expressed as % Si

† Three replicates composited for analysis

Table 22. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 6)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.116	0.190	0.124	0.129	0.205	0.228	0.201	0.149	0.178				0.216
830	0.198	0.255	0.249	0.312	0.280	0.266	0.260	0.282	0.264	0.209	0.260	0.301	0.315
1660	0.337	0.371	0.417	0.372	0.398	0.345	0.409	0.356	0.360				0.354

Control plot 0.301

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.189	0.168	0.178	0.156	0.105	0.220	0.170	0.120	0.164				0.238
830	0.299	0.293	0.211	0.315	0.242	0.245	0.200	0.195	0.195	0.456	0.310	0.242	0.494
1660	0.464	0.277	0.294	0.620	0.329	0.318	0.373	0.293	0.308				0.518

Control plot 0.453

* Expressed as % Si

† Three replicates composited for analysis

Table 23. Influence of residual Si, P and soil pH on whole-plant Si in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.130	0.175	0.181	0.144	0.138	0.202	0.174	0.135	0.154				0.264
830	0.198	0.278	0.262	0.257	0.218	0.282	0.276	0.295	0.291	0.344	0.207	0.269	0.324
1660	0.298	0.400	0.366	0.346	0.351	0.384	0.435	0.299	0.339				0.385

Control plot 0.253

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.204	0.185	0.181	0.176	0.154	0.191	0.271	0.163	0.129				0.286
830	0.425	0.360	0.221	0.336	0.230	0.248	0.296	0.163	0.193	0.380	0.368	0.257	0.504
1660	0.518	0.410	0.351	0.525	0.437	0.412	0.408	0.359	0.302				0.628

Control plot 0.305

* Expressed as % Si

† Means of 3 observations

Table 24. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 1)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	7.14	10.50	9.09	7.63	8.58	12.60	17.60	6.75	10.10				13.23
830	13.80	16.91	16.40	18.00	13.30	20.23	21.62	14.10	14.32	15.79	16.81	14.51	16.02
1660	15.00	26.93	27.10	21.50	27.70	26.80	25.90	19.10	24.94				31.50

Control plot 14.50

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.92	6.89	8.10	5.05	4.00	9.04	5.62	5.09	6.03				6.07
830	12.50	14.00	9.75	9.19	7.59	12.50	9.46	8.48	7.93	14.81	10.43	12.94	11.30
1660	20.10	16.50	19.50	18.40	15.70	15.70	13.80	12.90	10.60				17.00

Control plot 8.35

* Expressed as kg/ha

† Three replicates composited for analysis

Table 25. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 2)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	11.80	14.23	11.73	8.24	9.31	19.91	8.16	8.42	11.02				13.64
830	23.3	24.62	20.94	19.00	14.50	21.83	16.30	19.00	21.08	22.43	20.81	22.20	17.08
1660	25.1	32.71	24.50	25.40	25.50	28.51	26.60	26.40	21.92				26.03

Control plot 11.0

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3.06	3.52	5.82	3.23	2.44	6.06	3.25	4.11	3.79				2.20
830	7.00	8.83	6.36	5.52	6.81	8.82	5.35	5.05	4.41	7.14	7.0	6.37	4.86
1660	10.70	13.10	13.70	7.06	10.50	11.30	5.82	5.67	9.70				9.01

Control plot 5.06

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* Expressed as kg/ha

† Three replicates composited for analysis

Table 26. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 3)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	17.04	9.95	11.28	11.30	11.33	18.08	13.14	11.21	14.74				17.31
830	22.81	23.90	22.21	19.12	15.85	24.83	18.45	24.90	22.85	28.10	17.42	25.10	22.34
1660	44.20	37.60	36.34	33.60	36.02	30.00	26.12	21.43	28.18				28.25

Control plot 12.70

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.52	5.83	5.45	3.34	2.72	6.44	6.80	4.94	4.48				5.58
830	10.10	7.61	6.03	7.49	5.89	9.15	6.83	4.45	5.22	7.42	7.63	7.79	10.10
1660	15.30	11.80	11.0	11.30	12.20	11.30	13.60	7.77	10.50				14.20

Control plot 2.40

* Expressed as kg/ha

† Three replicates composited for analysis

Table 27. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 4)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.91	5.51	8.39	4.75	5.99	6.53	5.24	4.71	6.56				8.97
830	8.14	12.30	10.60	8.68	7.32	10.40	7.42	11.12	9.39	12.53	7.69	11.21	10.10
1660	16.70	11.90	15.30	10.10	11.20	13.10	15.60	10.6	12.90				13.30

Control plot 8.50

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.20	5.28	5.31	5.15	4.09	6.73	6.72	5.83	7.33				4.68
830	8.70	6.95	6.70	8.10	7.75	8.90	5.93	4.71	7.28	8.65	7.86	9.32	7.74
1660	14.90	10.30	13.80	12.10	10.10	12.10	8.84	10.00	11.10				12.60

Control plot 2.87

* Expressed as kg/ha

† Three replicates composited for analysis

Table 28. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 5)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	8.20	6.93	7.12	7.54	7.29	12.20	9.94	6.31	11.74				10.42
830	11.43	13.70	18.80	14.40	12.50	12.25	11.10	13.90	15.85	16.45	12.31	13.10	12.51
1660	18.50	18.60	18.40	17.90	17.00	17.44	22.20	16.50	19.72				15.63

Control plot 0.48

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3.61	5.95	3.00	4.22	3.16	6.88	3.50	4.03	5.13				7.50
830	6.48	7.75	6.00	7.50	5.20	10.00	7.51	6.15	6.17	14.62	9.15	8.24	17.43
1660	12.00	6.67	10.70	17.30	14.00	15.20	11.60	6.16	11.00				17.20

Control plot 3.00

* Expressed as kg/ha

† Three replicates composited for analysis

Table 29. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 6)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.76	6.60	5.81	4.65	9.51	10.43	9.14	6.25	8.94				7.62
830	8.22	12.41	11.73	11.50	11.00	13.70	10.90	13.60	12.50	10.30	7.65	11.30	7.43
1660	14.00	18.04	18.50	16.61	18.70	18.28	18.30	18.00	17.40				9.40

Control plot 0.14

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2.99	3.55	3.56	4.22	2.62	5.34	3.71	2.89	5.31				3.51
830	6.16	6.45	4.86	6.65	5.56	6.15	4.77	4.47	5.18	5.18	5.41	4.92	7.09
1660	10.30	5.93	7.32	11.90	9.50	10.50	8.82	7.12	7.13				9.50

Control plot 0.48

* Expressed as kg/ha

† Three replicates composited for analysis

Table 30. Influence of residual Si, P and soil pH on Si uptake by kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.60	6.65	9.63	5.02	5.81	9.93	4.58	5.09	6.81				7.50
830	7.87	10.90	10.30	8.46	8.51	14.00	9.29	7.08	8.85	7.32	6.01	10.6	7.68
1660	9.18	18.50	17.30	10.80	11.20	17.80	11.00	13.00	15.80				10.00

Control plot 4.39

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3.30	4.34	6.05	4.18	4.28	5.77	5.32	4.97	4.74				4.12
830	9.15	9.62	7.71	8.00	6.03	10.60	7.42	5.02	7.32	6.02	6.96	6.47	6.80
1660	10.30	13.10	11.60	7.70	12.80	15.20	10.10	11.20	8.81				9.77

Control plot 1.25

* Expressed as kg/ha

† Means of 3 observations

Table 31. Influence of residual Si, P and soil pH on combined Si uptake of 7 harvests by kikuyugrass and desmodium*

Kikuyugrass

Si x P x pH

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	59	60	63	49	58	90	68	50	70				79
830	96	115	111	99	83	117	95	104	105	113	89	108	93
1660	143	164	157	136	147	152	146	125	141				134

Control plot 52

Desmodium

Si x P x pH

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	27	35	37	29	23	46	38	32	37				34
830	60	61	47	52	45	66	47	38	44	64	54	56	65
1660	94	77	88	86	85	91	73	61	69				89

Control plot 23

* Expressed as kg/ha

Table 32. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 1)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.25	0.23	0.32	0.24	0.25	0.32	0.25	0.26	0.31				0.17
830	0.23	0.27	0.31	0.22	0.26	0.30	0.23	0.28	0.29	0.26	0.28	0.30	0.18
1660	0.20	0.26	0.32	0.22	0.27	0.31	0.21	0.29	0.31				0.17

Control plot 0.14

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.18	0.23	0.25	0.19	0.23	0.26	0.20	0.22	0.29				0.16
830	0.19	0.24	0.26	0.20	0.22	0.27	0.20	0.23	0.29	0.18	0.20	0.25	0.17
1660	0.22	0.22	0.26	0.19	0.23	0.25	0.21	0.22	0.29				0.15

Control plot 0.19

* Expressed as % P

† Three replicates composited for analysis

Table 33. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 2)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.18	0.18	0.25	0.19	0.20	0.24	0.17	0.20	0.25				0.19
830	0.19	0.21	0.25	0.16	0.20	0.24	0.18	0.22	0.25	0.18	0.18	0.23	0.16
1660	0.20	0.21	0.23	0.16	0.18	0.25	0.18	0.22	0.24				0.15

Control plot 0.14

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.23	0.22	0.28	0.22	0.24	0.31	0.18	0.22	0.33				0.16
830	0.21	0.26	0.30	0.20	0.23	0.32	0.19	0.26	0.31	0.23	0.22	0.27	0.20
1660	0.22	0.29	0.29	0.22	0.26	0.32	0.20	0.25	0.30				0.17

Control plot 0.22

* Expressed as % P

† Three replicates composited for analysis

Table 34. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 3)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.13	0.13	0.18	0.12	0.14	0.19	0.11	0.14	0.19				0.10
830	0.13	0.14	0.19	0.11	0.14	0.17	0.10	0.14	0.16	0.10	0.13	0.16	0.10
1660	0.12	0.15	0.17	0.12	0.16	0.17	0.09	0.14	0.18				0.09

Control plot 0.09

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.19	0.21	0.24	0.16	0.18	0.23	0.14	0.19	0.28				0.13
830	0.17	0.23	0.23	0.17	0.19	0.25	0.16	0.20	0.27	0.17	0.15	0.23	0.13
1660	0.18	0.24	0.24	0.16	0.19	0.24	0.16	0.18	0.25				0.13

Control plot 0.18

* Expressed as % P

† Three replicates composited for analysis

Table 35. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 4)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.20	0.17	0.24	0.18	0.22	0.26	0.16	0.18	0.25				0.12
830	0.17	0.20	0.25	0.17	0.19	0.23	0.14	0.22	0.25	0.18	0.18	0.22	0.16
1660	0.17	0.22	0.24	0.16	0.20	0.23	0.18	0.21	0.26				0.15

