ANALYSIS OF PLANT NUTRIENTS
IN SOIL BY ION EXCHANGE RESIN EXTRACTION
AND
X-RAY FLUORESCENCE SPECTROMETRY

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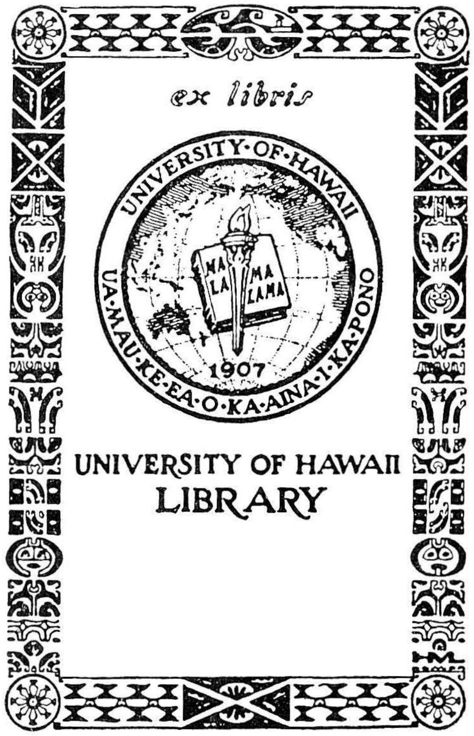

We certify that we have read this dissertation and that in our opinion it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosphy in Agronomy and Soil Science.

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To the memory of my grandmother

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ABSTRACT

A combined ion exchange resin and a multi-element x-ray fluorescence method was developed as an alternative to existing soil testing methods. By shaking soil and an ion exchange membrane sandwiched between permeable paper discs in an extraction cell, it was possible to extract and analyze all plant nutrient elements except B and N in soils.

Using six soils with different physical, mineralogical and chemical properties, the effects of soil sample size, soil-water ratio and equilibration time on nutrient extraction by resin were investigated to determine optimum conditions for use in a routine extraction procedure. The results showed that increasing soil sample size and equilibration time increased the concentration of nutrients adsorbed by resin. In high base soils monovalent cation adsorption by resin decreased as polyvalent cation adsorption increased with time. This relationship was attributed to greater preference by resin for the latter. In contrast, increasing the soil-water ratio decreased the concentration of polyvalent cations and increased the monovalent cations adsorbed by resin. The capacity of the resin to adsorb nutrients, restricted by the absence of contact exchange, was dependent on the nutrient concentration in the soil solution. Thus, the quantity adsorbed was regarded as a reflection of the quantity-intensity parameter of the soil nutrient pool since the quantity of a particular nutrient removed from soil by the ion exchange resin was found to be largely determined by the nutrient concentration in the soil.

A comparison between cation exchange resin and 1<u>N</u> ammonium acetate showed that both methods were very significantly correlated for Al, Ca,

Mg, and K in a Typic Gibbsihumox (low base soil), and very poorly correlated for Ca and Mg in a Typic Chromustert(high base soil). This difference was attributed to the selective adsorption of nutrients by ion exchange resin, in contrast to the non-selective extraction by the ammonium acetate solution. It was also pointed out that the quantity of a particular nutrient adsorbed by resin can be limited by competition among cations and the total exchange capacity of the resin. This extraction procedure using Cl^--saturated anion exchange membrane to estimate P, was only marginally sucessful. The dependence of the resin on water-soluble P in the absence of contact exchange was believed to be responsible for this. Therefore, the use of a different and/or OH^--saturated anion exchange resin was suggested for P extraction.

By multiple regression analysis of experimental data, equations containing cation concentration ratios were employed to describe yield response and nutrient uptake by sudax (*Sorghum bicolor* x *Sorghum sudanensis*). The results showed that when only nutrient cations were considered in such equations, ion exchange resin was superior to 1*N* ammonium acetate extraction, in predicting yield response. Similarly, legume yields obtained from a field experiment designed to study the relative response of tropical and temperate legumes to liming, were adequately predicted by resin-extractable cations.

In conclusion, the multi-element approach to soil testing presents a more sensitive method for assessing nutrient deficiencies and excesses in soils, and offers a means to study the delicate concentration dependent interactions among nutrient elements and their effects on nutrient uptake by plants.

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INTRODUCTION

Most methods used for estimating plant nutrients in soils are based on measuring the quantity of nutrients which goes into solution when a soil is treated with an extracting solution. Such methods however, do not necessarily extract the quantity which can be removed by the plant root. For example, in the determination of available soil phosphorus the number of methods used by soil analysts is enormous, ranging from dilute acid to boiling NaOH treatment, and the quantity of phosphorus extracted is different depending upon the method used. Therefore, some methods over-estimate and others under-estimate the soil phosphorus which is available to plants.

Similarly, in the measurement of cation exchange capacity a variety of different index cations (Pratt and Holowaychuk, 1954; and DeEndredy and Quagraine, 1960), saturating solution pH, and procedures have been used. In general, Ba^{+}, Sr^{+2}, Ca^{+2} or Mg^{+2} ions used as index cations tend to give higher values for cation exchange capacity than NH_4^{+} or Na^{+} ions (Hesse, 1971). Also, the cation exchange capacity tends to vary with soil pH (Hanna and Reed, 1948). Conventionally, the cation exchange capacity of a soil is measured by saturating a soil sample with an index cation, washing the sample to remove the excess saturating salt and subsequently displacing the adsorbed index cation by another cation for analysis. Okazaki et al. (1963) have pointed out that in each of these steps there is potential for error, but most errors occur in the washing step. Most washing procedures generally specify a fixed amount of washing solution. However, as soils differ in their capacity to retain salts, some soils may retain excess index cation after washing. On the other hand, with some soils the index cation may be hydrolyzed during washing. Consequently, the measured cation exchange capacity may be higher or lower than its true value.

Furthermore, in most routine determinations of exchangeable bases and cation exchange capacity, a normal neutral ammonium acetate solution is used. In some highly weathered acid soils NH_4^+ ions are easily fixed (Mikami, 1966), as well as in moist saline and alkaline soils (Bower et al. 1952). Therefore, cation exchange capacity measurements in such soils using ammonium acetate may give low results. Tucker (1960) has also indicated that ammonium acetate gives poor results because the acetate anion tends to dissolve the organic components of soils, thereby increasing the solubility of non-exchangeable bases. He attributes this to the fact that metal cations dissolve more readily in solutions containing anions of weak acids.

The above factors make it difficult to compare or interpret cation exchange capacity measurements. Further evidence of extracting solutions interfering with the normal behavior of soils was demonstrated by Williams (1950) who showed that more phosphorus was taken up by plant after the soil was acid treated than before treatment.

Bearing in mind that only the plant can determine the available soil nutrient, it becomes desirable to develop a method which can better simulate the soil-plant root relationship. Extraction of nutrients by ion exchange resins appears to offer such a method. The application of exchange resins to soil analysis is a simple and convenient method for estimating all the readily exchangeable ions and ions from water-soluble and acid-soluble compounds without unduly altering the clay minerals.

Over the last several years many studies have been conducted on the use of cation and anion exchange resins in soil systems. Anion exchange resins have mostly been used to estimate available soil phosphorus and cation exchange resins have been used to asses non-exchangeable potassium, magnesium, calcium and minor elements.

A combined application of ion exchange resin and x-ray fluorescence spectrometry adds a new dimension to soil analysis. X-ray fluorescence spectrometry not only offers a rapid method for elemental analysis but also provides analytical accuracy and precision.

The objectives of this study are to:

1) develop a method of plant nutrient extraction from soils using ion exchange resin,
2) measure nutrients adsorbed on ion exchange resins by x-ray fluorescence spectrometry,
3) correlate ammonium acetate and ion exchange resin-extractable cations, and
4) correlate nutrient uptake by plant with nutrients extracted by ion exchange resins.

REVIEW OF LITERATURE

ION EXCHANGE IN SOILS

A. Historical development

The discovery that soil exhibit ion exchange properties dates back many centuries. Aristotle found that sea water lost some of its salts upon percolating through "certain sands" (Helfferich, 1962). In 1845 Thompson, through the work of an assistant, discovered that when a solution of $(NH_4)_2SO_4$ was percolated through a column packed with soil, the effluent contained no ammonium salts but considerable amounts of $CaSO_4$ instead. This discovery was reported to Way in 1850, who immediately verified it and began a series of investigations on the subject. This was the beginning of the concept of ion exchange in soils.

B. Ion exchange process

The ion exchange reaction $R\text{-}X + Y^+ = R\text{-}Y + X^+$ between two counter-ion species X^+ and Y^+ on an exchange resin, R, and in solution respectively, may be predicted by the double layer theory. According to this theory the equilibrium distribution of X^+ and Y^+ ions is a function of the ratio of their concentrations. This equilibrium distribution which may be expressed in the form of the mass action equation is

$$K = \frac{(R\text{-}X)\ (Y^+)}{(X^+)\ (R\text{-}Y)}$$

where K is the equilibrium constant.

When an exchange resin is placed in contact with soil, the double layers of the resin and soil interact with each other. Consequently, the potential of the combined double layers is less than what each would be at a greater distance from each other. The significance of this is that each ion exchanger (resin and soil) has its characteristic exchange isotherm (which varies with the nature of the counter-ions) so that when the resin exchange isotherm (Helfferich, 1962) is superimposed on that of the soil (Sinanuwong, 1972; Fox, 1974), each is altered. Thus, the capacity of an exchange resin to adsorb nutrients from soil depends on the strength of its adsorption isotherm. The rate of ion transfer from one exchanger to the other governs the length of equilibration time.

Various ions including H^+, NH_4^+, OH^- and Cl^- have been used as counter-ions for the exchange resin extraction of soil nutrients. With each counter-ion, the resulting exchange isotherm is different and this means the quantity and quality of extracted nutrients are different. Thus, it is apparent that the effectiveness of an exchange resin in nutrient adsorption from soil is governed by its adsorption isotherm which is in turn determined by the nature and valence of the counter-ion on the resin and the soil.