Control plot 0.13

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.20	0.22	0.29	0.18	0.21	0.28	0.16	0.20	0.27				0.17
830	0.17	0.23	0.24	0.15	0.20	0.28	0.16	0.22	0.26	0.19	0.22	0.28	0.20
1660	0.20	0.21	0.26	0.20	0.22	0.29	0.16	0.20	0.30				0.15

Control plot 0.21

* Expressed as % P

† Three replicates composited for analysis

Table 36. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 5)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.18	0.16	0.24	0.18	0.20	0.25	0.16	0.17	0.26				0.15
830	0.18	0.19	0.24	0.18	0.18	0.25	0.15	0.21	0.25	0.16	0.19	0.23	0.13
1660	0.18	0.20	0.21	0.16	0.18	0.24	0.18	0.21	0.28				0.14

Control plot 0.11

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.23	0.22	0.30	0.23	0.26	0.34	0.21	0.25	0.36				0.17
830	0.21	0.26	0.31	0.22	0.23	0.33	0.22	0.31	0.35	0.20	0.25	0.30	0.18
1660	0.21	0.27	0.32	0.21	0.25	0.32	0.24	0.28	0.36				0.19

Control plot 0.20

* Expressed as % P

† Three replicates composited for analysis

Table 37. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 6)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.16	0.18	0.25	0.16	0.18	0.23	0.16	0.19	0.25				0.15
830	0.18	0.22	0.27	0.16	0.16	0.22	0.16	0.20	0.25	0.15	0.20	0.25	0.14
1660	0.15	0.19	0.24	0.16	0.18	0.23	0.16	0.18	0.24				0.16

Control plot 0.14

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.31	0.28	0.37	0.23	0.28	0.36	0.24	0.31	0.32				0.19
830	0.25	0.31	0.32	0.25	0.31	0.39	0.27	0.32	0.36	0.25	0.28	0.35	0.20
1660	0.21	0.31	0.37	0.22	0.26	0.35	0.25	0.30	0.37				0.19

Control plot 0.20

* Expressed as % P

† Three replicates composited for analysis

Table 38. Influence of residual Si, P and soil pH on whole-plant P in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.14	0.15	0.19	0.16	0.14	0.18	0.13	0.13	0.19				0.13
830	0.14	0.16	0.19	0.12	0.14	0.20	0.13	0.17	0.20	0.13	0.14	0.19	0.13
1660	0.12	0.16	0.20	0.13	0.15	0.20	0.13	0.14	0.18				0.13

Control plot 0.15

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.17	0.21	0.27	0.19	0.25	0.30	0.17	0.19	0.29				0.17
830	0.20	0.24	0.28	0.17	0.20	0.30	0.18	0.24	0.30	0.19	0.21	0.27	0.16
1660	0.21	0.26	0.29	0.19	0.22	0.30	0.19	0.21	0.31				0.17

Control plot 0.16

* Expressed as % P

† Means of 3 observations

Table 39. Influence of residual Si, P and soil pH on P uptake by kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	4.80	5.82	10.00	5.08	5.71	8.55	3.41	5.04	7.83				3.65
830	5.53	6.30	8.00	4.12	5.34	9.90	4.39	4.46	6.15	3.15	4.47	7.43	3.58
1660	3.87	7.49	9.35	4.30	4.80	9.35	3.58	6.23	8.64				4.32

Control plot 2.57

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3.56	5.09	8.96	4.75	6.80	8.92	3.55	5.97	10.70				2.54
830	7.74	6.72	10.30	4.40	5.07	10.20	4.62	7.80	11.00	4.02	4.26	6.95	3.24
1660	4.15	8.30	9.69	2.97	6.48	10.50	5.17	6.78	9.41				3.47

Control plot 0.65

* Expressed as kg/ha

† Means of 3 observations

Table 40. Influence of residual Si, P and soil pH on combined P uptake of 7 harvests by kikuyugrass and desmodium*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	64.4	60.0	87.2	58.7	66.2	89.5	58.8	68.4	97.7				46.1
830	65.1	72.4	89.7	52.5	64.2	93.8	54.3	75.7	81.9	49.1	59.8	76.5	43.1
1660	56.9	73.9	91.1	53.8	71.8	87.5	55.2	73.8	91.0				42.3

Control plot 24.0

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	48.8	59.4	76.6	51.6	61.2	80.4	44.9	64.0	93.5				33.6
830	49.5	67.8	74.1	52.2	58.2	79.2	52.7	67.2	86.7	42.3	49.9	67.5	36.5
1660	52.6	67.3	83.7	44.9	65.7	88.5	52.5	62.5	84.0				37.0

Control plot 19.2

* Expressed as kg/ha

Table 41. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 1)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	697	691	517	787	506	1891	1452	787	1534				1405
830	388	449	787	517	337	955	674	1517	1292	2297	1141	1405	1679
1660	1000	826	758	1124	420	1000	1405	663	730				927
												Control plot	1068

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	421	980	2067	1007	1272	1208	1100	1272	1033				1023
830	1177	362	673	1033	901	1283	742	1404	1272	1987	1362	2156	1245
1660	843	662	572	1728	991	647	1484	1828	880				1436
												Control plot	1086

* Expressed as ppm Al

† Three replicates composited for analysis

Table 42. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 2)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1378	1390	1293	2014	2120	2141	1325	1221	1219				4527
830	1770	1431	2576	2491	1438	3498	1325	1403	1654	2703	2478	2735	5406
1660	3604	1394	2650	2067	1425	1166	1675	1043	1113				2205

Control plot 1961

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2703	1749	4876	2226	806	1092	2904	4048	1526				886
830	4232	3339	1272	3678	1486	1859	3816	1378	1134	4159	1884	1378	1484
1660	2735	975	3127	1855	1399	2871	1251	1632	1442				4159

Control plot 1378

* Expressed as ppm Al

† Three replicates composited for analysis

Table 43. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 3)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1134	1293	996	2427	1314	2003	1632	1622	1537				3445
830	938	1251	865	778	674	1473	3010	1007	1420	1823	656	691	2078
1660	2212	882	1654	2724	2735	837	812	823	1071				847

Control plot 1039

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	944	799	1340	1111	694	917	2692	882	1139				556
830	681	778	660	889	764	1340	1063	556	736	625	681	708	1320
1660	694	833	792	806	938	1138	2014	1083	1278				715

Control plot 1042

* Expressed as ppm Al

† Three replicates composited for analysis

Table 44. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 4)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2205	1717	1728	2173	1452	1251	3032	1452	1632				2491
830	1643	2014	1855	1537	1389	2883	2576	1770	2120	1749	1304	1717	823
1660	1802	2184	2661	1866	2311	2014	1982	768	1802				3657

Control plot 1954

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	3180	2120	2565	4102	3445	2745	4770	2763	4346				2279
830	4028	2332	3095	3572	4028	3625	2777	2703	3763	2003	3339	1897	1770
1660	3180	2777	4430	4028	3572	3625	2597	5088	2809				2300

Control plot 1039

* Expressed as ppm Al

† Three replicates composited for analysis

Table 45. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 5)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1345	817	1395	1450	1840	1400	1020	807	1990				2820
830	611	515	1560	970	591	1180	714	1500	2550	2285	1655	677	1655
1660	1280	1120	1120	1750	2820	845	1500	732	1040				1053

Control plot 525

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1625	3090	990	2515	1182	2550	2180	7430	1770				1075
830	3895	2550	1525	3225	2956	2255	2550	1860	790	4970	2690	1225	4435
1660	1395	1880	2420	1612	1075	3225	1720	1180	1840				2760

Control plot 1525

* Expressed as ppm Al

† Three replicates composited for analysis

Table 46. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 6)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	357	2391	488	539	3120	1825	766	364	738				2850
830	350	965	601	453	258	1840	422	659	711	1290	835	1310	4350
1660	1050	659	4220	2104	3010	711	519	316	436				491

Control plot 5400

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	965	1850	3990	3815	426	3870	1225	1840	3870				539
830	1525	1180	790	2061	3060	1290	814	1665	1050	3225	1505	1892	8864
1660	1280	1451	1760	584	738	2550	1225	1645	711				1343

Control plot 3870

* Expressed as ppm Al

† Three replicates composited for analysis

Table 47. Influence of residual Si, P and soil pH on whole-plant Al in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1646	2593	2089	2550	3102	1768	1327	1008	1045				3552
830	953	1199	1032	1006	901	3753	2171	946	876	1611	1685	2307	1695
1660	1041	1767	2081	1100	1749	1469	2403	1532	2418				1283

Control plot 1731

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	694	1137	1517	787	560	794	3338	1462	1426				935
830	1803	763	601	2217	1978	1306	1464	646	1013	1117	1148	1044	3518
1660	531	812	1041	727	414	1498	1480	3197	792				1915

Control plot 1290

* Expressed as ppm Al

† Means of 3 observations

Table 48. Influence of residual Si, P and soil pH on Al uptake by kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	7.39	10.20	11.10	9.86	15.30	8.11	3.85	4.43	4.84				10.70
830	3.82	4.98	5.26	2.88	3.57	11.80	7.98	1.74	2.31	3.60	5.04	9.71	4.78
1660	3.85	8.50	10.20	4.16	5.43	7.42	9.30	7.57	11.40				5.61

Control plot 3.00

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1.46	2.75	5.34	1.95	1.53	2.36	6.34	4.43	5.25				1.15
830	4.04	2.12	2.04	5.58	5.24	5.34	3.64	2.37	4.03	2.71	2.61	2.42	12.20
1660	1.08	2.49	3.95	1.30	1.26	5.80	4.25	9.79	2.41				4.38

Control plot 0.53

* Expressed as kg/ha

† Means of 3 observations

Table 49. Influence of residual Si, P and soil pH on combined Al uptake of 7 harvests by kikuyugrass and desmodium*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	47.5	48.8	45.9	60.3	69.3	68.9	52.8	42.4	57.8				95.7
830	35.7	42.0	49.0	36.5	27.3	79.5	57.3	45.5	54.5	61.8	43.4	50.6	75.0
1660	67.9	45.4	83.0	66.5	77.0	41.8	50.0	32.5	45.9				42.9

Control plot 23.9

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	32.4	38.0	62.7	53.3	33.0	47.3	63.7	70.5	63.4				22.0
830	51.4	36.3	31.5	53.0	50.9	55.0	46.7	38.6	41.8	48.3	40.3	36.1	58.2
1660	35.6	33.1	53.5	38.7	27.8	60.2	48.0	63.6	40.1				42.2

Control plot 11.7

* Expressed as kg/ha

Table 50. Influence of residual Si, P and soil pH on whole-plant K in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2.54	2.49	2.40	2.47	2.49	2.45	2.58	2.47	2.52				2.60
830	2.68	2.62	2.63	2.65	2.60	2.51	2.60	2.56	2.49	2.47	2.54	2.51	2.51
1660	2.43	2.53	2.45	2.58	2.65	2.40	2.42	2.46	2.38				2.67

Control plot 2.79

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2.54	2.90	3.08	2.74	3.01	3.29	2.81	2.86	3.01				2.36
830	2.74	3.12	3.05	2.53	2.92	2.94	2.58	3.08	3.08	2.54	2.83	3.22	2.40
1660	3.04	3.04	3.11	2.80	2.88	2.93	2.76	2.90	3.19				2.72

Control plot 2.36

* Expressed as % K

† Means of 3 observations

Table 51. Influence of residual Si, P and soil pH on whole-plant Ca in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.262	0.287	0.334	0.343	0.335	0.342	0.369	0.347	0.359				0.361
830	0.263	0.342	0.330	0.347	0.341	0.356	0.384	0.398	0.394	0.301	0.304	0.326	0.347
1660	0.293	0.347	0.331	0.344	0.368	0.353	0.386	0.329	0.356				0.422

Control plot 0.277

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.731	0.838	0.714	0.918	0.952	0.788	1.088	1.080	1.001				0.805
830	0.825	0.804	0.773	0.856	0.992	0.903	1.087	1.080	1.058	0.755	0.747	0.777	0.759
1660	0.787	0.805	0.803	0.903	0.894	0.853	0.925	1.047	1.053				0.902

Control plot 0.339

* Expressed as % Ca

† Means of 3 observations

Table 52. Influence of residual Si, P and soil pH on whole-plant Mg in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.100	0.095	0.099	0.099	0.113	0.113	0.131	0.123	0.109				0.122
830	0.117	0.105	0.105	0.119	0.105	0.117	0.139	0.122	0.122	0.128	0.109	0.125	0.126
1660	0.110	0.116	0.098	0.122	0.114	0.107	0.137	0.144	0.126				0.139

Control plot 0.119

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.140	0.139	0.117	0.112	0.126	0.144	0.163	0.128	0.123				0.169
830	0.151	0.133	0.112	0.136	0.130	0.127	0.136	0.135	0.131	0.182	0.160	0.148	0.184
1660	0.145	0.130	0.114	0.171	0.114	0.112	0.149	0.145	0.136				0.177

Control plot 0.264

* Expressed as % Mg

† Means of 3 observations

Table 53. Influence of residual Si, P and soil pH on whole-plant Mn in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	91	127	123	101	108	107	56	56	58				169
830	108	137	131	86	81	143	68	55	41	154	115	158	159
1660	127	111	131	109	105	93	83	60	73				162

Control plot 273

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	123	95	92	57	46	58	41	34	30				117
830	139	101	102	82	67	61	38	26	22	142	139	111	110
1660	104	82	75	79	36	55	36	35	34				149

Control plot 254

* Expressed as ppm Mn

† Means of 3 observations

Table 54. Influence of residual Si, P and soil pH on whole-plant Zn in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	46	52	50	40	46	43	39	30	33				44
830	47	46	54	43	40	33	43	41	38	45	60	53	36
1660	40	45	47	40	49	66	34	37	33				42

Control plot 63

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	68	72	63	45	55	59	45	59	49				45
830	82	69	64	46	50	51	44	37	44	53	62	50	45
1660	64	54	63	49	37	51	42	45	56				61

Control plot 53

* Expressed as ppm Zn

† Means of 3 observations

Table 55. Influence of residual Si, P and soil pH on index-tissue Si in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.070	0.760	0.081	0.063	0.061	0.093	0.084	0.071	0.089				0.067
830	0.122	0.148	0.149	0.167	0.139	0.142	0.122	0.169	0.152	0.162	0.135	0.185	0.161
1660	0.230	0.242	0.240	0.218	0.175	0.263	0.195	0.187	0.221				0.222
											Control plot		0.046

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.051	0.055	0.037	0.047	0.053	0.054	0.056	0.043	0.038				0.041
830	0.089	0.092	0.073	0.127	0.094	0.075	0.084	0.072	0.057	0.088	0.099	0.074	0.095
1660	0.175	0.141	0.131	0.164	0.116	0.108	0.147	0.116	0.086				0.141
											Control plot		0.036

* Expressed as % Si

† Three replicates composited for analysis

Table 56. Influence of residual Si, P and soil pH on index-tissue P in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.19	0.19	0.26	0.17	0.20	0.24	0.16	0.18	0.23				0.16
830	0.18	0.21	0.26	0.15	0.17	0.24	0.15	0.19	0.24	0.15	0.18	0.23	0.17
1660	0.18	0.20	0.24	0.16	0.17	0.24	0.17	0.19	0.25				0.14

Control plot 0.13

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.23	0.32	0.34	0.24	0.28	0.37	0.19	0.26	0.38				0.22
830	0.26	0.28	0.33	0.22	0.28	0.33	0.24	0.26	0.31	0.22	0.26	0.32	0.22
1660	0.23	0.29	0.32	0.24	0.31	0.36	0.19	0.28	0.37				0.21

Control plot 0.23

* Expressed as % P

† Three replicates composited for analysis

Table 57. Influence of residual Si, P and soil pH on index-tissue Al in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	34.8	20.8	24.9	29.7	14.6	39.9	21.6	16.2	14.3				24.7
830	33.4	19.2	27.0	15.1	24.0	21.9	14.8	17.1	32.1	9.6	14.9	14.8	25.4
1660	31.9	21.1	28.3	14.6	32.4	22.8	19.4	16.3	16.0				21.6

Control plot 20.5

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	31.5	42.6	27.6	36.4	41.4	41.4	38.3	29.8	21.8				38.8
830	26.9	36.7	51.4	30.4	31.4	26.5	45.8	24.9	28.8	46.8	48.0	22.5	33.2
1660	43.0	31.5	36.3	42.0	33.2	41.4	25.5	19.7	22.6				28.9

Control plot 46.3

* Expressed as ppm Al

† Three replicates composited for analysis

Table 58. Influence of residual Si, P and soil pH on index-tissue K in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2.5	2.4	2.3	2.3	2.4	2.2	2.4	2.4	2.3				2.4
830	2.4	2.4	2.3	2.4	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.3	2.4
1660	2.4	2.3	2.3	2.3	2.4	2.3	2.3	2.4	2.4				2.4

Control plot 2.5

Desmodium

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	2.2	2.5	2.3	2.3	2.3	2.3	2.2	2.2	2.1				2.2
830	2.2	2.2	2.2	2.3	2.3	2.2	2.2	2.1	1.9	2.2	2.2	2.2	2.2
1660	2.1	2.0	2.3	2.2	2.3	2.3	2.1	2.1	2.2				2.2

Control plot 2.1

* Expressed as % K

[†] Three replicates composited for analysis

Table 59. Influence of residual Si, P and soil pH on index-tissue Ca in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.21	0.20	0.21	0.21	0.22	0.22	0.22	0.22	0.25				0.21
830	0.20	0.19	0.23	0.21	0.21	0.24	0.22	0.23	0.22	0.21	0.21	0.20	0.21
1660	0.20	0.20	0.21	0.21	0.20	0.23	0.23	0.21	0.24				0.19

Control plot 0.14

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.82	0.76	0.76	1.01	1.07	1.01	1.16	1.10	1.21				0.96
830	0.85	0.82	0.90	1.16	1.10	0.95	1.08	1.23	1.26	0.79	0.75	0.88	0.96
1660	0.95	0.91	0.87	1.06	1.01	0.96	1.09	1.08	1.00				0.98

Control plot 0.53

* Expressed as % Ca

† Three replicates composited for analysis

Table 60. Influence of residual Si, P and soil pH on index-tissue Mg in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
(kg/ha)	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	870	800	780	820	800	840	980	980	1000				1050
830	740	700	680	800	780	900	1070	1010	1010	1020	770	910	970
1660	970	770	840	920	820	790	1160	930	1050				930

Control plot 760

Desmodium

Si x P x pH†

Si	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
(kg/ha)	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	1360	1280	1270	1280	1320	1320	1480	1370	1420				1620
830	1040	1220	1160	1360	1270	1340	1510	1370	1420	1480	1400	1280	1450
1660	1340	1200	1140	1440	1390	1290	1570	1450	1510				1520

Control plot 1950

* Expressed as ppm Mg

† Three replicates composited for analysis

Table 61. Influence of residual Si, P and soil pH on index-tissue Mn in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	50	74	48	45	30	43	26	18	24				64
830	59	54	56	45	50	45	23	28	28	84	59	63	52
1660	73	47	56	53	56	34	30	27	35				78

Control plot 83

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	109	82	61	68	48	40	26	26	29				104
830	98	93	69	64	57	54	29	31	31	112	96	74	73
1660	122	81	59	60	41	38	35	20	29				107

Control plot 147

* Expressed as ppm Mn

† Three replicates composited for analysis

Table 62. Influence of residual Si, P and soil pH on index-tissue Zn in kikuyugrass and desmodium (Harvest 7)*

Kikuyugrass

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	32	16	14	26	5	11	12	11	12				24
830	21	13	18	13	12	20	15	15	17	24	21	20	17
1660	19	10	17	6	10	15	13	21	19				12

Control plot 19

Desmodium

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	39	31	31	29	26	33	12	18	15				24
830	46	30	36	21	30	19	15	28	10	50	45	21	26
1660	36	25	25	14	31	28	13	20	24				21

Control plot 33

* Expressed as ppm Zn

† Three replicates composited for analysis

Table 63. Influence of residual Si, P and soil pH on water-extractable soil Si and modified Truog-extractable P at 27 months

Water-extractable Si*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.56	0.65	0.69	0.53	0.48	0.83	0.50	0.43	0.66				0.60
830	1.31	1.50	1.31	1.39	1.21	1.39	0.89	1.41	1.16	1.34	1.16	1.18	1.23
1660	2.11	1.98	1.66	1.88	1.61	1.78	1.63	1.46	1.78				1.80

Control plot 0.40

Modified Truog-extractable P**

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	23	47	235	29	59	236	26	42	178				14
830	29	72	142	31	56	196	28	55	217	31	50	178	16
1660	24	52	172	28	51	221	33	47	260				12