C. The nature and properties of synthetic ion exchange resins

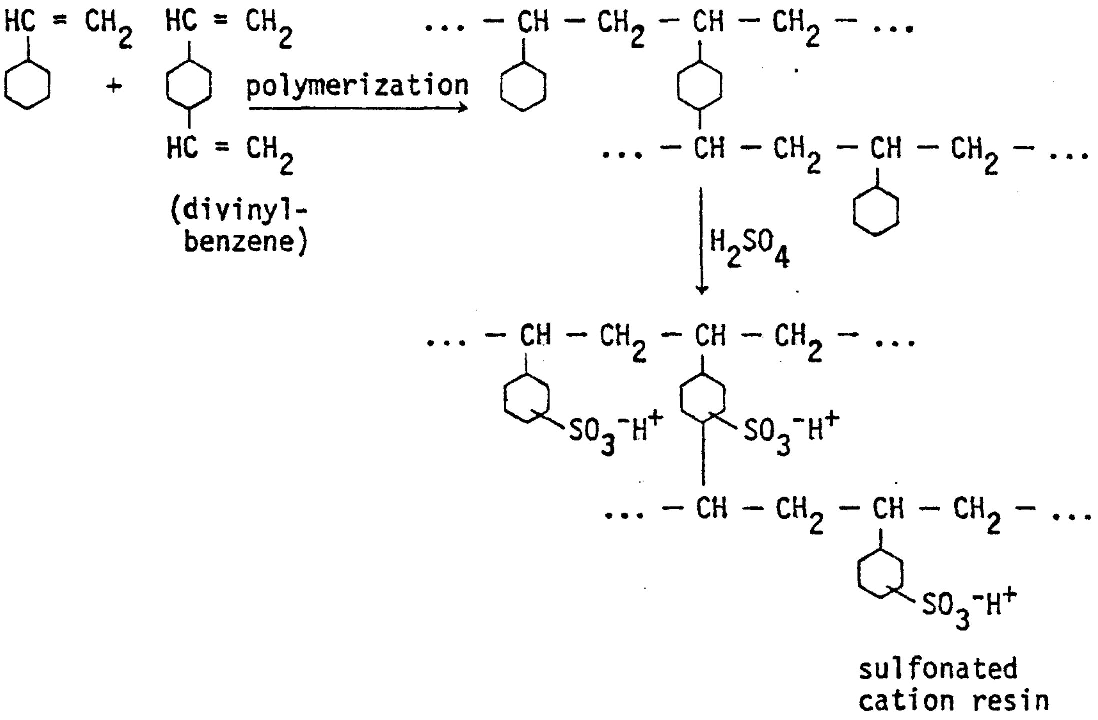
1. Structure

A synthetic ion exchange resin is a three dimensional, crosslinked hydrocarbon polymer with fixed acidic or basic groups which ionize to form a positively or negatively charged resin. Unlike the linear polymers, crosslinked polymers are insoluble in water since crosslinking creates a matrix in which the polymer chains are interconnected. The degree of crosslinking is a function of the divinylbenzene content of the resin. There are several forms of ion exchange resins, namely, beads (spheres), gels, liquids and membranes, and they are classified into cation and anion exchange resins.

Most of the earlier cation exchange resins were condensation products of phenol derivatives and aldehydes. Similarly, most of the earlier anion exchange resins were condensation products of aromatic or aliphatic amines and aldehydes, dihaloparaffins or haloepoxides. Present day ion exchange resins are addition copolymers prepared from vinyl monomers. Amphoteric resins prepared from conventional resins by polymerization of monomeric counter-ions within the resin also exist.

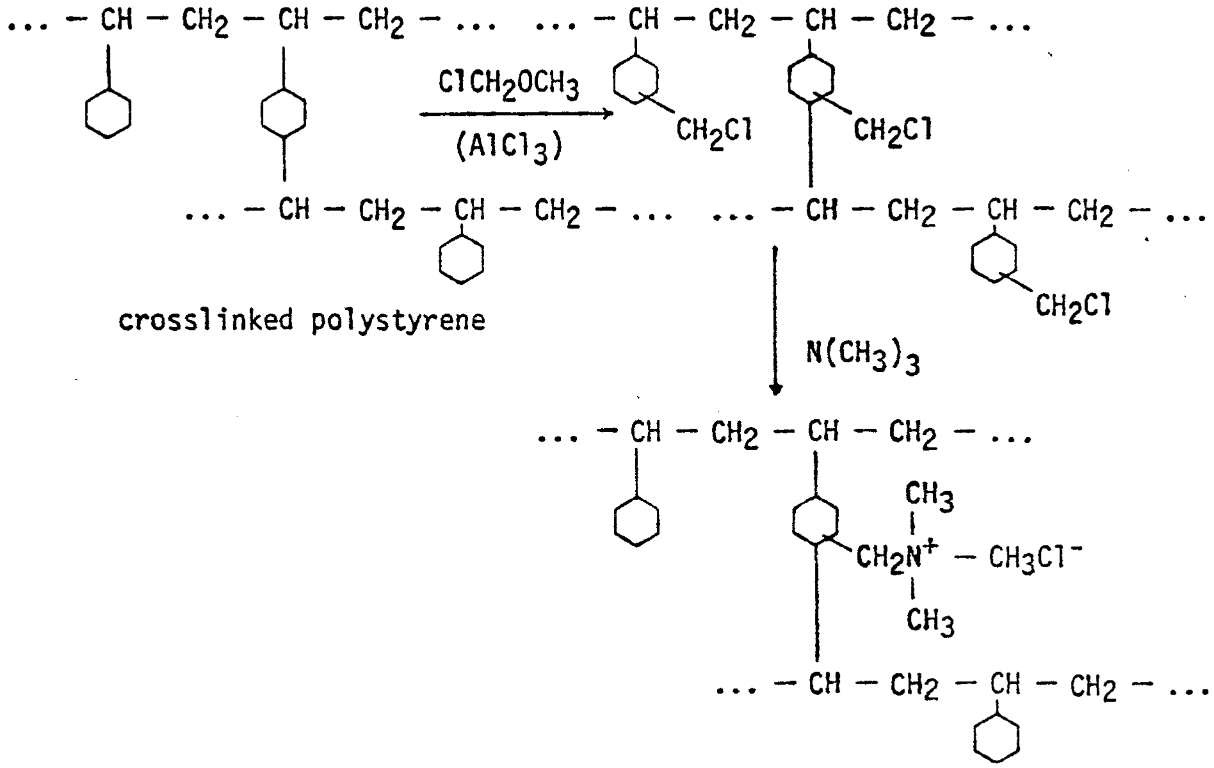
a. Cation exchange resin

A typical example of a cation exchange resin is the sulfonated strong acid resin. It is manufactured by the following process:



b. Anion exchange resin

This type of resin is manufactured by chloromethylation of a crosslinked polystyrene through the Friedel-Crafts reaction and subsequent treatment with a tertiary alkyl amine. The reaction of the chloromethylated intermediate with the tertiary amine (quarternization) forms a strong-base anion resin with quarternary ammonium groups as the fixed ions.



The fixed groups as revealed by x-ray diffraction are randomly dispersed throughout the interior of the resin (Boyd et al., 1947).

2. Physical and chemical properties

a. Swelling

Ion exchange resins have an elastic matrix which tends to swell in an aqueous solution due to the following factors: First, the fixed and mobile ions have the tendency to solvate. This tendency is greater in polar solvents, like water. Secondly, the resin interior is usually at a higher osmotic pressure than the exterior due to the high concentration of fixed and mobile ions. Therefore, the tendency to dilute the interior solution by absorbing more solvent, results in the swelling of the resin. However, the degree of swelling is controlled by the amount of crosslinking. A weakly crosslinked resin swells more than an excessively crosslinked resin with a rigid matrix. Hence, swelling is inversely proportional to the degree of crosslinking.

b. Ion selectivity

Ion selectivity may be defined as the adsorption of one counter-ion in preference to another by an ion exchanger. Factors controlling ion selectivity are:

(i) Degree of crosslinking

Generally, ion selectivity tends to increase with an increasing degree of crosslinking. This is due to an increase in the density of exchange sites and reduction in the dielectric constant within the resin. According to Lindenbaum et al. (1959) both factors result in stronger ion binding and therefore increases ion selectivity. The reduction in dielectric constant, however, is a consequence of the disorganization of water structure as water molecules are oriented around fixed groups and counter-ion species.

Furthermore, there is an overlapping of the electric fields of fixed ionic groups, such that the electrostatic attraction between a counter-ion and a fixed group becomes greater.

(ii) Effect of counter-ion valence

As a rule an ion exchange resin prefers the counter-ion of higher valence. This is not due to any intrinsic affinity of the resin for high valency ions, but rather the effect of the mass-action law. The distribution of ions depends on the charges and concentrations in both the resin and external solution phases according to Donnan potential. The Donnan potential induces the resin to attract counter-ions of higher valence, since the force of attraction is proportional to the ionic charge. Usually, ion exchange resins have a high internal molality due to the fixed ionic groups. Therefore, the preference for higher valency ions is greatest for resins with high internal molality and dilute external solution.

(iii) Counter-ion solvation

In general, ion exchange resins prefer the counter-ion species which has a smaller solvated volume (Helfferich, 1962). According to Reichenberg (1966) when a resin is highly swollen there is a large shell of hydration around each fixed group in which the solvated counter-ions dwell. This means a large inter-ionic distance exists between fixed groups and counter-ions so that the force of Coulombic attraction between ions is weak. The attractive force between two interacting ion species depends on their ionic radii and is greater for small ions.

As permanent dipoles, water molecules in the proximity of cations are polarized by the cations. The number of polarized water molecules increases with the polarizing ability of the cation species; and the polarizing ability increases with valence and decreases with ion size.

For example, in the alkali metal series Li^+ has the smallest ion size and attracts the most water, while Cs^+ with the largest ion size attracts the least water. Consequently, the hydrated ionic radius (or hydrodynamic radius) is largest for Li^+ and smallest for Cs^+, which means the force of attraction is greatest for Cs^+. Therefore, selectivity by resin is in the following order:

$$Cs^+ > Rb^+ > K^+ > Na^+ > Li^+ .$$

c. Kinetics

The kinetics of ion exchange resins has been a major interest of many workers, including Boyd et al. (1947), Reichenberg (1953), Helfferich (1962), Rieman III and Watton (1970), Sharma et al. (1970), and Vaidyanathan (1970). An ion exchange reaction may be described as consisting essentially of a stoichiometric redistribution of counter-ions between adsorbent and solution, aided by a diffusion process. The driving force for diffusion is the concentration gradient.

Counter-ions adsorbed by an exchange resin diffuse into solution as a stoichiometrically equivalent amount of ions in solution diffuse to the resin surface. According to Boyd and co-workers (1947), the ion exchange reaction represented by the simple equation below:

$$R\text{-}Li + Na^+ \longrightarrow R\text{-}Na + Li^+$$

actually occurs in five steps. The steps are:

1) Na^+ ions diffuse from the bulk solution to the resin surface, and then to the exchange sites in the resin interior.
2) Ionic exchange between Na^+ and Li^+ ions results in the depletion of Li^+ ions from the exchange sites.
3) Na^+ ions are chemically adsorbed at the exchange sites through

bond formation.

4) Liberated Li^+ ions diffuse from the exchange sites in the resin interior to the surface.