Control plot 12

* Expressed as ppm Si in solution

** Expressed as ppm P in soil

† Means of 3 observations

Table 64. Influence of residual Si, P and soil pH on water-extractable soil Si at 40 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.91	1.47	0.75	0.93	0.98	1.33	0.61	0.85	1.10				0.98
830	1.56	1.72	1.49	2.08	1.45	1.52	1.32	1.46	1.43	1.66	1.59	1.52	1.46
1660	1.87	2.87	2.27	2.28	2.33	2.27	2.24	2.23	2.41				2.50

Control plot 0.69

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.77	1.24	0.89	0.85	0.89	1.84	0.74	0.96	1.09				0.96
830	1.62	1.86	1.59	2.14	1.71	1.66	1.66	1.46	1.74	1.74	1.81	1.34	1.44
1660	2.18	2.39	2.53	2.72	2.52	2.35	2.40	2.69	2.16				2.73

Control plot 0.62

* Expressed as ppm in solution

† Means of 3 observations

Table 65. Influence of residual Si, P and soil pH on water-extractable soil Si at 56 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.70	0.66	0.67	0.54	0.62	0.85	0.51	0.54	0.74				0.66
830	0.97	1.22	1.22	1.33	1.02	1.25	0.94	1.12	1.13	1.22	0.94	1.09	1.09
1660	1.73	2.00	1.83	1.42	1.41	1.78	2.00	1.52	1.68				1.75

Control plot 0.37

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	0.60	0.56	0.54	0.61	0.57	0.80	0.61	0.62	0.78				0.59
830	1.39	1.25	0.96	1.38	1.16	1.44	1.01	1.19	1.23	1.20	1.16	0.94	1.10
1660	1.77	1.82	1.72	2.13	1.91	1.63	1.81	1.99	1.74				1.77

Control plot 0.43

* Expressed as ppm Si in solution

† Means of 3 observations

Table 66. Influence of residual Si, P and soil pH on modified Truog-extractable soil P at 40 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	22	36	196	24	51	143	26	36	189				15
830	26	61	208	29	36	200	22	58	226	22	57	206	27
1660	24	50	153	26	42	265	42	58	229				15

Control plot 9

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	24	33	208	28	48	143	27	36	203				13
830	31	47	199	28	24	206	24	68	200	28	66	192	30
1660	65	61	154	24	40	248	31	53	217				11

Control plot 9

* Expressed as ppm P in soil

† Three replicates composited for analysis

Table 67. Influence of residual Si, P and soil pH on modified Truog-extractable soil P at 56 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	23	22	124	15	21	101	15	23	130				10
830	18	35	120	18	22	116	17	40	123	13	32	138	11
1660	11	35	101	15	26	164	25	30	136				8

Control plot 4

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	17	24	147	17	34	120	14	23	167				10
830	20	36	112	15	24	169	20	36	140	14	25	140	10
1660	19	37	144	14	32	149	26	37	150				10

Control plot 4

* Expressed as ppm P in soil

† Means of 3 observations

Table 68. Influence of residual Si, P and soil pH on sorbed P at 56 months[*]

Kikuyugrass sites

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	855	866	506	845	830	628	918	866	595				851
830	826	770	520	783	810	548	918	843	651	886	838	583	860
1660	823	720	551	785	820	480	880	820	653				818

Control plot 920

Desmodium sites

Si x P x pH[†]

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	843	771	510	756	713	521	876	775	540				840
830	810	711	533	735	748	480	806	730	551	858	730	515	790
1660	763	678	456	753	728	466	800	730	540				803

Control plot 980

[*] Expressed as µg P/g soil at 0.2 ppm P in solution

[†] Means of 3 observations

Table 69. Influence of residual Si, P and soil pH on actual soil pH and $BaCl_2$-extractable soil Al at 27 months

Soil pH*

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.5	5.5	5.5	5.9	6.0	5.9	6.6	6.5	6.3				5.9
830	5.5	5.5	5.5	6.0	6.0	5.8	6.4	6.2	6.5	5.1	5.1	5.2	5.9
1660	5.7	5.5	5.4	6.0	5.9	6.0	6.3	6.3	6.4				5.7

Control plot 4.8

$BaCl_2$-extractable Al**

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	43.2	43.6	41.9	13.1	6.7	9.2	0.2	0.1	2.9				14.6
830	48.7	36.4	30.7	5.5	6.4	13.8	0.7	0.9	0.1	75.9	86.1	68.4	10.8
1660	30.1	37.3	44.0	12.8	12.2	8.9	0.8	0.2	0.4				15.8

Control plot 126.0

* Determined in the 1:2.5 soil-water suspension

** Expressed as ppm Al in soil

† Means of 3 observations

Table 70. Influence of residual Si, P and soil pH on actual soil pH at 40 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.0	5.3	5.0	5.7	5.6	5.3	6.6	6.4	6.0				5.3
830	5.0	5.0	5.1	5.7	5.5	5.3	6.3	6.1	6.1	4.8	4.7	4.8	5.3
1660	5.2	5.1	5.3	5.7	5.5	5.7	6.3	6.4	6.1				5.1

Control plot 4.3

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.1	5.1	5.1	5.3	5.7	5.2	6.5	6.0	6.2				5.4
830	5.0	5.0	5.2	5.6	5.6	5.4	6.2	6.2	6.3	4.8	4.8	4.8	5.2
1660	5.1	5.1	5.3	5.6	5.5	5.5	6.1	6.3	6.4				5.3

Control plot 4.4

* Determined in the 1:2.5 soil-water suspension

† Three replicates composited for analysis

Table 71. Influence of residual Si, P and soil pH on actual soil pH at 56 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.4	5.2	5.2	5.9	5.8	5.8	6.7	6.4	6.2				5.7
830	5.1	5.4	5.4	6.0	5.9	5.6	6.4	6.4	6.4	5.4	4.8	5.2	5.7
1660	5.4	5.5	5.3	5.9	5.9	6.1	6.3	6.4	6.3				5.6

Control plot 4.7

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	5.3	5.5	5.2	5.6	5.8	5.8	6.3	6.2	6.1				5.9
830	5.4	5.3	5.2	5.9	5.8	5.7	6.4	6.1	6.3	5.3	4.9	5.0	5.7
1660	5.6	5.4	5.5	5.9	5.9	5.7	6.3	6.2	6.2				5.6

Control plot 4.5

* Determined in the 1:2.5 soil-water suspension

† Means of 3 observations

Table 72. Influence of residual Si, P and soil pH on $BaCl_2$-extractable soil Al at 40 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	100.1	60.9	72.5	33.2	20.4	42.7	0.1	0.0	1.3	175.3	235.4	154.2	58.6
830	111.3	94.5	72.4	13.3	24.0	29.0	0.5	1.3	1.7				68.4
1660	63.8	72.5	46.2	25.8	40.9	9.4	1.8	0.2	1.7				75.6

Control plot 232

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	84.1	54.4	81.6	25.0	15.3	39.4	0.0	0.7	1.3	171.2	161.3	125.0	43.2
830	86.2	77.8	50.4	9.9	12.2	27.1	0.7	0.1	0.3				55.6
1660	49.9	68.4	33.3	13.7	21.8	22.9	1.7	0.4	1.9				44.9

Control plot 199

* Expressed as ppm Al in soil

† Three replicates composited for analysis

Table 73. Influence of residual Si, P and soil pH on $BaCl_2$-extractable soil Al at 56 months*

Kikuyugrass sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	57.0	59.1	43.6	18.0	11.6	12.9	1.7	0.7	11.6				23.2
830	81.5	49.8	37.6	8.4	7.6	16.0	2.1	0.4	3.6	88.2	157.0	82.5	23.6
1660	35.9	32.0	44.6	10.8	11.5	4.7	3.7	0.8	11.5				36.7
												Control plot	137.0

Desmodium sites

Si x P x pH†

Si (kg/ha)	pH 5.5			pH 6.0			pH 6.5			pH 5.0			pH 6.0
	P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)			P (kg/ha)
	110	280	1120	110	280	1120	110	280	1120	110	280	1120	0
0	78.1	82.5	75.8	16.8	11.4	13.6	0.3	0.5	5.3				17.3
830	59.6	61.3	57.3	7.9	14.2	21.1	1.9	1.1	0.7	82.4	126.0	102.0	24.5
1660	48.4	62.5	54.2	7.6	11.9	15.7	3.1	1.5	12.4				21.2
												Control plot	133.0

* Expressed as ppm Al in soil

† Means of 3 observations

Table 74. Influence of residual Si and soil pH on distribution of water-extractable soil Si in profiles at 9 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	0.50	0.79	1.33	0.46	0.89	1.38	0.36	1.20	1.90
15-30	0.34	0.30	0.37	0.22	0.42	0.32	0.34	0.40	0.38
30-60	0.06	0.06	0.15	0.07	0.12	0.08	0.20	0.12	0.18
60-90	0.06	0.07	0.08	0.08	0.12	0.07	0.12	0.12	0.08
90-120	--	0.08	0.08	--	0.09	0.07	--	0.11	0.11

Depth x Si††

Depth cm	Si (kg/ha)		
	0	830	1660
0-15	0.44	0.96	1.54
15-30	0.30	0.37	0.36
30-60	0.11	0.10	0.14
60-90	0.09	0.10	0.08
90-120	--	0.09	0.09

Depth x pH†††

Depth cm	pH		
	5.5	6.0	6.5
0-15	0.87	0.91	1.15
15-30	0.34	0.32	0.37
30-60	0.09	0.09	0.17
60-90	0.07	0.09	0.11
90-120	0.08	0.08	0.11

* Expressed as ppm Si in solution

† Means of 3 observations

†† Means of 9 observations

††† Means of 9 observations except for data in the 90-120 cm depth which are means of 6 observations

Table 75. Influence of residual Si and soil pH on distribution of water-extractable soil Si in profiles at 27 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	0.65	1.51	1.98	0.48	1.21	1.61	0.43	1.14	1.46
15-30	0.43	0.56	0.59	0.31	0.54	0.80	0.31	0.48	0.45
30-45	0.21	0.16	0.16	0.13	0.13	0.19	0.15	0.13	1.18
45-60	0.14	0.08	0.08	0.09	0.09	0.06	0.09	0.10	0.13
60-75	0.07	0.09	0.06	0.08	0.10	0.07	0.07	0.10	0.07
75-90	0.10	0.09	0.10	0.09	0.11	0.09	0.08	0.12	0.07
90-120	0.08	0.10	0.12	0.08	0.09	0.10	0.09	0.16	0.09

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	0.52	1.29	1.68	1.16
15-30	0.35	0.53	0.61	0.50
30-45	0.16	0.14	0.18	0.16
45-60	0.11	0.09	0.09	0.10
60-75	0.07	0.10	0.07	0.08
75-90	0.09	0.11	0.09	0.10
90-120	0.08	0.12	0.10	0.10
Ave.	0.20	0.34	0.40	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	1.38	1.10	1.01	1.16
15-30	0.53	0.55	0.41	0.50
30-45	0.18	0.15	0.15	0.16
45-60	0.10	0.08	0.11	0.10
60-75	0.07	0.08	0.08	0.08
75-90	0.10	0.10	0.09	0.10
90-120	0.10	0.09	0.11	0.10
Ave.	0.35	0.31	0.28	

[*] Expressed as ppm Si in solution

[†] Means of 3 observations

[††] Means of 9 observations

Table 76. Influence of residual Si and soil pH on distribution of water-extractable soil Si in profiles at 40 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	0.73	1.59	2.43	0.72	1.49	2.28	0.76	1.35	2.09
15-30	0.40	0.55	0.61	0.35	0.37	0.56	0.45	0.43	0.55
30-45	0.14	0.13	0.14	0.11	0.14	0.18	0.14	0.10	0.12
45-60	0.06	0.05	0.07	0.05	0.05	0.07	0.14	0.04	0.08
60-75	0.04	0.07	0.07	0.07	0.06	0.07	0.18	0.06	0.04
75-90	0.04	0.05	0.08	0.05	0.06	0.06	0.07	0.08	0.06
90-120	0.06	0.09	0.10	0.07	0.08	0.12	0.11	0.12	0.09

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	0.74	1.48	2.27	1.50
15-30	0.40	0.45	0.57	0.47
30-45	0.13	0.12	0.15	0.13
45-60	0.08	0.05	0.07	0.07
60-75	0.10	0.06	0.06	0.07
75-90	0.05	0.06	0.07	0.06
90-120	0.08	0.10	0.10	0.09
Ave.	0.22	0.33	0.47	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	1.58	1.50	1.40	1.49
15-30	0.52	0.43	0.48	0.48
30-45	0.14	0.14	0.12	0.13
45-60	0.06	0.06	0.09	0.07
60-75	0.06	0.07	0.09	0.07
75-90	0.06	0.06	0.07	0.06
90-120	0.08	0.09	0.11	0.09
Ave.	0.36	0.34	0.34	

* Expressed as ppm Si in solution

† Means of 3 observations

†† Means of 9 observations

Table 77. Influence of residual Si and soil pH on distribution of water-extractable soil Si in profiles at 56 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	0.53	1.09	1.80	0.43	1.09	1.35	0.49	1.01	1.57
15-30	0.39	0.57	0.73	0.33	0.40	0.50	0.31	0.38	0.47
30-45	0.17	0.14	0.17	0.14	0.14	0.10	0.12	0.11	0.10
45-60	0.07	0.06	0.07	0.06	0.05	0.04	0.05	0.06	0.08
60-75	0.05	0.05	0.07	0.05	0.05	0.05	0.05	0.07	0.08
75-90	0.07	0.06	0.08	0.05	0.06	0.06	0.06	0.09	0.06
90-120	0.09	0.06	0.07	0.06	0.11	0.08	0.10	0.13	0.09

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	0.48	1.06	1.57	1.04
15-30	0.34	0.45	0.57	0.44
30-45	0.14	0.13	0.12	0.13
45-60	0.06	0.06	0.06	0.06
60-75	0.05	0.06	0.07	0.06
75-90	0.06	0.07	0.07	0.07
90-120	0.08	0.10	0.08	0.09
Ave.	0.17	0.26	0.36	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	1.14	0.96	1.02	1.04
15-30	0.56	0.41	0.39	0.45
30-45	0.16	0.13	0.11	0.13
45-60	0.07	0.05	0.06	0.06
60-75	0.06	0.05	0.07	0.06
75-90	0.07	0.06	0.07	0.07
90-120	0.07	0.08	0.11	0.09
Ave.	0.30	0.25	0.26	

[*] Expressed as ppm Si solution

[†] Means of 3 observations

[††] Means of 9 observations

Table 78. Influence of residual Si and soil pH on distribution of phosphate-extractable soil Si in profiles at 9 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	47	92	128	52	96	130	63	143	296
15-30	35	35	38	32	57	41	45	45	52
30-60	22	24	25	22	30	26	33	30	40
60-90	23	26	38	24	32	30	48	43	46
90-120	--	35	39	--	46	37	--	56	56

Depth x Si[††]

Depth cm	Si (kg/ha)		
	0	830	1660
0-15	54	110	185
15-30	37	46	44
30-60	26	28	30
60-90	32	34	38
90-120	--	46	44

Depth x pH[†††]

Depth cm	pH		
	5.5	6.0	6.5
0-15	89	93	167
15-30	36	43	47
30-60	24	26	34
60-90	29	29	46
90-120	37	52	56

[*] Expressed as ppm Si in soil

[†] Three replicates composited for analysis

[††] Means of 3 observations

[†††] Means of 3 observations except for data in the 90-120 cm depth which are means of 2 observations

Table 79. Influence of residual Si and soil pH on distribution of phosphate-extractable soil Si in profiles at 27 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	68	144	177	70	170	209	106	230	296
15-30	38	48	51	37	53	72	36	52	77
30-45	26	30	27	24	23	31	22	30	40
45-60	21	19	17	20	29	21	21	33	27
60-75	20	19	23	19	30	21	23	43	25
75-90	27	19	29	23	30	26	26	52	37
90-120	29	24	34	28	36	38	39	50	41

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	81	181	227	163
15-30	37	51	67	52
30-45	24	29	32	29
45-60	20	25	22	22
60-75	21	30	23	25
75-90	26	34	31	30
90-120	32	37	38	36
Ave.	34	55	63	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	130	150	211	164
15-30	46	54	55	52
30-45	28	27	31	29
45-60	19	21	27	22
60-75	21	23	30	25
75-90	25	27	38	30
90-120	29	34	44	36
Ave.	42	48	62	

* Expressed as ppm Si in soil

† 3 replicates composited for analysis

†† Means of 3 observations

Table 80. Influence of residual Si and soil pH on distribution of phosphate-extractable soil Si in profiles at 40 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5 Si (kg/ha) 0	pH 5.5 Si (kg/ha) 1660	pH 6.0 Si (kg/ha) 0	pH 6.0 Si (kg/ha) 1660	pH 6.5 Si (kg/ha) 0	pH 6.5 Si (kg/ha) 1660
0-15	50	163	57	175	103	329
15-30	37	53	36	48	38	50
30-45	26	25	18	24	30	30
45-60	21	24	18	22	31	18
60-75	22	29	21	23	34	21
75-90	25	31	24	26	32	28
90-120	31	55	26	37	34	35

Depth x Si[††]

Depth cm	Si (kg/ha) 0	Si (kg/ha) 1660	Ave.
0-15	70	222	146
15-30	37	50	44
30-45	25	26	26
45-60	23	21	22
60-75	26	24	25
75-90	27	28	28
90-120	30	42	36
Ave.	34	59	

Depth x pH[†††]

Depth cm	pH 5.5	pH 6.0	pH 6.5	Ave.
0-15	106	116	216	146
15-30	45	42	44	44
30-45	26	21	30	26
45-60	22	20	24	22
60-75	26	22	28	25
75-90	28	25	30	28
90-120	43	32	34	36
Ave.	43	40	58	

[*] Expressed as ppm Si in soil

[†] Three replicates composited for analysis

[††] Means of 3 observations

[†††] Means of 2 observations

Table 81. Influence of residual Si and soil pH on distribution of phosphate-extractable soil Si in profiles at 56 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	59	107	188	65	120	176	101	187	303
15-30	40	57	59	36	47	48	36	47	46
30-45	31	24	24	26	21	21	22	31	22
45-60	24	19	19	19	18	15	20	28	17
60-75	23	18	24	22	22	18	23	34	24
75-90	26	21	34	26	30	20	28	41	30
90-120	36	28	39	25	41	24	35	49	40

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	75	138	222	145
15-30	38	50	51	46
30-45	26	25	22	25
45-60	21	22	17	20
60-75	23	24	22	23
75-90	26	30	28	28
90-120	32	39	34	35
Ave.	34	47	57	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	118	120	197	145
15-30	52	44	43	46
30-45	26	22	25	25
45-60	21	17	22	20
60-75	22	20	27	23
75-90	27	25	33	28
90-120	34	30	41	35
Ave.	43	40	55	

[*] Expressed as ppm Si in soil

[†] Means of 3 observations

[††] Means of 9 observations

Table 82. Influence of residual Si and soil pH on distribution of modified Truog-extractable soil P in profiles at 27 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	47.3	72.2	52.0	58.6	56.0	51.2	41.8	54.9	47.5
15-30	7.7	13.0	8.5	10.5	10.2	12.5	8.3	11.6	8.0
30-45	3.9	4.0	6.3	2.5	4.2	5.1	1.2	2.7	3.5
45-60	2.9	3.4	3.7	5.7	4.2	4.8	3.1	5.6	5.0
60-75	2.3	2.6	1.7	4.1	3.9	3.2	3.1	2.5	1.0
75-90	3.6	2.2	2.4	2.8	3.4	3.0	2.3	1.0	1.2
90-120	1.9	5.1	4.1	2.2	3.6	2.6	3.6	2.6	1.8

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	49.2	61.0	50.2	53.5
15-30	8.8	11.6	9.7	10.0
30-45	2.5	3.6	5.0	3.7
45-60	3.9	4.4	4.5	4.3
60-75	3.2	3.0	2.0	2.7
75-90	2.9	1.9	2.2	2.3
90-120	2.6	3.8	2.8	3.1
Ave.	10.4	12.7	10.9	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	57.2	55.3	48.1	53.5
15-30	9.7	11.1	9.3	10.0
30-45	4.7	3.9	2.5	3.7
45-60	3.3	4.9	2.6	4.3
60-75	2.2	3.7	2.2	2.7
75-90	2.7	3.1	1.5	2.3
90-120	3.7	2.8	2.7	3.1
Ave.	11.9	12.1	10.2	

[*] Expressed as ppm P in soil

[†] Means of 3 observations

[††] Means of 9 observations

Table 83. Influence of residual Si and soil pH on distribution of modified Truog-extractable soil P in profiles at 40 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	31.4	38.1	46.1	36.3	29.4	41.6	32.4	44.6	67.5
15-30	10.1	4.4	14.3	5.7	6.6	9.6	4.5	7.3	36.0
30-45	8.2	3.5	5.6	3.6	4.3	2.4	3.4	3.1	5.0
45-60	4.5	2.3	4.7	2.3	1.9	2.8	2.8	1.9	7.9
60-75	1.9	1.6	3.3	2.3	1.9	1.7	2.3	1.7	2.9
75-90	2.5	1.1	4.2	1.4	3.9	1.4	1.6	1.4	6.7
90-120	2.1	1.7	2.0	1.3	3.6	1.5	3.3	1.3	2.0