5) Li^+ ions finally diffuse through the Nernst film into the bulk solution.

The diffusion of Na^+ and Li^+ ions occurs simultaneously but in opposite directions.

In general, most ion exchange reactions take place in a multi-ionic environment such as the soil-soil solution system. Ion exchange in such a system is a very complex phenomenon involving a simultaneous diffusion of many different ionic species. For example, in a solution containing x_1, x_2, x_3, ... x_n counter-ion species, each counter-ion has a different velocity and affinity for the resin. Therefore, in competing for adsorption sites on an exchange resin containing Y-counter-ions, the more mobile counter-ion in solution, say x_1, rapidly replaces the initial counter-ions. However, as the slower counter-ion, say x_2 or x_3, arrives it quickly replaces some of the x_1 counter-ions that have been adsorbed by the resin so that the quantity of each counter-ion adsorbed has a definite relation to that in solution. Furthermore, the relative amounts adsorbed bear a certain relationship to one another.

Boyd and co-workers (1947) were the first to recognize that the rate of ion exchange was controlled by two kinds of diffusion processes, namely, particle diffusion (through the pores of the resin matrix), and film diffusion (through a hydrostatic film on the resin surface). The slower of the two was considered to be the rate-controlling process, which may be distinguished as follows:[1]

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[1] Mathematical formulae adapted from Helfferich, 1962.

$$\frac{\bar{C}\,\bar{D}\,\delta}{C\,D\,r}(5 + 2\alpha_{A/B}) << 1 \qquad \text{particle-diffusion control}$$

$$\frac{\bar{C}\,\bar{D}\,\delta}{C\,D\,r}(5 + 2\alpha_{A/B}) >> 1 \qquad \text{film-diffusion control}$$

where $\bar{C}$ is the counter-ion concentration in the resin; C is the counter-ion concentration in solution; $\bar{D}$ is the apparent diffusion coefficient in the resin; D is the diffusion coefficient in the hydrostatic film (Nernst film); δ is the thickness of the film; r is the radius of the resin bead, and $\alpha_{A/B}$ is the ion selectivity coefficient.

1. Particle diffusion

The inter-ionic diffusion coefficient of counter-ions inside an exchange resin is affected by:

a) High degree of crosslinking,
b) Large resin bead diameter,
c) The nature of the exchanging ion,
d) High external solution concentration, and
e) Temperature.

It has been indicated that the degree of crosslinking is inversely related to the degree of swelling of an ion exchange resin. This means that a highly crosslinked resin does not swell greatly. According to Rieman III and Watton (1970), the interdiffusion coefficient in a highly swollen resin is many times greater than that in a weakly swollen resin. Therefore, the exchange rate in a highly crosslinked resin is slow and particle-diffusion controlled. In general, a small resin diameter favors rapid exchange regardless of the diffusion mechanism. However, when the particle diameter is large the exchanging ions have a longer average distance to travel. Consequently, the rate of exchange is inversely proportional to the square of the resin particle radius. Furthermore, the diffusing ions are subject to Coulombic attraction by the fixed ionic groups and so the greater the valence of the ion the greater is the retarding force, and the rate of ion exchange decreases as the charge on the exchanging ion increases. The following relationship for the apparent diffusion coefficient $\overline{D}$, of Cs, Ca and La illustrates this concept (Sharma et al., 1970):

$$\overline{D}_{Cs^+} > \overline{D}_{Ca^{2+}} > \overline{D}_{La^{3+}}$$

Large ions due to extensive solvation, are greatly retarded in their diffusion through the hydrocarbon matrix. According to several workers including Boyd et al. (1947), the rate of ion exchange decreases as the size of the hydrated ion increases. However, this is in disagreement with the findings of Sharma et al. (1970). The latter group studied the exchange of Cs^+, Rb^+ and Na^+ in a K^+-saturated resin using tracer exchange techniques, and found that the rate of ion exchange decreased as the size of the hydrated ion decreased. In other words, the diffusion coefficient decreased in the order $\overline{D}_{Na} > \overline{D}_{Rb} > \overline{D}_{Cs}$. They pointed out that the concepts of earlier workers were not very useful because they based their self-diffusion coefficients on the alkali ions in resin systems containing the same ion. In self-diffusion, the resin ionic form is the same as the element tested. This means the apparent water content in each resin form is different since the elements differ in their solvation characteristics. Consequently, Sharma et al. (1970) pointed out, the amount of free water content for diffusion inside the resin is different for each element, being largest for Cs diffusion in a Cs-saturated resin and smallest for Na diffusion in a Na-saturated resin. Therefore, comparison of the self-diffusion coefficients obtained by the earlier workers was considered not valid since these self-diffusion coefficients were not obtained under an identical resin environment.

The rate of exchange decreases as the external solution concentration increases (Sharma et al., 1970). This results from the fact that as the external solution concentration increases the resin water content decreases and therefore the rate of diffusion decreases. Thus, particle diffusion becomes rate limiting when the external solution concentration is 0.1$\underline{N}$ or greater (Boyd et al., 1947). The particle diffusion coefficient of counter-ions changes according to the relative concentrations of the diffusing ions. In general, the diffusion of the ion in smaller concentration controls the rate of exchange. A rate equation for particle diffusion based on Fick's second law applied to systems with spherical geometry has been given by Boyd et al. (1947), as follows:

$$F(t) = 1 - \frac{Q(t)}{Q_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(- \frac{\overline{D} t \pi^2 n^2}{r^2})$$

where F(t) is the rate of exchange (i.e. fractional attainment of equilibrium at time t); Q(t) is the quantity (me/cm^3) of counter-ion in ion exchange resin at time t; Q_∞ is the quantity exchanged at equilibrium (infinite time); $\overline{D}$ is the interdiffusion coefficient, cm^2/sec; and r is the radius (cm) of the resin bead.

Temperature has a significant effect on diffusion within the resin since a rise in temperature from 25° to 50°C doubles the diffusion coefficient and hence the exchange rate (Rieman III and

Watton, 1970).

2. Film diffusion

In film diffusion-controlled ion exchange, the rate of exchange is inversely related to and highly dependent upon the thickness of the liquid film on the resin surface. This film thickness as given by Helfferich (1962) is of the order of 10^{-3} to 10^{-2} cm which can be reduced to a certain degree by agitation. Usually, film diffusion-controlled ion exchange is favored by a low degree of crosslinking such that the resin becomes highly swollen in an aqueous solution. Also, it is favored by a low external solution concentration and gentle agitation. According to Boyd et al. (1947), the film diffusion affects the exchange rate only at a concentration of 0.01N or less. An equation which describes the rate of exchange controlled by film diffusion is presented below (Boyd et al., 1947):

$$F(t) = 1 - \exp(-3DCt/r\delta\overline{C})$$

where $F(t)$ is the rate of exchange; C and $\overline{C}$ are the counter-ion concentrations in the external solution and the resin interior respectively; D is the diffusion coefficient in the liquid film; r is the radius of the resin bead; δ is the thickness of the film layer; and t is time.

D. Application of ion exchange resin in soil analysis

One of the early applications of ion exchange resin to plant nutrient extraction from soil was made by Wiklander (1949). Working with H-saturated Wolfatit-K cation exchange resin beads he extracted various amounts of Mn, Cu, Zn and K from finely ground soil. This pioneering work thus demonstrated that synthetic ion exchange resins can offer a simple and convenient method for estimating exchangeable bases in soils. Since then a variety of studies with ion exchange resins have been carried out in many research problems.

Lisk (1954), Sheard and Caldwell (1955), and Amer et al. (1955) investigated the use of anion exchange resins as a method for evaluating the phosphorus supplying power of soils. Sheard and Caldwell (1955) determined 'A' values using monocalcium phosphate and P-saturated anion exchange resin and concluded that the latter could be a suitable substitute for the former in determining 'A' values. Amer and co-workers (1955) conducted several experiments to determine whether resin adsorption of phosphorus was controlled by the nature of the soil phosphorus status or by resin characteristics. Lathwell et al. (1958) determined available phosphorus in 21 New York soils by several chemical and resin methods. Similarly, Moser et al., (1959), and Williams (1965) compared resin extraction of available phosphorus with various laboratory methods, including the method of Bray and Kurtz[2], the 0.5 M $NaHCO_3$ method of Olsen and the phosphate potential method of Schofield.

Cooke and Hislop (1963) determined available phosphorus using the method of Amer et al. (1955), and emphasized that any method of assessing available phosphorus, if it is to be applicable to all soils, must avoid chemical destruction of the soil. Others working on the problem of soil phosphorus determination by resin extraction include

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[2] Not included in Williams' analysis.

Van Diest et al. (1960), Sidorina (1962)[3], Saunder and Metelerkamp (1962), Saunders(1964), Hislop and Cooke (1968), Vaidyanathan and Talibudeen (1970), Sinclair (1971), Zunino et al. (1972), and Gibson et al. (1974).

Van Diest et al. (1960) compared the resin method with the 0.03<u>N</u> NH_4F-0.025<u>N</u> HCl method of Bray and Kurtz. Sidorina used the Russiam anion exchange resin EDE-10P in his soil phosphorus study. Saunder and Metelerkamp (1962) compared phosphorus released to resin with that extracted by boiling NaOH; and Saunders (1964) compared phosphorus extraction by anion exchange resin beads and by resin membranes. Hislop and Cooke (1968) developed a resin extraction procedure suited to a large scale, routine, advisory work. Similarly, Zunino et al. (1972) developed a method especially for use with volcanic ash soils. Vaidyanathan and Talibudeen (1970) were interested in the kinetics of phosphorus adsorption by anion exchange resin, and the factors controlling the rate of release. Sinclair (1971) developed a qualitative method for studying the distribution of phosphorus in the soil profile. Gibson (1974), applying the filtration technique of Campbell et al. (1966), transferred phosphorus which was extracted with a sulfate solution to anion exchange resin papers.

Bhella and Dawson (1972) determined available molybdenum by anion exchange resin. Similarly, Melville et al. (1969) extracted sulfur using chelating resin.

Karpachevsky and Orekhova (1974) studied the dynamics of plant nutrient availability in the field, using cation and anion exchangers. In their study resins were placed in bags made of cellophane and

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[3] Cited by Williams, 1965.

inserted into knife-made slits in the soil, and the variations in the soil nutrient status, resulting from leaching, uptake by plant and replenishment by litter, were monitored. Edwards (1967) determined the CEC of soil by transferring NH_4^+ ions from an Amberlite-200 cation exchange resin to soil, which was steam distilled after separation of the resin; and the ammonia collected was titrated against a standard acid.

Tabikh and Russel (1961) used cation exchange resins to evaluate soil salinity. Portions of a saturation extract were added to columns of H-saturated Dowex-50 resin, and after five minutes contact the columns were flushed with water. The displaced H^+ ions were determined by titration against a base.