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	33.4	37.4	51.7	40.8
15-30	6.8	6.1	10.3	7.7
30-45	5.1	3.6	4.3	4.4
45-60	3.2	2.0	5.0	3.4
60-75	2.2	1.7	2.7	2.2
75-90	1.8	2.1	4.1	2.7
90-120	2.2	2.2	1.8	2.1
Ave.	7.8	7.9	12.8	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	38.5	35.8	48.2	40.8
15-30	9.6	7.3	15.9	10.9
30-45	5.8	3.5	3.8	4.4
45-60	3.8	2.3	4.2	3.4
60-75	2.3	2.0	2.3	2.2
75-90	2.6	2.2	3.2	2.7
90-120	1.9	2.1	2.2	2.1
Ave.	9.2	7.9	11.4	

[*] Expressed as ppm P in soil

[†] Means of 3 observations

[††] Means of 9 observations

Table 84. Influence of residual Si and soil pH on distribution of modified Truog-extractable soil P in profiles at 56 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	16.9	20.6	27.1	23.9	23.2	20.8	17.9	31.6	30.7
15-30	2.6	2.6	3.4	3.6	2.6	3.9	3.7	3.3	3.5
30-45	2.1	1.6	2.1	1.5	1.3	2.2	1.5	1.7	1.7
45-60	1.3	1.5	1.4	1.1	1.4	1.4	1.1	1.2	1.9
60-75	2.8	1.2	1.4	1.0	1.2	1.4	1.5	1.0	1.0
75-90	2.2	1.0	1.3	0.8	2.7	1.1	1.4	1.3	2.2
90-120	1.8	1.2	1.0	0.7	1.5	1.0	1.1	0.9	1.0

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	19.6	25.1	26.2	23.6
15-30	3.3	2.8	3.6	3.2
30-45	1.7	1.6	2.0	1.7
45-60	1.2	1.4	1.6	1.4
60-75	1.8	1.2	1.3	1.4
75-90	1.5	1.7	1.5	1.6
90-120	1.2	1.2	1.0	1.1
Ave.	4.3	5.0	5.3	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	21.5	22.6	26.7	23.6
15-30	2.8	3.6	3.5	3.3
30-45	1.9	1.6	1.6	1.7
45-60	1.4	1.3	1.4	1.4
60-75	1.8	1.2	1.2	1.4
75-90	1.5	1.5	1.6	1.6
90-120	1.4	1.1	1.0	1.1
Ave.	4.6	4.7	5.3	

* Expressed as ppm P in soil

† Means of 3 observations

†† Means of 9 observations

Table 85. Actual soil pH in profiles at 27 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	5.18	5.31	5.23	5.64	5.25	5.83	6.33	5.92	6.28
15-30	4.71	4.69	4.85	4.83	4.62	5.18	5.10	5.05	5.18
30-45	4.85	4.86	5.20	4.99	4.96	4.98	5.02	5.16	5.17
45-60	4.90	4.86	5.22	5.04	5.51	5.14	5.13	5.22	5.40
60-75	5.06	4.87	5.22	5.03	5.52	5.12	5.19	5.22	5.24
75-90	5.34	5.00	5.26	5.15	5.63	5.09	5.17	4.98	5.30
90-120	4.94	5.02	5.24	5.18	5.62	5.25	5.17	5.02	5.22

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	5.72	5.49	5.78	5.66
15-30	4.88	4.79	5.07	4.91
30-45	4.95	4.99	5.12	5.02
45-60	5.02	5.20	5.25	5.16
60-75	5.09	5.20	5.19	5.16
75-90	5.22	5.20	5.22	5.21
90-120	5.10	5.22	5.24	5.19
Ave.	5.14	5.16	5.27	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	5.24	5.57	6.18	5.66
15-30	4.75	4.88	5.11	4.91
30-45	4.97	4.98	5.12	5.02
45-60	4.99	5.23	5.25	5.16
60-75	5.05	5.22	5.22	5.16
75-90	5.20	5.29	5.15	5.21
90-120	5.07	5.35	5.14	5.19
Ave.	5.04	5.22	5.31	

[*] Determined in a saturated soil paste

[†] Means of 3 observations

[††] Means of 9 observations

Table 86. Actual soil pH in profiles at 40 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	4.70	4.78	4.97	5.20	5.12	5.40	5.97	5.90	6.24
15-30	4.59	4.55	4.65	4.75	4.87	4.83	5.04	5.00	4.89
30-45	5.03	4.96	5.00	4.87	5.02	5.00	5.19	5.39	5.18
45-60	5.10	5.13	5.33	5.19	5.21	5.19	5.21	5.53	5.26
60-75	5.25	5.11	5.23	5.30	5.33	5.11	5.22	5.42	5.38
75-90	5.21	5.04	5.08	5.14	5.37	5.19	5.30	5.18	5.24
90-120	5.13	4.93	5.27	5.20	5.33	5.44	5.08	5.06	5.24

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	5.29	5.27	5.54	5.37
15-30	4.79	4.81	4.79	4.80
30-45	5.03	5.12	5.06	5.07
45-60	5.17	5.29	5.26	5.24
60-75	5.26	5.29	5.24	5.26
75-90	5.22	5.20	5.17	5.20
90-120	5.14	5.11	5.32	5.19
Ave.	5.13	5.16	5.20	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	4.82	5.24	6.04	5.37
15-30	4.60	4.82	4.98	4.80
30-45	5.00	4.96	5.25	5.07
45-60	5.19	5.20	5.33	5.24
60-75	5.20	5.25	5.34	5.26
75-90	5.11	5.23	5.24	5.19
90-120	5.11	5.32	5.13	5.19
Ave.	5.00	5.15	5.33	

* Determined in a saturated soil paste

† Three replicates composited for determinations

†† Means of 3 observations

Table 87. Actual soil pH in profiles at 56 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	5.10	5.09	5.31	5.59	5.36	5.44	5.97	6.11	6.08
15-30	4.83	4.93	4.89	4.93	5.00	5.03	5.35	5.35	5.16
30-45	5.09	5.09	5.18	5.26	5.27	5.26	5.38	5.38	5.40
45-60	5.30	5.20	5.28	5.34	5.36	5.23	5.45	5.58	5.42
60-75	5.25	5.19	5.28	5.38	5.39	5.29	5.50	5.60	5.57
75-90	5.19	5.17	5.43	5.29	5.34	5.17	5.47	5.57	5.47
90-120	5.21	5.30	5.39	5.24	5.39	5.21	5.38	5.47	5.39

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	5.55	5.52	5.61	5.56
15-30	5.04	5.09	5.03	5.05
30-45	5.24	5.25	5.28	5.26
45-60	5.36	5.38	5.31	5.35
60-75	5.38	5.39	5.38	5.38
75-90	5.32	5.36	5.36	5.35
90-120	5.28	5.39	5.33	5.33
Ave.	5.31	5.34	5.28	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	5.17	5.46	6.05	5.56
15-30	4.88	4.99	5.29	5.05
30-45	5.12	5.26	5.39	5.26
45-60	5.26	5.23	5.48	5.35
60-75	5.24	5.35	5.56	5.38
75-90	5.26	5.27	5.50	5.34
90-120	5.30	5.28	5.41	5.33
Ave.	5.13	5.27	5.53	

* Determined in a saturated soil paste

† Means of 3 observations

†† Means of 9 observations

Table 88. Influence of residual Si and soil pH on distribution of $BaCl_2$-extractable soil Al in profiles at 27 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	43.2	34.9	37.4	4.81	13.7	8.4	6.3	6.8	3.8
15-30	113.0	126.1	106.4	87.2	73.3	39.6	64.8	54.5	37.4
30-45	45.0	24.6	29.6	25.8	19.8	42.8	39.9	9.7	19.0
45-60	18.9	5.2	8.2	9.7	7.0	6.7	14.2	3.1	2.3
60-75	4.0	2.7	1.5	3.1	1.8	3.1	3.8	2.1	2.2
75-90	4.3	1.6	1.1	1.7	1.2	2.9	2.2	3.2	0.7
90-120	2.7	2.4	1.6	1.8	1.4	4.4	2.7	5.3	1.0

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	18.1	18.4	16.5	17.7
15-30	88.3	84.6	61.0	78.0
30-45	36.9	18.0	30.5	28.5
45-60	14.3	5.1	5.7	8.4
60-75	3.6	2.2	2.3	2.7
75-90	2.7	2.0	1.6	2.1
90-120	2.4	3.0	2.4	2.6
Ave.	23.8	19.0	17.1	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	38.5	9.0	5.6	17.7
15-30	115.0	66.7	52.2	78.0
30-45	33.1	29.5	22.9	28.5
45-60	10.7	7.8	6.5	8.3
60-75	2.7	2.7	2.7	2.7
75-90	2.3	1.9	2.0	2.1
90-120	2.2	2.5	3.0	2.6
Ave.	29.2	17.2	13.6	

* Expressed as ppm Al in soil

† Three replicates composited for analysis

†† Means of 3 observations

Table 89. Influence of residual Si and soil pH on distribution of $BaCl_2$-extractable soil Al in profiles at 40 months*

Depth x Si x pH†

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	92.4	54.9	48.6	19.5	22.9	16.8	4.2	1.0	2.2
15-30	109.2	107.1	94.4	86.9	49.7	79.1	41.2	65.5	29.9
30-45	29.0	14.4	25.2	34.5	20.2	19.2	16.6	14.2	18.7
45-60	1.90	1.2	2.0	3.3	2.5	2.4	6.5	1.82	7.4
60-75	1.1	1.0	1.9	0.8	1.2	2.5	4.8	0.81	0.4
75-90	1.0	1.9	2.1	1.5	1.3	2.0	1.1	1.31	0.3
90-120	3.8	2.5	5.7	2.1	1.8	2.5	6.6	3.2	1.1

Depth x Si††

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	38.7	26.3	22.5	29.2
15-30	79.0	74.1	67.8	73.6
30-45	26.7	16.3	21.0	21.3
45-60	3.9	1.8	4.0	3.2
60-75	2.2	1.0	1.6	1.6
75-90	1.2	1.5	1.5	1.4
90-120	4.2	2.5	3.1	3.2
Ave.	22.3	17.6	17.3	