Many investigators have studied the removal of non-exchangeable K by H-saturated cation exchange resin, as a means of assessing the ability of plants to absorb K from non-exchangeable sources. These include Arnold (1958), Stahlberg (1959a), Barber and Mathews (1962), Haagsma and Miller (1963), Waddy and Vimpany (1970), and Lee and Gibson (1974).

Both Arnold (1958) and Stahlberg (1959a) extracted non exchangeable K from soils and minerals, using Na-, Ca-, and H-saturated cation exchange resin. They showed that H-saturated resin was more effective in extracting non-exchangeable K than any of the other resin forms. Barber and Mathews (1962) reported that non-exchangeable K released to H-resin was better correlated with plant uptake than exchangeable K. However, they found that a combination of both K forms was superior to either one alone.

Haagsma and Miller (1963) studying the effects of temperature, water content and the counter-ion on non-exchangeable K adsorption by resin reported that the most satisfactory conditions for optimum extraction were incubation at 80°C for 24 hours in a 1:1 resin-soil suspension. Waddy and Vimpany (1970) modified the above method by including a shaking procedure, and developed it for a routine laboratory method of determining non-exchangeable K. MacLean (1961) reported that the quantities of non-exchangeable K extracted by H-resin, and by repeated boiling in $1\underline{N}$ HNO_3, as well as by leaching with $0.01\underline{N}$ HCl were significantly correlated with each other and with plant uptake. Salmon (1965) found that non-exchangeable K removed by grass from 30 Rhodesian soils in four weeks was correlated with that released to H-resin in three days; and the total K (i.e. plant uptake + residual exchangeable K) available on cropping was also significantly correlated with the total amount extracted by H-resin. Similarly, Salomon and Smith (1957) found that hay yields were better correlated with H-resin extractable K than with K extracted by buffered acetate or normal nitric acid. In comparing resin and two acid methods, Lee and Gibson (1974) concluded that the resin method was easier, safer and quicker than boiling nitric acid methods in estimating non-exchangeable K.

Bolton (1973) estimated total K, Na, Ca and Mg in the sand, silt and clay fractions of some British and Malaysian soils, and showed that H-resin extracted more K and Na than normal ammonium acetate extraction. Acquaye et al. (1972) estimated available Mn, Fe, Cu and Zn in soils with H-saturated zeo-karb 215 resin, and obtained a good correlation between resin-extractable Mn and plant uptake. They further showed that resin extraction of Cu was superior to many chemical methods; but resin extraction of Zn was not as good as dilute HCl extraction. Stahlberg (1959b) studied the adsorption of Ca by H-saturated resin, and Lee and Gibson (1976) added Mg to the list.

1. Methodology

Most resin extraction procedures have involved mixing resin beads with finely ground air-dried soil. Generally, the soil is ground to pass a finer mesh than the resin particle size so that the resin can easily be separated from soil by wet sieving. Equilibration is normally achieved by shaking resin and soil in a water suspension for several hours (not necessarily continuous shaking).

However, there are certain drawbacks to this technique. Saunders (1964) has pointed out that the major limitation is that the soil has to be finely ground, and such grinding requires that the soil must first be air-dried. According to Zunino et al. (1972) this method is not applicable to volcanic ash soils which are characterized by high water retention capacity, high permeability and porosity, since these soils cannot easily be ground and sieved in their moist state. Furthermore, the drying process affects their chemical and physical properties. Amer et al. (1955) found that dehydration resulting from air drying inactivates some of the exchange sites on the soil exchange complex, so that rehydration on re-wetting the soil increases the adsorption capacity, and therefore reduces the release of phosphorus to ion exchange resin. The work of Bolton (1973) in which more exchangeable cations were released from finely ground sandy soil (100 mesh size) than from whole soil is a good example that extraction from finely ground soil over-estimates available nutrients. Again, Zunino et al.

(1972) indicated that many resin beads may be damaged by soil abrasion during shaking, and this may prevent their recovery.

Recognizing the above limitations, Saunders (1964) compared nutrient extraction by ion exchange membranes and resin beads. In the case of the resin membrane, a strip was shaken in a soil suspension, or was buried in soil maintained at 100% water holding capacity. The results of his study showed that phosphorus extracted by resin beads was comparable to phosphorus extracted by membrane shaken in a soil suspension. This work also demonstrated that ion exchange membrane can be used to extract nutrients from soil. The advantage of the resin membrane over resin beads is that the soil does not need to be air-dried and finely ground. Besides, the resin membrane can be used in a variety of different soil conditions, including soil burial under field conditions.

Another approach by Sinclair (1971) involved the use of ion exchange resin impregnated filter papers. He developed a method which closely resembled an autoradiography. In this qualitative method, Reeve Angel anion exchange papers were placed in direct contact with wet soil; and the phosphorus immobilized on the papers was reacted with molybdate and reducing solutions to produce phosphomolybdate blue in a pattern corresponding to the distribution of phosphorus at the surface of contact. By comparing the intensity of the phosphomolybdate blue in the sample with that of a standard, the distribution of phosphorus in the soil was measured. The advantage of this technique is its simplicity in determining phosphorus. However, it is not suited for measuring soil phosphorus for fertilizer recommendation.

Hesse (1971) obtained unsatisfactory but encouraging results by shaking soil with resin beads enclosed in small perforated plastic capsules.

2. Factors affecting ion exchange between soil and resin

The following factors are expected to affect the quantity of soil ionic constituents adsorbed by resin. They are:

a) soil-water ratio
b) resin-soil ratio
c) equilibration time
d) temperature
e) agitation of resin-soil suspension
f) counter-ion species initially on resin
g) soil pH

a. Soil-water ratio

The effect of water content on the quantity of ions extracted by an ion exchange resin is two-fold. Water content controls the diffusion of ions from the soil surface to the resin surface, and therefore determines the nature and proportion of various ions adsorbed by the resin.

Several investigators have reported that the principle mechanism of ion mobility in soil is by diffusion (Barber, 1962; Barber et al., 1963), which is highly dependent upon the volumetric soil water content (Rowell et al., 1967). Brown (1953) measured cation exchange in soils as a function of soil water content between the moisture range from saturation to the wilting percentage, to determine the extent to which cation exchange reactions were altered by variations in soil water content. His results showed a relatively small increase from the wilting percentage to the moisture equivalent, and a sharp increase from the latter to a saturated condition. Such variation in cation exchange, no doubt, was attributed to the discontinuity of water films in pore volumes at low soil water contents which consequently restricted the movement of ions, giving low cation exchange values.

Haagsma and Miller (1963) showed that the limitation set by low soil water content to the adsorption of non-exchangeable K by H-saturated resin was by far greater at 50° and 80°C than at 5° and 25°C where temperature was considered to be the limiting factor. They indicated that by reducing the resin particle size to reduce the diffusion path between the site of ion release and the resin surface, the limitation due to water content could be minimized. The implication here is that fine-grained resin beads make better contact with soil particles and hence their effectiveness to extract soil nutrients is not greatly limited by the soil water content. Acquaye et al. (1972) extracted Mn, Fe, Cu and Zn from 5 gm soil at different water contents (50, 100 and 200 ml), and found that there was no significant difference in the amounts extracted. It is possible that at these high water contents, soil-water ratio was not a limiting factor.

It has been reported (Gapon, 1933; Eaton and Sokoloff, 1935; Ivanov and Gapon, 1941; and Reitmeier, 1946) that in a soil-water system the adsorption (by soil colloids) of higher valence cations increases and cations of lower valence are displaced into the soil solution as the equilibrium solution concentration is diluted. Gapon's theory was stated as follows: In a base exchange involving two cations of equal valence, the equilibrium is not affected by the addition of water, but if the cations are of different valence, the cation of higher valence is preferred. Khasawneh and Adams (1967) showed that dilution decreased the level of solution Ca and increased the level of solution K, as well as the total electrolyte content. The effect of this on resin extraction is that with dilution of the equilibrium soil solution the relative proportion of monovalent to divalent cations adsorbed would increase. However, because of the preponderance of divalent cations (e.g., Ca and Mg) over monovalent cations (e.g., K and Na), this effect may not be very large in soils.

b. Resin-soil ratio

The primary objective of the resin extraction method is to remove a fraction of the cationic and/or anionic soil nutrient elements in a manner which simulates removal by a crop.

Soil base content and the resin exchange capacity determine the quantity of a nutrient or nutrients adsorbed by resin. Thus, it is important to determine the resin-soil ratio that would give the best results.

Wiklander (1949) found that with a resin-soil ratio of 1:1, practically all exchangeable cations were transferred to a H-saturated cation exchange resin. Amer et al. (1955) showed that with a ratio of 1:1 or greater the rate of phosphorus release from soil rather than the rate of adsorption controlled the quantity of phosphorus adsorbed by a strong base anion exchange resin.

In determining an optimum resin-soil ratio for routine estimation of plant available non-exchangeable K, Waddy and Vimpany (1970) used

5 gm soil samples with increasing amounts of resin, up to a maximum resin exchange capacity of 70 me. Similarly, Lee and Gibson (1976) extracted non-exchangeable Mg from 5 gm soil samples at various resin-soil ratios, with a maximum total resin exchange capacity of 80 me. In both studies, it was shown that the quantity of non-exchangeable K or Mg extracted depended on the nature of the soil. Thus, for some soils equilibrium was attained at low resin-soil ratios and for other soils the quantities extracted continued to increase with increasing amounts of resin added.

Kalovoulos and Paxinos (1963) extracted exchangeable K, from fithian illite and found that the quantity of K adsorbed increased as the resin-illite ratio increased. According to Acquaye et al. (1972) the quantities of Cu, Mn and Zn adsorbed by cation exchange resin increased with increasing quantity of resin. However, they pointed out that increases were generally only significant between 1 gm and 5 gm, and 10 gm and 20 gm of resin, with 5 gm of soil. By using 1:5 resin-soil ratio Sidorina[4] noted that exchange was very slow, whereas with a ratio of 1:1 the exchange proceeded at a more rapid rate.

c. Equilibration time

Adsorption of ions is rapid initially, but with time the last traces of exchangeable ion and non-exchangeable ion are adsorbed at a lower pace. Thus, the relationship between resin extraction and time is usually that of a sharp initial increase followed by a gradual, steady increase which levels off at equilibrium. This concept is supported by the work of Barber and Mathews (1962) who showed an initial,

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[4] Cited by Williams, 1965.

rapid release of non-exchangeable K to zeokarb resin followed after two days by a slower but constant rate of release for eight days. The release in the first two days was described as moderately-available K, and that from two to eight days as difficultly-available K.