Depth x pH††

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	65.3	19.7	2.5	29.2
15-30	103.0	71.9	45.5	73.5
30-45	22.9	24.6	16.5	21.3
45-60	1.7	2.7	5.2	3.2
60-75	1.3	1.5	2.0	1.6
75-90	1.7	1.6	0.9	1.4
90-120	4.0	2.2	3.6	3.2
Ave.	28.5	17.7	10.9	

* Expressed as ppm Al in soil

† Three replicates composited for analysis

†† Means of 3 observations

Table 90. Influence of residual Si and soil pH on distribution of $BaCl_2$-extractable soil Al in profiles at 56 months[*]

Depth x Si x pH[†]

Depth cm	pH 5.5			pH 6.0			pH 6.5		
	Si (kg/ha)			Si (kg/ha)			Si (kg/ha)		
	0	830	1660	0	830	1660	0	830	1660
0-15	79.0	73.0	33.9	8.6	18.5	27.2	1.0	1.2	0.6
15-30	113.0	87.0	86.2	99.6	57.9	66.3	68.4	35.1	69.5
30-45	25.7	18.0	27.4	21.1	11.2	12.6	22.5	5.3	15.4
45-60	2.7	2.8	4.6	3.6	3.1	3.4	3.5	1.7	4.2
60-75	1.3	1.0	2.2	1.2	1.4	7.6	1.5	1.1	1.7
75-90	1.9	1.5	1.2	0.7	0.7	7.0	0.9	1.7	0.7
90-120	2.9	1.7	1.4	1.1	2.0	4.1	2.3	1.8	1.4

Depth x Si[††]

Depth cm	Si (kg/ha)			Ave.
	0	830	1660	
0-15	29.5	30.9	20.6	27.0
15-30	93.7	60.0	74.0	75.9
30-45	23.1	11.5	18.5	17.7
45-60	3.3	2.5	4.1	3.3
60-75	1.3	1.2	3.8	2.1
75-90	1.2	1.3	3.0	1.8
90-120	2.1	1.8	2.3	2.1
Ave.	22.0	15.6	18.0	

Depth x pH[††]

Depth cm	pH			Ave.
	5.5	6.0	6.5	
0-15	62.0	18.1	0.9	27.0
15-30	94.5	74.6	57.7	75.6
30-45	23.7	15.0	14.4	17.7
45-60	3.9	3.4	3.1	3.5
60-75	1.5	3.4	1.4	2.1
75-90	1.5	2.8	1.1	1.8
90-120	2.0	2.4	1.8	2.1
Ave.	27.0	17.1	11.5	

[*] Expressed as ppm Al in soil

[†] Means of 3 observations

[††] Means of 9 observations

Table 91. Soil analyses of control plot profile at 56 months

Depth cm	H_2O-ext. Si ppm sol'n	PO_4-ext. Si ppm soil	Soil pH	$BaCl_2$-ext. Al ppm soil	Mod. Truog-ext. P ppm soil
0-15	0.40	49.5	4.39*	147.0	4.6
15-30	0.32	39.4	4.90	52.7	1.8
30-45	0.16	26.3	4.91	25.2	1.9
45-60	0.08	16.7	4.90	6.4	1.4
60-75	0.05	12.7	5.02	2.0	1.4
75-90	0.05	14.7	5.02	1.1	1.0
90-120	0.06	17.0	4.97	1.2	0.9

* Determined in a saturated soil paste

Table 92. Influence of residual Si and soil pH on dry matter yield and whole-plant Si concentration of rice*

Applied Si kg/ha		pH 5.5			pH 6.0			pH 6.5		
		0	830	1660	0	830	1660	0	830	1660
Depth (cm)					Yield (g/pot)					
0-15	Plant	3.33	3.34	3.16	3.02	3.17	3.19	2.80	2.45	2.68
	Ratoon	1.11	1.09	1.16	1.05	0.93	1.03	0.76	1.04	0.59
	Total	4.44	4.43	4.32	4.07	4.10	4.22	3.56	3.49	3.27
15-30	Plant	3.38	3.22	3.12	3.27	3.24	3.18	3.11	3.23	3.18
	Ratoon	1.06	0.93	1.07	0.96	0.88	0.96	0.92	0.92	0.95
	Total	4.44	4.15	4.19	4.23	4.12	4.14	4.03	4.15	4.13
					Si (%)					
0-15	Plant	0.10	0.15	0.25	0.14	0.20	0.22	0.21	0.40	0.44
	Ratoon	0.12	0.17	0.29	0.27	0.32	0.32	0.65	0.75	1.18
15-30	Plant	0.08	0.10	0.11	0.07	0.10	0.09	0.08	0.09	0.10
	Ratoon	0.14	0.16	0.15	0.15	0.19	0.18	0.20	0.19	0.20

* Means of 3 observations

Filter paper blank yield (g/pot) = Plant 2.24
Ratoon 0.25

Si (%) = Plant 0.01
Ratoon 3.03

Table 93. Influence of residual Si and soil pH on soil Si extracted by phosphate solution and rice plants (plant and ratoon crops)*

Applied Si kg/ha	pH 5.5			pH 6.0			pH 6.5		
	0	830	1660	0	830	1660	0	830	1660
Depth (cm)					Phosphate extraction (kg/ha)				
0-15	105	190	331	116	211	313	178	330	538
15-30	70	99	104	62	83	84	64	82	80
0-30	175	289	435	178	294	397	242	412	618
					Plant extraction (kg/ha)				
0-15 Plant crop	100	165	270	137	214	231	198	331	400
15-30 Plant crop	81	109	116	73	101	95	75	95	100
0-30 Plant crop	181	274	386	210	315	326	273	426	500
0-15 Ratoon crop	46	64	117	98	106	114	169	268	234
15-30 Ratoon crop	50	48	53	47	56	56	63	63	68
0-30 Ratoon crop	96	112	170	145	162	170	232	331	302
0-30 Plant and ratoon	277	386	556	355	477	496	505	757	802
Applied Si extracted									
PO_4-ext.	--	114	260	--	116	219	--	170	376
Plant-ext.	--	109	279	--	122	141	--	252	297

* Means of 3 observations

Table 94. Influence of soil mineralogy and pH on corn yield and plant and soil composition (Experiment 1)*

Soil	Mineralogy	Rainfall cm	Soil pH	Dry matter g/pot		Plant Al ppm		1N NH_4OAc, 7.0 Extractable	
				Tops	Roots	Tops	Roots	Ca	Mg
								ppm soil	
Akaka	Allophane Gibbsite Magnetite	560	3.4	$4.6^{a\dagger}$	2.0^{a}	128.4^{b}	2975	94	137
Halii	Gibbsite Fe-oxides	230	4.2	21.0^{b}	6.0^{b}	17.2^{a}	775	962	71
Wahiawa	Halloysite	100	5.3	24.8^{b}	7.0^{b}	20.3^{a}	1710	1242	402
Lualualei	Montmorillonite	50	7.3	41.0^{c}	9.3^{c}	16.2^{a}	1190	11460	3050
Kawaihae	Kaolin Geothite Magnetite	25	6.4	33.0^{bc}	6.1^{b}	16.9^{a}	1478	8570	1785

* Means of 3 observations

† Means not followed by the same letter are significantly different at the 5% level.

Table 95. Influence of pH differentials on corn yield and plant and soil composition in Akaka and Halii soils (Experiment 2)*

Treatments meq Ca/100 g soil	Soil pH	Dry matter g/pot		Al ppm		P %	Ca %	Si %	1N NH_4OAc, pH 7.0 extractable	
		Tops	Roots	Tops	Roots	Tops	Tops	Tops	Ca	Mg
									ppm soil	
				Akaka soil						
0 $CaSiO_3$	3.7	5.2	1.2	81.2	2200	0.09	0.25	0.15	139	137
2	4.5	12.0	5.5	17.6	1550	0.11	0.64	0.94	937	231
8	5.2	14.8	5.6	19.4	1125	0.08	0.68	1.74	3870	175
16	5.7	12.5	3.3	21.5	1215	0.09	0.73	2.21	7700	190
32	6.3	7.9	1.2	24.8	853	0.09	0.99	2.01		
				Halii soil						
0 $CaSiO_3$	4.0	11.8	5.9	23.0	1262	0.10	0.76	0.32	892	75
2	4.1	11.6	5.9	23.3	725	0.10	0.88	0.93	1135	79
8	4.8	13.8	5.1	19.4	1187	0.09	0.98	1.64	2230	76
16	5.3	11.0	4.4	30.9	600	0.09	1.20	1.93	3620	78
0 $CaCO_3$	4.0	12.6	5.4	27.5	1887	0.11	0.63	0.27	990	83
8	4.9	11.3	5.5	16.0	783	0.09	1.12	0.20	2465	74
16	5.5	9.3	5.6	25.0	627	0.10	1.38	0.16	3470	60

* Means of 3 observations

Table 96. Influence of pH differentials on desmodium yield and plant and soil composition in Akaka and Halii soils (Experiment 3)*

Treatments meq Ca/100 g soil	Soil pH	Dry matter g/pot Tops	Roots	Al ppm Tops	Roots	P % Tops	Ca % Tops	Si % Tops	1N NH_4OAc, pH 7.0 extractable Ca ppm soil	Mg
					Akaka soil					
0 $CaSiO_3$	4.3	11.8	2.42	56.8^{b}[†]	2725^{b}	0.14	0.36	0.14	117	228
8	5.1	15.1	2.65	28.3^{a}	4162^{c}	0.12	1.57	0.59	3485	203
16	5.6	17.0	2.53	31.3^{a}	2581^{b}	0.11	1.58	0.66	7015	161
32	6.4	20.7	3.11	34.3^{a}	1598^{a}	0.12	1.61	0.51	11790	127
					Halii soil					
0 $CaSiO_3$	4.1	23.0	3.98	33.2	4225	0.11	1.45	0.08	577	40
2	4.3	22.5	3.79	29.9	4818	0.13	1.75	0.23	1170	66
8	4.9	22.8	4.16	31.1	3046	0.16	2.05	0.38	2020	73
16	5.5	21.9	3.39	21.3	2220	0.12	1.91	0.41	3465	79
0 $CaCO_3$	4.1	23.0	3.47	38.3	3005	0.12	1.69	0.09	744	43
16	5.6	25.8	3.21	25.1	1504	0.13	2,10	0.03	3400	67

* Means of 3 observations

[†] Means not followed by the same letter are significantly different at the 5% level

Table 97. Influence of pH differentials on whiteclover yield and plant and soil composition in Akaka and Halii soils (Experiment 4)*

Treatments meq Ca/100 g soil	Soil pH	Dry matter g/pot Tops	Dry matter g/pot Roots	Plant Al ppm Tops	Plant Al ppm Roots	1N NH_4OAc, pH 7.0 extractable Ca ppm soil	1N NH_4OAc, pH 7.0 extractable Mg ppm soil
			Akaka soil				
0 $CaSiO_3$	4.0	$3.07^{a\dagger}$	0.94^{a}	117.3^{b}	3720	108	107
8	5.3	17.00^{b}	4.69^{b}	28.3^{a}	1989	3200	111
16	5.9	18.50^{c}	4.03^{b}	22.6^{a}	1763	6350	135
			Halii soil				
0 $CaSiO_3$	4.4	4.00^{a}	0.80^{a}	144.2	1828^{c}	240	236
8	5.3	10.90^{ab}	2.75^{b}	65.5	764^{b}	2430	234
16	5.7	17.70^{b}	4.31^{c}	53.1	473^{a}	3630	179

* Means of 3 observations

† Means not followed by the same letter are significantly different at the 5% level

Table 98. Soil Al (ppm soil) extracted by various methods from soil samples after corn (Experiments 1 and 2)*

Soils	Soil pH	Extraction method: 1N KCl			1N $BaCl_2$			1N NH_4OAc, pH 4.8			1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8			0.01M $CaCl_2$	H_2O
		A[†]	B	C	A	B	C	A	B	C	A	B	C		
							Experiment 1								
Akaka	3.4	227.1	239.3	269.4	328.9	449.1	535.0	543	756	1019	596	1110	1416	69.1	217.0
Halii	4.2	7.4	4.7	8.1	17.1	47.3	24.1	56	143	177	69	209	202	0.4	0.2
Wahiawa	5.3	0.9	0.2	0.5	2.1	1.4	1.8	36	44	72	44	74	61	0.2	0.1
Lualualei	7.3	0.3	0.2	0.5	0.1	0.1	0.6	33	33	26	33	49	29	0.3	0.2
Kawaihae	6.4	0.2	0.2	0.4	1.1	0.1	0.3	20	26	29	33	57	38	0.3	0.1
Treatments meq Ca/100 g soil							Experiment 2								
							Akaka soil								
0 $CaSiO_3$	3.7	141.8	138.4	168.1	219.2	294.3	332.8	474	650	1025	546	1031	1168	34.2	97.0
2	4.5	27.4	35.0	34.3	78.0	96.1	123.4	310	533	841	277	807	942	2.0	0.6
8	5.2	1.7	1.9	2.3	9.3	13.4	14.2	159	319	497	156	485	572	0.2	0.8
16	5.7	1.0	0.5	1.1	1.2	1.2	2.1	111	206	380	115	312	390	0.1	0.7
32	6.3	0.9	0.5	1.6	0.8	0.7	1.2	143	220	363	123	305	335	0.1	0.5
							Halii soil								
0 $CaSiO_3$	4.0	39.1	46.3	35.7	43.8	103.0	94.3	93	313	327	119	374	375	10.9	9.1
2	4.1	30.8	31.0	26.9	40.0	83.2	79.5	82	264	317	124	330	340	5.4	2.6
8	4.8	6.4	3.7	4.3	10.1	19.5	13.2	46	166	219	38	206	226	0.5	0.4
16	5.3	1.1	0.6	0.7	1.6	2.7	2.8	27	108	147	29	141	150	0.2	0.4
0 $CaCO_3$	4.0	23.0	46.0	36.0	46.0	98.0	97.0	89	279	321	111	355	363	12.0	
8	4.9	3.1	2.1	0.9	6.1	21.0	13.0	48	174	231	44	217	242	0.3	
16	5.5	0.5	0.4	1.1	0.7	1.0	1.0	27	120	161	27	153	167	0.1	

* Means of 3 observations

[†] A Immediate mixing and extraction

B One and a half hour shaking and filtration

C Overnight equilibration and extraction

Table 99. Soil Al (ppm soil) extracted by various methods from Akaka and Halii soils after desmodium (Experiment 3)*

Treatments meq Ca/100 g soil	Soil pH	Extraction method												
		1N KCl			1N $BaCl_2$			1N NH_4OAc. pH 4.8			1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8			0.01M $CaCl_2$
		A[†]	B	C	A	B	C	A	B	C	A	B	C	
						Akaka soil								
0 $CaSiO_3$	4.3	58.2	91.2	82.9	131.0	156.1	231.2	271	586	832	337	904	957	38.6
8	5.1	1.8	2.7	2.1	10.7	15.4	20.1	102	272	423	113	415	498	1.4
16	5.6	0.2	1.1	0.6	1.4	1.4	1.7	50	168	233	48	220	278	0.5
32	6.4	0.1	0.7	1.9	0.8	0.5	0.7	67	180	223	58	242	233	0.4
						Halii soil								
0 $CaSiO_3$	4.1	29.0	44.9	46.5	49.4	103.0	112.2	89	258	289	129	357	339	39.5
2	4.3	25.5	35.9	36.4	33.5	73.3	99.0	93	222	267	122	303	308	28.2
8	4.9	3.5	4.9	6.1	11.5	19.5	23.9	39	129	145	62	186	178	0.9
16	5.5	0.4	0.9	0.5	1.7	2.1	3.0	23	82	99	23	110	107	0.4
0 $CaCO_3$	4.1	28.9	44.9	40.6	45.8	92.1	119.1	113	255	289	103	341	326	51.0
16	5.6	0.3	0.6	0.1	1.2	1.2	2.0	19	83	119	11	128	128	0.9

* Means of 3 observations

[†]A Immediate mixing and extraction

B One and a half hour shaking and filtration

C Overnight equilibration and extraction

Table 100. Soil Al (ppm soil) extracted by various methods from Akaka and Halii soils after whiteclover (Experiment 4)*

Treatments meq Ca/100 g soil	Soil pH	Extraction method													
		1$\underline{N}$ KCl			1$\underline{N}$ $BaCl_2$			1$\underline{N}$ NH_4OAc, pH 4.8			1$\underline{N}$ NH_4OAc + 0.2$\underline{N}$ $BaCl_2$, pH 4.8			0.01$\underline{M}$ $CaCl_2$	H_2O
		A†	B	C	A	B	C	A	B	C	A	B	C		
								Akaka soil							
0 $CaSiO_3$	4.0	173.0	186.1	204.3	351.1	413.7	386.3	398	966	940	441	919	1152	41.7	99.0
8	5.3	2.3	2.5	0.9	39.0	66.3	22.5	86	349	341	115	366	472	1.0	0.1
16	5.9	0.5	0.2	0.2	1.5	2.2	1.2	53	178	207	64	213	262	0.7	0.1
								Halii soil							
0 $CaSiO_3$	4.4	33.0	66.6	58.0	108.3	211.0	173.0	150	549	361	190	540	551	2.7	0.6
8	5.3	1.2	1.7	1.8	33.0	40.5	16.6	46	171	164	66	239	246	0.3	0.6
16	5.7	1.1	0.4	1.4	1.7	2.0	1.8	27	113	113	37	146	156	0.7	0.5
Overall mean (all expts.)		25.6	31.4	32.7	49.4	73.6	77.2	119	270	309	133	359	420	10.4	21.5

* Means of 3 observations

†A Immediate mixing and extraction

B One and a half hour shaking and filtration

C Overnight equilibration and extraction

Table 101. Simple correlation coefficients (r) for relationships between various extraction methods for soil Al (data for all experiments combined, n = 96)

Extracting solution		1N KCl			1N $BaCl_2$			1N NH_4OAc, pH 4.8			1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8			0.01M $CaCl_2$ 16 hours shaking	H_2O*
		A†	B	C	A	B	C	A	B	C	A	B	C		
1N KCl	A	1.00	0.96**	0.98	0.96	0.96	0.97	0.91	0.84	0.82	0.91	0.84	0.86	0.69	0.93
	B		1.00	0.98	0.94	0.97	0.98	0.89	0.87	0.82	0.90	0.86	0.86	0.71	0.92
	C			1.00	0.95	0.95	0.97	0.90	0.84	0.81	0.90	0.84	0.85	0.69	0.93
1N $BaCl_2$	A				1.00	0.97	0.96	0.90	0.89	0.92	0.91	0.85	0.87	0.60	0.88
	B					1.00	0.98	0.90	0.91	0.89	0.90	0.87	0.87	0.68	0.86
	C						1.00	0.83	0.83	0.86	0.93	0.90	0.89	0.70	0.92
1N NH_4OAc, pH 4.8	A							1.00	0.89	0.94	0.97	0.94	0.97	0.67	0.85
	B								1.00	0.94	0.89	0.95	0.94	0.60	0.70
	C									1.00	0.93	0.98	0.98	0.64	0.73
1N NH_4OAc + 0.2N $BaCl_2$, pH 4.8	A										1.00	0.94	0.95	0.67	0.86
	B											1.00	0.98	0.66	0.76
	C												1.00	0.63	0.79
0.01M $CaCl_2$	16 hours													1.00	0.56
H_2O	shaking														1.00

* n = 57, H_2O-extractable Al analysed from soil samples collected from Experiments 1, 2 ($CaSiO_3$ treatments only) and 4.

†A Immediate mixing and extraction

B One and a half hour shaking and filtration

C Overnight equilibration and extraction

** All values significant at the 1% level

Table 102. Soil Ca and Mg extracted with 1N KCl (1.5 hour shaking) from soil samples after corn and whiteclover (Experiments 1, 2, and 4)*

Experiment 1			
Soil	Soil pH	Ca ppm soil	Mg ppm soil
Akaka	3.4	13	105
Halii	4.2	907	58
Wahiawa	5.3	941	489
Lualualei	7.3	8890	2655
Kawaihae	6.4	6855	1723

	Experiment 2			Experiment 4		
Treatments meq Ca/100g soil	Soil pH	Ca ppm soil	Mg ppm soil	Soil pH	Ca ppm soil	Mg ppm soil
	<u>Akaka soil</u>			<u>Akaka soil</u>		
0 $CaSiO_3$	3.7	42	129	4.0	22	82
2	4.5	950	172	--	--	--
8	5.2	3293	141	5.3	2900	90
16	5.7	5758	133	5.9	5224	104
	<u>Halii soil</u>			<u>Halii soil</u>		
0 $CaSiO_3$	4.0	782	67	4.4	250	209
2	4.1	1006	67	--	--	--
8	4.8	1816	61	5.3	1977	208
16	5.3	2663	59	5.7	2966	144

* Means of 3 observations

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