Bolton (1973), similarly reported rapid release of K to H-saturated cation exchange resin from some British soils during the first three days, followed by slow release for about 43 days. On the basis of this he described three categories of soil K:

1) NH_4-exchangeable K, extracted by resin in one hour.
2) Easily extracted non-exchangeable K removed by resin in three days, which probably includes K fixed from fertilizers.
3) Non-exchangeable K, unaffected by field treatments and released at a constant rate to resin after three days.

Lee and Gibson (1976) showed that the release of non-exchangeable Mg was greater at 24 hours than at 20 or 16 hours equilibration, and Kalovoulos and Paxinos (1963) showed that K extraction continued with time of resin-soil contact. Amer et al. (1955) observed that phosphorus adsorbed by anion exchange resin increased with increasing contact time. They considered such increase to be a measure of both the rate of desorption and the diffusion rate. Williams (1965) also showed an increase in phosphorus adsorbed by resin with increase in shaking time.

d. Temperature

Helfferich (1962) has stated that diffusion coefficients in ion exchangers increase with increase in temperature. This follows from the Arrhenius equation, thus:

$$D = Ae^{-E/RT}$$

where D is the diffusion coefficient; E is the activation energy; A is the activation constant; T is the absolute temperature (°K); and R is the gas constant.

Kalovoulos and Paxinos (1963) using cation exchange resins to extract soil K found that the quantity of K adsorbed was tripled as the temperature was increased from 25° to 50°C. Similarly, Haagsma and Miller (1963) showed that the release of non-exchangeable K to H-saturated cation exchange resin increased as the temperature was raised from 5° to 80°C. However, they observed that factors controlling exchange were different at different temperatures. Thus, whereas temperature was rate limiting at 5°C, both temperature and water content were considered to be limiting at 25°C. Also, a study by Cooke and Hislop (1963) indicated that temperature had a marked effect on the quantity of phosphorus extracted by resin from soil.

e. Agitation of resin-soil mixture

The importance of agitation in reducing the thickness of the thin liquid layer (Nernst film) on the resin surface has been emphasized by Helfferich (1962). Agitation creates a thorough mixing of the resin and soil suspension and thereby hastens the exchange process.

Zueva (1967)[5] found that the release of K was increased by shaking the resin-soil suspension for one hour per day for about ten days. When resin-soil mixtures were shaken for one week, MacLean (1961) found that considerably more non-exchangeable K was adsorbed by resin than when the mixtures were incubated at room temperature for three months without

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[5] Cited by Waddy and Vimpany (1970).

shaking, although the resin-soil ratio was less in the latter experiment. Waddy and Vimpany (1970) showed that shaking improved reproducibility and also the quantity of K adsorbed was greater than that obtained without shaking.

f. Counter-ion species initially on resin

The counter-ion initially on an exchange resin also influences the quantity of nutrients adsorbed by the resin. This has been observed by Arnold (1958), Stahlberg (1959a), and Haagsma and Miller (1963). These workers found that more K was removed from soil or K-bearing mineral by H-saturated resin than by Ca- or Na-saturated resin. Stahlberg (1959a) indicated that Ca-saturation inhibited K uptake by resin. Arnold also found that K release to all three resin forms varied with the nature of the K-bearing mineral. Similarly, Stahlberg (1959b) studying the release of Ca and Mg from different size fractions of various minerals to H-resin, found that Mg release varied with the type of mineral. Haagsma and Miller (1963) reported that K released to Na- and Ca-saturated resin increased only when the proportion of H-resin in each resin system was increased. This supports the view held by Waddy and Vimpany (1970) that the release of K was probably dependent on the concentration of H^+ in the resin-soil-water system.

It is well known that K in soil may be fixed in wedge-shaped edges of micaceous clay minerals. H^+, on account of its small size and high mobility, probably exchanges with K by rapid proton transfer through water as H_3O (Rich, 1964). Wiklander (1949) has emphasized that soil colloids are weakly acidic in property and have strong affinity for H^+ ions. According to Jenny (1932) the high affinity of clays for H^+ is a consequence of strong chemical bonds which the H^+ ion forms with the oxygen and hydroxyl groups of clay mineral surfaces. Both Wiklander (1949), and Stahlberg (1959a) have stated that ion exchange resins release their H^+ ions in exchange for other cations quite readily. Thus, such ready release by resin and strong adsorption by soil gives the H^+ ion a very high replacing power over other saturating cations.

g. Competition from soluble ions in solution

The effect of salt concentration on resin extraction of phosphorus has been studied by Amer et al. (1955), and Cooke and Hislop (1963). According to these workers, anion competition at the resin surface can limit the quantity of phosphorus extracted. However, they pointed out, such interference can be minimized by increasing the volume of the suspension so that the concentration of the interfering ion is reduced.

Bolton (1973) reported that K removal from some acid Malaysian soils by H-saturated cation exchange resin stopped after three days equilibration due to Al^{3+} ion saturation of the exchange resin. Similarly, Lee and Gibson (1976) noted that soils which contained high levels of non-exchangeable Mg resulted in anomalous resin-extractable K.

h. Soil pH

An important advantage of the resin method is that nutrients are estimated at the prevailing soil pH. However, the resin may alter the pH of the soil. The effect of soil pH may be subdivided into:

1) Effect of soil pH on ion exchange resin performance.
2) Effect of resin on soil pH.

The pH of most soils is within the range suited to ion exchange resin adsorption of nutrients. Hence, the performance of an exchange resin is not affected by soil pH.

In most cases, the initial soil pH is altered by the counter-ions released from the resin and this affects the quantity of nutrients adsorbed.

Melville et al. (1969) found that the quantity of sulfur extracted by a chelating resin depended upon the pH of the resin-soil suspension. Similarly, Amer et al. (1955) reported that the amount of phosphorus extracted varied as the pH varied. In most cases, the chloride form of the strong base anion exchange resin is used. According to Van Diest et al. (1960) this resin is only slightly buffered and hence has little effect on the pH of the soil.

Bolton (1973) observed that non-exchangeable Mg was readily released to H-saturated resin but not to crops in pot and field experiments. He concluded that pH differences were probably responsible. This was the view held by Waddy and Vimpany (1970) who found that the concentration of H^+ ions in the resin-soil system accounted for the greater adsorption of non-exchangeable K by H-saturated resin. Further evidence of a probable pH effect on K release was reported by Haagsma and Miller (1963). They found that the pH of a hydrogen resin-soil suspension could attain values below 3, the point at which acid decomposition of K-bearing minerals occurs. This may explain the results obtained by Wiklander (1949) that more Mn was extracted by H-saturated resin than had been applied.

E. Soil-Plant relationship in nutrient uptake

Plant root surfaces exhibit cation exchange properties (Williams and Coleman, 1950; and Drake et al., 1951). Such cation exchange characteristics have been linked to the presence of various complex organic acids (e.g. pectic acid) located in the root cell wall. These are known to contain carboxylic and phenolic groups from which H^+ ions dissociate. Thus, it appears cation uptake is a consequence of the tendency of plants to exchange their H^+ ions with bases in the soil.

Differences in the ability of plants to take up nutrients from soil are largely controlled by the root cation exchange capacity. Studies (Gray et al., 1953; and Mitsui and Ueda, 1963) have shown that in general, monocotyledonous plants have lower root CEC and hence tend to accumulate more monovalent cations while the dicotyledonous plants with higher root CEC tend to accumulate more divalent cations from soil. This phenomenon is in agreement with the theory of ion exchange that the adsorption of divalent ions in relation to monovalent ions is favored by a higher exchange capacity of the adsorber (Mattson and Larson, 1945; and Wiklander, 1949). Furthermore, the release of nutrients to plant is determined by the degree of base saturation and the clay mineral type in the soil (Jenny and Ayers, 1939; Elgabaly and Wiklander, 1949; Wiklander and Gieseking, 1948; and Brown, 1955).

Nutrient availability to plants has been described by Beckett (1964a), using the concept of activity ratio. He introduced the activity ratio, $a_K/\sqrt{a_{Ca} + a_{Mg}}$ as an index of plant available K in soil. He also suggested the use of the factor $\Delta Q/\Delta I$ (the potential buffering capacity) to describe the soil's ability to replenish the solution concentration against depletion by plant uptake. In applying this concept to interpret yield response to K fertilization of oil palms, Tinker (1964a,b) found that in highly acid sandy soils of Nigeria the activity ratio,

$$a_K/(\sqrt{a_{Ca} + a_{Mg}} + q\ \sqrt[3]{a_{Al}})$$

where q is an arbitrary constant, gave better prediction of yield than that proposed by the Beckett (1964a,b) model.

X-RAY FLUORESCENCE SPECTROMETRY

The combined application of ion exchange resin and x-ray fluorescence spectrometry is new in soils research, but has been used in metallurgical research for sometime. For example, Spano et al. (1963, 1964) determined metallic impurities in tungsten by a combined ion exchange resin — x-ray fluorescence method, after the first of such method by Grubb and Zemany (1955). Others include Campbell et al. (1966); Davis et al. (1968); and Walton (1971), just to mention a few.

X-ray fluorescence spectrometry, also called x-ray spectrochemical analysis, x-ray emission spectrography, x-ray spectroscopy or x-ray fluorescence analysis, is the determination of elemental composition by measurement of the intensity of secondary or fluorescent x-rays emitted from a sample irradiated by primary x-rays. The application of x-rays to elemental analysis was first attempted in 1923 by Von Hevesy[6], but did not become widespread until the last two decades, many years after its discovery in 1895 by W.C. Roentgen. X-ray fluorescence spectrometry is a rapid, non-destructive analytical procedure which is amenable to simultaneous elemental analysis.

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[6] Cited by Bertin, 1973.

A. Theory

X-ray fluorescence spectrometry is a qualitative as well as a quantitative method of elemental analysis. Excitation occurs when x-ray photons from a primary source irradiate the sample resulting in the ejection of electrons from all atoms of the sample. Excited atoms return to the ground state by an electronic transition from an outer shell to the inner ionized shell. Obeying the law of the conservation of energy, these inward transitions bring about the release of energy which appears as secondary or fluorescent x-rays whose wavelengths are characteristic of each element in the sample and becomes the basis for qualitative analysis. Quantitative analysis is based on the x-ray intensity of a given wavelength, which is approximately proportional to an element's concentration.

B. Factors affecting measurement of fluorescent x-rays

The measurement of secondary x-ray emission is affected by sample matrix and background radiation. These factors are discussed separately.

1. Sample matrix effects

Except in highly diluted samples, x-ray fluorescent intensities are not directly proportional to concentration because of matrix effects. These effects have been discussed by many authors, including Jenkins and DeVries (1970), Müller (1972), Liebhafsky et al. (1972) and Bertin (1973). The most important matrix effects are:

a) absorption of primary and secondary x-rays, and

b) enhancement of secondary x-rays due to interelement effects.

For this study, absorption is the most important component of the matrix effects. As primary x-rays enter a sample, they are absorbed by the sample matrix (all elements including the analyte). Absorption is a function of the x-ray photon energy and the sample matrix weight. The matrix weight is the sum of products of the weight fraction and atomic number of each element present.

In order for an atom to become excited to emit secondary x-rays, a primary photon with an energy which equals or slightly exceeds the binding energy of a specific electron shell must be absorbed by the atom. The energy required for excitation is low for light elements (for this work, elements from Na to Cl) and high for heavy elements (K and above). Consequently, in a sample which contains a mixture of light and heavy elements, which is ususally the case for soil and plant tissue samples, the low energy (long wavelength) primary photons are absorbed by the heavier elements, thus reducing the probability of excitation of the light elements. However, the use of a rhodium target primary x-ray tube elminates this problem[7]. For the suite of elements of interest for plant nutrition, rhodium possesses an ideal x-ray spectrum which has a wide range of strong characteristic lines capable of exciting a large number of both light and moderately heavy elements. The x-ray tube window is also a strong absorber of the low energy (long wavelength) primary photons which are necessary for the photo ionization of the light elements. It is for this reason that the rhodium target x-ray tube is equipped with a very thin beryllium window which transmits a relatively strong flux of long wavelength photons.

From this account it is noted that the emission of secondary

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[7] Personal communication with Dr. R.C. Jones.

x-rays by an element in a multi-element sample depends not only on the energy of the primary radiation but also on the nature and amount of the other elements present. The contribution of an element to the absorption of x-rays is a function of its mass absorption coefficient for a particular wavelength as well as its concentration.

The matrix absorption effect can be predicted for samples of known composition by using the summation of two forms of Beer's law. The first applies to the absorption of primary x-rays by the sample, as follows:

$$I_\lambda = I_{o\lambda} e^{-\bar{\mu}_\lambda \bar{\rho} x}$$

where I_λ = intensity at a given wavelength, λ, for a given depth (x) within the sample;

$I_{o\lambda}$ = intensity of the (incident) radiation at a given wavelength with no attenuation;

$\bar{\mu}_\lambda$ = the mass attenuation coefficient (cm^2/gm) of the sample. Here it is assumed that the same is a homogeneous medium. The mass attenuation coefficient is the quotient of the linear absorption coefficient μ and the density ρ, of the absorber;

$\bar{\rho}$ = density of the sample (gm/cm^3);

x = thickness of the absorber (cm).

The mass attenuation coefficient for the sample may be defined as:

$$\mu_\lambda = \sum Wi \mu_{\lambda i}$$

where Wi = the weight fraction of each element, i, present in the sample;

$\mu_{\lambda i}$ = the mass attenuation coefficient for a given λ for each element, i, present in the sample.

Similarly, the sample density is defined as follows:

$$\bar{\rho} = \sum W_j \rho_j$$

where W_j = the weight fraction of each constituent j, present in the sample. A constituent is defined as any molecule possessing a given configuration of atoms.

ρ_j = the density of each constituent, j, present in the sample.

The second form of Beer's law that must be considered is the first form integrated over the range of X = 0 (the surface of the sample) to a depth at which the attenuation of secondary x-rays at a given wavelength approaches 100 percent. The most practical form of this equation is for the solution of X as the sample approaches an infinite thickness of each element of inerest, i.e.,

$$X_\lambda = - \frac{1}{\bar{\mu}_\lambda \bar{\rho}} \ln(1 - \frac{I_\lambda}{I_{o\lambda}})$$

where the symbols are the same as above. By means of this equation the exchange membrane was found to be infinitely thick for all elements analyzed when $I_\lambda/I_{o\lambda}$ was 0.95 or less[8].

Matrix absorption of secondary radiation may be accompanied by an enhancement of an analyte. This occurs as a result of a matrix element producing a strong line at or slightly above the absorption edge of the analyte. However, enhancement is usually not encountered unless the enhancing matrix element is present in very high concentration.

Particle size and surface roughness are other factors associated with the sample which may affect secondary x-ray emission. Particle

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[8] Personal communication with Dr. R.C. Jones.

size variation may result in sample heterogeneity. Thus, chemically different particles may coexist in the sample. Also, variations in particle size may cause a shielding effect on small particles by large particles at the surface of the sample (Gunn, 1960). According to Allen and Rose (1972) the fluorescent x-ray intensity of the lighter elements increases with decreasing particle size. Ion exchange membranes have essentially a uniform surface roughness so that specimen surface effects are constant and therefore can be ignored.

2. Background effect

Background radiation may be defined as the line intensity that would be measured if the element of interest were absent. It is perhaps the most noticeable of all factors affecting x-ray fluorescence spectrometry and its significance is that it limits the minimum detectable quantity of an element.

Components of background radiation include:

a) Scattered primary radiation,

b) Spectral impurities originating in the x-ray tube target and window,

c) Electronic noise from instrument, and

d) Secondary x-rays from analyzing crystal.

With particular reference to this work, the only source of background radiation of importance is the scattered primary x-rays. However, the use of a "standard" backing of pressed boric acid, placed underneath sample during analysis, insured a constant background radiation for all samples. Interfering spectral lines from the x-ray tube and secondary radiation from the analyzing crystals were non-existent. Similarly, electronic noise from instrument was less than 1% of the intensity of a given element present in a sample[9].

C. Correction of matrix effects

There are several methods for correction of matrix effects, but only those applicable to this study will be discussed. They are:

1) Statistical method (multiple regression).
2) External standard method.

1. Multiple regression method

Multiple regression is a statistical tool used to study correlation between observed data and to form equations which relate one dependent variable with several independent variables. The regression equations permit the calculation of unknown sample concentrations without visual reference to a calibration curve. The application of multiple regression techniques to matrix effect correction in x-ray fluorescence spectrometry has been discussed by Lucas-Tooth and Pyne (1964), Alley and Myers (1965), Mitchell and Hopper (1966) and Bernstein (1969). The multiple regression equation illustrated below and proposed by Bernstein (1969) is considered most applicable to this study. The equation has the form,

$$C_A = K_0 + K_1 I_A + K_2 I_A I_B + K_3 I_A I_C + \ldots + K_n I_A I_n$$

where C_A is the concentration sought for the element A, $K_0 \ldots K_n$ are the regression coefficients and $I_A \ldots I_n$ are the x-ray intensities of all the elements analyzed.

The coefficients are computed from the intensities of standards

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[9] Personal communication with Dr. R.C. Jones.

which contain all the elements desired. This is accomplished by the method of least squares embodied in a Biomedical Stepwise Regression Program, BMD-02R (Dixon, 1973). The values of the coefficients are dependent on the instrument settings and require the same settings during sample analysis to obtain comparable results.

2. External standard method

In the external standard method (Campbell and Thatcher, 1959; Gribble, 1974), the unknowns are compared to a large number of accurately analyzed standards. These are of similar composition to the unknowns so that the same matrix effects apply in both cases. The standards are generally chosen to include a wide concentration range for each element. By this means calibration curves are established for each element which relate x-ray intensity to concentration. Gribble (1974) found that the reliablility of the external standard method was substantially improved by applying the multiple linear regression technique to minimize matrix effects.

D. Application of x-ray fluorescence spectrometry in plant tissue analysis

Kubota and Lazar (1971) have described techniques and uses of x-ray fluorescence spectrometry in the elemental analysis of forage crops, horticultural crops, grains and woody plants. Fieldes and Furkert (1971) described a thin specimen approach in plant tissue analysis by x-ray fluorescence. Also, Jones and Okazaki (1973) have discussed the simultaneous determination of several elements in plant tissue by means of a high speed x-ray fluorescence spectrometer. Other applications include work done by Brandt and Lazar (1958), Whittig et al. (1960), Lytle et al. (1961), and Dixon and Wear (1964). In each case, the authors cited above used external standards in a variety of forms, however, a wide range of different techniques have been employed to correct for matrix effects the most sucessful to date being multiple linear regression.

MATERIALS AND METHODS

SOIL CHARACTERISTICS

The soils used in this study were selected to include a wide range of physical, chemical and mineralogical properties. Some chemical properties of the A_p horizon of these soils are given in Table 1.

Lualualei (very fine, montmorillonitic, isohyperthermic, Typic Chromustert)

This is a dark, high base, clay soil which has developed from fine-textured alluvial deposit from basic igneous rocks. It occurs near the sea shore and in valley bottoms with a mean annual rainfall of 38-75 cm. It is predominantly montmorillonitic in mineralogy and contains some $CaCo_3$ and $CaSO_4$, particularly in the subsoil.

Wahiawa, (clayey, kaolinitic, isohyperthermic, Tropeptic Eutrustox)

The Wahiawa soil has developed from olivine basalt. It is a well-drained, dusky-red (2.5YR 2/2, wet) or dark red (2.5YR 3/4, dry) soil with an average annual rainfall of 100-138 cm. The predominant clay mineral is kaolinite but haematite and some mica greatly influence its properties. Texturally the Wahiawa is a clay soil but owing to its kaolinitic mineralogy feels and behaves like a silty clay. The soil is well aggregated and the aggregates possess large numbers of very fine pores.

The soil is normally rich in bases but in many cases, particularly under pineapple culture, has been acidified by many years of ammoniacal fertilizer application.

Waimea (medial, isothermis, Typic Eutrandept)

Developed from volcanic ash at an elevation of about 1000 meters under an average annual rainfall of 75 cm, the Waimea soil consists of a well-drained, very friable, non-sticky, non-plastic, strongly magnetic, very fine sandy loam. The predominant minerals include amorphous hydrated aluminosilicates and small amounts of halloysite, quartz and feldspar. The soil is rich in bases and is sometimes used for vegetable culture.

Paaloa (clayey, oxidic, isothermic, Humoxic Tropohumult)

The Paaloa is a silty clay soil which has developed from olivine basalt at an elevation of approximately 360 meters. The soil contains small to moderate amounts of Kaolinite, oxides of Fe and Al and small amounts of titanium. The average annual rainfall is 175-250 cm. This is an acid soil which has been depleted of bases.

Halii (clayey, ferritic, isothermic, Typic Gibbsihumox)

The Halii soil is highly weathered and is formed from olivine basalt, under a high rainfall regime of approximately 400 cm per annum. Consequently, there is a depletion of silicon and an enrichment of sesquioxides. The predominant clay minerals are gibbsite and goethite, with small amounts of halloysite. It is characterized by the presence of many iron stone gravels and nodules, and hence it has a gravelly silty clay texture. The subsoil material is generally net positively charged.

Hilo (thixotropic, isohyperthermic, Typic Hydrandept)

This is a silty clay loam formed from volcanic ash under humid

Table 1. Selected Chemical Properties of Soils.

	pH			Organic	CEC	Exchangeable Bases					
Soil	H_2O	1N KCl	ΔpH	Carbon	me/100gm	Na	K	Ca	Mg	Al	P[1]
	1:1	1:1		%			(me/100gm)				(ppm)
Lualualei	7.41	6.44	-0.97	1.4	61.9	2.63	1.55	23.70	27.94	--	257
Wahiawa	5.91	4.87	-1.04	1.3	21.2	0.29	0.61	6.50	1.25	--	56
Waimea	6.57	5.67	-0.90	4.6	71.1	1.40	8.11	36.10	10.80	--	88
Paaloa	5.07	4.22	-0.85	3.5	19.6	0.26	0.14	1.70	0.78	0.35	13
Halii	3.80	4.05	+0.25	5.8	33.0	0.19	0.12	0.70	0.78	1.57	6
Hilo	5.22	5.10	-0.12	6.0	60.8	0.15	0.11	0.26	0.23	0.06	15

[1] Extractable P by modified Truog procedure.

conditions. It is low in bases and silicon. The annual rainfall is about 400-500 cm and the predominant clay minerals include gibbsite, hydrated oxides of Fe, Al and Ti, and amorphous aluminosilicates. The soil dehydrates irreversibly to sand- and gravel-sized aggregates. Small amounts of quartz are also present. The subsoil material has a net positive charge.

ION EXCHANGE RESINS

Cation and anion exchange membranes supplied by Ionics Incorporated, were used in this study. These were selected primarily because of their physical form and their suitability for x-ray fluorescence spectrometry and equilibration with soil.

Ion exchange membranes have a uniform thickness and a smooth surface which are essential qualities for x-ray fluorescence spectrometry. Resin membranes also minimize contamination after soil nutrient extraction since less handling is required in sample preparation for analysis by x-ray fluorescence.

A. Characteristics of ion exchange membranes

The ion exchange membranes consist of homogeneous resin gels which are reinforced by incorporating supporting wide mesh plastic tissue. They have high permselectivity and electrical conductivity, and are physically very durable when wet, but shrink and even crack when dried.

1. Cation exchange membranes

These comprise sulfonated copolymers of vinyl compounds, and possess the following properties. They are:

a) unaffected by non-oxidizing solutions below pH 11, and fairly stable up to pH 14,

b) usable up to a temperature of 55°C,

c) 0.6 mm in thickness with a water content of 46% when wet, an exchange capacity of 2.7 me/gm of dry resin, a dynel content of 36% of dry weight (or specific weight of 14.6 mg/cm^2) and can withstand a maximum pressure of 8 kg/cm^2.

2. Anion exchange membranes

These contain strong-base, quarternary ammonium groups and they are:

a) very stable to non-oxidizing solutions between pH 3 and 9 at room temperature, and fairly stable to many other solutions outside this range such as 4 to 5N HCl and H_2SO_4,

b) easily rendered non-functional by chlorine, hypochlorites, 2N HNO_3 and strong bases like 0.5N NaOH, as well as by high molecular weight organic compounds like humic acids, lignin and tannins,

c) 0.6 mm in thickness, with a water content of 43% when wet, an exchange capacity of 1.8 me/gm of dry resin, a dynel content of 34% (or specific weight of 14 mg/cm^2), and can withstand a pressure of 9 kg/cm^2 and a temperature of 45°C.

B. Resin treatment

Sheets of ion exchange membrane, 45 cm by 50 cm, were cut into circular discs measuring 3.5 cm in diameter, by means of a cylindrical stainless steel cutter.

1. Cation exchange membranes

The cation exchange membrane was initially a Na-saturated but was subsequently converted into a H-membrane. This was achieved by replacing Na^+ with NH_4^+ in a neutral normal ammonium acetate solution. The 3.5 cm discs were placed in a wide-mouth 1.0 liter polyethylene jar and equilibrated with 500 ml of ammonium acetate solution, with occasional shaking. After this treatment, the resin was washed with 500 ml of deionized water. The ammonium acetate-water treatment was repeated four times. After replacement with NH_4^+ the resin was equilibrated with two 500 ml portions of 0.5N HCl, rinsed with deionized water and stored for later use. The NH_4^+ saturation rendered conversion to H-saturated resin simpler.

2. Anion exchange membranes

This resin was initially Cl-saturated and did not require any further treatment except to wash the anti-freeze agent added during shipment and residual HCl which was sometimes present. The anion exchange membrane was used in its chloride form.

3. Storage of ion exchange resin

The cation and anion exchange resin discs were stored in polyethylene jar containing deionized water, at a constant temperature of 20°C.

4. Preparation of ion exchange resin standards

a. Cation standards

A standard solution containing 1000 ppm Na, K, Mg, Ca and Al; and 500 ppm Mn, Fe, Cu and Zn was prepared by dissolving separately and combining weighed amounts of the salts (chloride) or pure metals of the elements. The combined solution was made up to a standard volume and diluted to several concentrations. By adding additional amounts of selected elements to some dilutions, it was possible to establish a wide range of solution concentrations for each element.

In the preparation of the ion exchange resin standards, 10 ml of each standard solution were equilibrated with a resin disc in a 100 ml plastic jar which was sealed with saran wrap and capped. The standards were equilibrated overnight with gentle shaking. Each was replicated three times. After equilibration each resin disc was held with a pair of stainless steel forceps, rinsed with 5 ml of deionized water (to remove excess electrolyte) for about one or two seconds in a clean plastic jar, and placed in a plastic petri dish for freeze-drying.

b. Anion standards

The procedure was the same as that for the cation standards, except that the standard solution contained 250 ppm P and S, 150 ppm Si and 50 ppm Mo, prepared from KH_2PO_4, K_2SO_4 and $NaSiO_3$ and Mo metal (dissolved in concentrated HCl) respectively.

c. Determination of elemental concentrations

By means of a Perkin Elmer atomic absorption spectrophotometer, the concentrations of cations remaining in solution were determined before and after ion exchange resin extraction. Anion concentrations were determined colorimetrically, except for Mo which was analyzed by atomic adsorption spectrophotometer.

In all determinations the concentration difference between the amount in the 10 ml solution aliquot and that remaining in solution (including the 5 ml rinse with deionized water) after extraction was considered to be adsorbed on the resin disc.

d. Drying of ion exchange resin for analysis by x-ray fluorescence spectrometry

Ion exchange resin standards (including resin samples after soil nutrient extraction) were freeze-dried. The freeze-drier used was a Virtis model 10-145 MR-BA, operated at a vacuum of 0.3 torr or less, and a temperature of -50°C.

Freeze-drying provided a means to obtain uniform drying which prevents warping noted in air-dried resin discs.

e. Calibration of standards

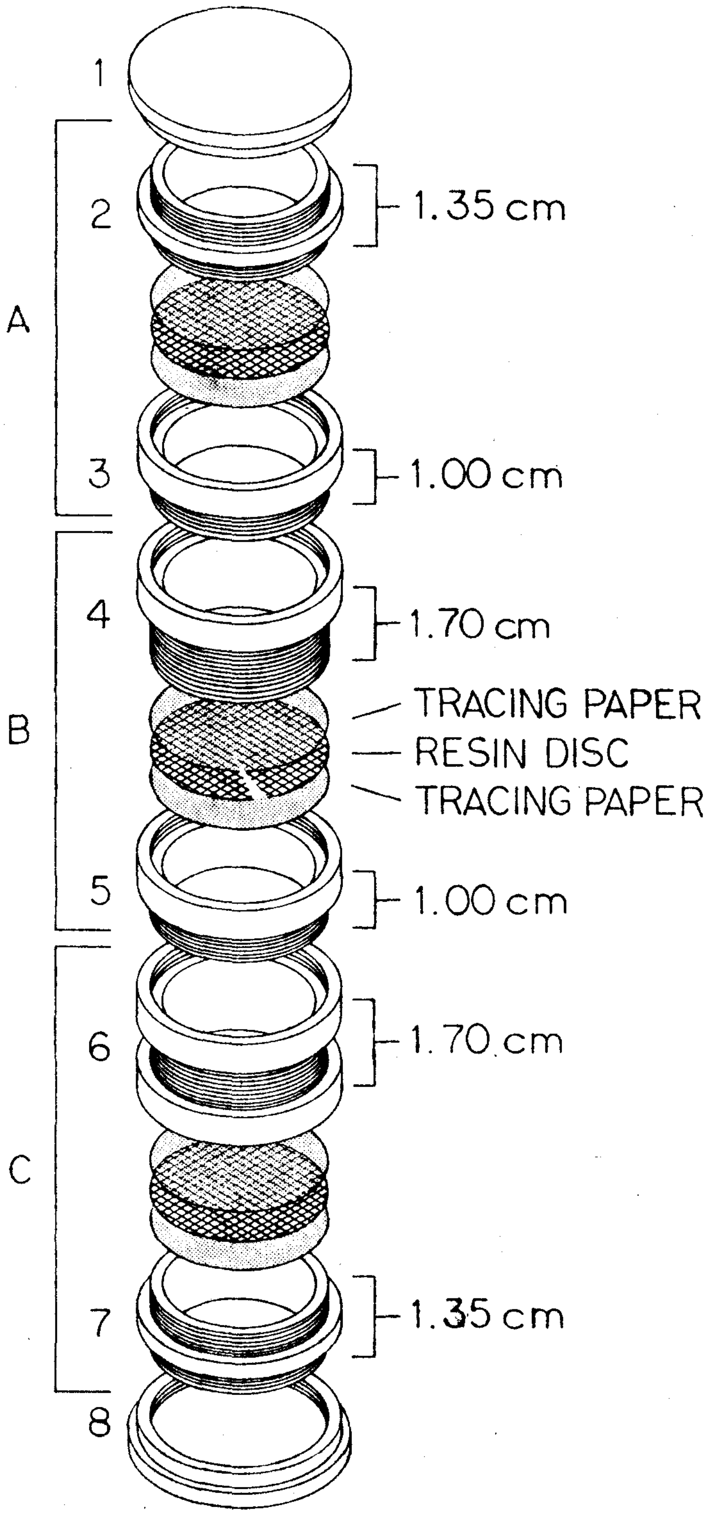
The resin standards were analyzed on the x-ray quantometer to obtain x-ray intensity readings for each element. These, together with their concentrations, were used in a stepwise multiple regression analysis to obtain relationships between element concentration and x-ray intensity.

C. Soil nutrient extraction

1. Extraction cell

The extraction cell consisted of sections of plexiglass tubing cut and re-assembled into units to accomodate soil, with the resin discs sandwiched between these units. Two tubes with inside diameters of 3.16 cm and 3.80 cm, and walls 0.32 cm thick were threaded as shown in Figure 1.

Figure 1 shows a combination of the units with four chambers and three resin discs. These units were designed as modular parts so that



EXTRACTION CELL

a completed cell could be assembled to contain any number of resin discs. In a one-disc cell, only section A plus the end caps were used, such that two soil chambers of equal volume sandwiched a single resin disc. In a two-disc cell, sections A and C were combined with the end caps to create three chambers separated by two discs, where units 2 and 7 had equal volumes, each half as much as the combined volume of units 3 and 6. In this way each side of a resin disc was exposed to an equal volume of both soil and water. For any resin-cell combination with more than two discs, units 4 and 5 (sandwiching a disc) and equivalents of these were inserted into a two-disc cell so that the combined volume of units 3 and 4 was the same as that of units 5 and 6.

2. Permeable paper

A fine grade Académie tracing paper was used to keep the resin membrane separated from soil. This paper is very porous and behaves as a semi-permeable membrane by allowing nutrient elements to pass through but not the soil.

3. Extraction procedure

a. Soil-resin equilibration

First, an ion exchange resin disc sandwiched between permeable paper discs was held in place in sections A, B, and C (Figure 1). Then, to maintain the same soil-water ratio throughout the entire cell and to expose each resin surface equally to soil, the soil and water were divided into three equal portions, the first two going into chambers 4 and 6 and the last portion equally divided between the two end chambers, units 2 and 7. Soil, then water, in that order, was added to chambers 2, 4 and

Figure 2. Single and multiple resin disc extraction cells containing soil.

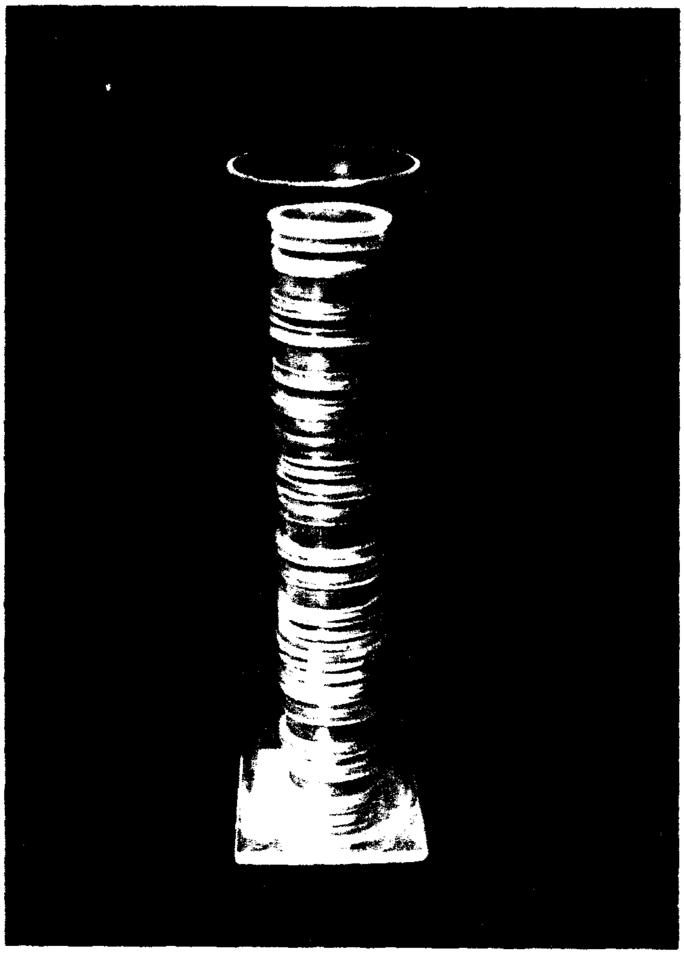


Figure 3. Extraction cells with soil stacked in a plexiglass tube.

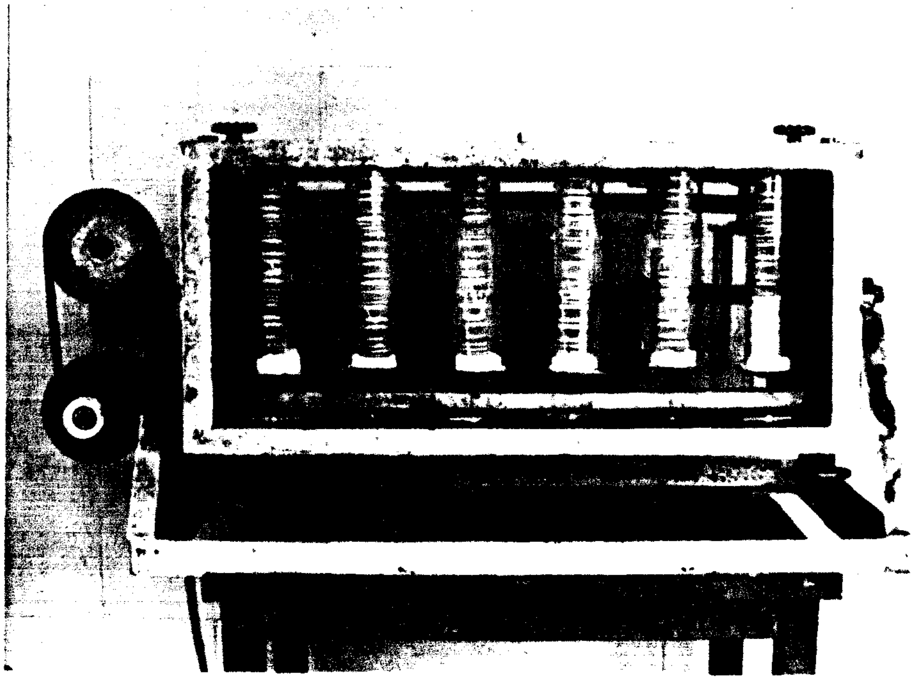


Figure 4. Plexiglass tubes containing extraction cells, arranged on a shaker.

6 in their designated proportions. Sections A, B and C could then be assembled and capped leaving chamber 7 the last to be filled and capped. A plastic gasket cut from plastic cloth was used at each junction to prevent leakage except where the resin disc was held. After assembling several of these cells, they were stacked in large plexiglass tubes and shaken end-over-end for prescribed times.

b. Resin preparation for drying after equilibration

After equilibration with soil, the resin discs were carefully removed from the cells with a pair of stainless steel forceps and dipped into deionized water for one or two seconds to remove any ions not adsorbed by the resin. The discs were then freeze-dried in plastic petri dishes.

4. Effect of soil mass, soil-water ratio and time on ion adsorption by resin

Test resin extractions were conducted on 2, 4, 6, 8 and 10 gm soil samples at 1:2 soil-water ratio and at various times to determine soil sample size for routine analysis. Soil-water ratio was based on weight at ratios 1:2, 1:3, 1:4, 1:5 and 1:6. Equilibration times tested were 12, 24, 36, 48, 60 and 72 hours. After preliminary testing it was determined that the 24, 36 and 48 hour equilibration times were adequate for assessing the effects of soil-water ratio.

5. Extractions with single and multiple resin discs

To determine whether the time involved in assembling a cell could be reduced by decreasing the number of resin discs used in each extraction procedure, one and two resin disc extractions were run, employing the cell-unit combinations previously described. By maintaining the same resin-soil ratio as used in a three-disc cell, the results would determine whether there was any difference from one resin-cell combination to another in correlating nutrient uptake by plant with the cations extracted.

X-RAY FLUORESCENCE UNIT INSTRUMENTATION AND SAMPLE ANALYSIS

The x-ray fluorescence unit used for sample analysis was an Applied Research Laboratories (ARL) quantometer, model 72000. This x-ray fluorescence unit with a capacity for 23 detectors was equipped with a 3 kilo-watt rhodium target primary x-ray tube having a beryllium window, and operated at 50 kilo-volts and 40 milliamperes. The monochrometers were 4 inch Johansson fully focussing.

Samples were analyzed in a vacuum of about 10^{-2} torr. To avoid changes in the d-spacings of the analyzing crystals and variations in detector gas densities, the detectors were maintained at a constant temperature of 31°C ± 0.1°C. The integration time (counting time) was based on the fluorescent yield of an external standard consisting of a titanium target which was situated near the tube window. This method of controlling the integration time compensated for any variation in primary x-ray flux. For each resin sample, two integrations (30 seconds each) were considered satisfactory and the average intensity was used to compute an element's concentration. The integrated intensities were printed as volts on a teletype.

A. Resin analysis

Before sample analysis, a standard with zero treatment was used to calibrate the instrument to establish the Y-intercept of the regression

Table 2. Specifications of the Spectrometers.

Element	Line	Wave Length Å	Crystal[1] Material	Detector Type	Primary Slit (mm)	Secondary Slit (mm)	PHD[2]	Take-off Angle of Spectrometer
Na	K	11.909	RAP	Flow Prop., P-10	1.00	1.00	yes	30
Mg	K	9.889	ADP	Ne Exatron Al	2.30	none	yes	40
Al	K	8.339	EDdT	Ne Exatron Al	2.30	none	yes	30
Si	K	7.126	EDdT	Ne Exatron Be	1.50	2.30	yes	40
P	K	6.155	Ge	Ne Exatron Be	1.00	1.80	yes	40
S	K	5.373	NaCl	Ne Exatron Be	1.00	1.80	yes	30
K	K	3.744	LiF	Ne Multitron	1.00	1.80		40
Ca	K	3.360	LiF	Ne Multitron	0.75	1.50		30
Mn	K	2.103	LiF	Ne Multitron	0.25	0.50		40
Fe	K	1.937	LiF	Ne Multitron	0.40	0.75		30
Cu	K	1.542	LiF	Ar Multitron	0.25	0.50		40
Zn	K	1.436	LiF	Ar Multitron	0.25	0.50		40
Mo	K	0.710	LiF	Kr Multitron	0.25	0.50		40

Crystal Designation	Crystal Name	d-spacing (Å)	Bragg Diffraction indices (hkl)
LiF	Lithium Fluoride	4.0267	200
RbAP	Rubidium acid Phthlate	26.121	100
Ge	Germanium	6.532	111
EDdT	Ethylene diamine D-Tartrate	8.808	020
ADP	Ammonium dihydrogen Phosphate	10.64	101
NaCl	Sodium Chloride	5.6410	200

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[1] All crystal radii except that for Mo (27.94 cm) were 10.16 cm.

[2] Pulse height discriminator.

line for each element. This intercept and the count corresponding to the highest concentration of each element were used to obtain the slope of the regression line.

B. Plant tissue analysis

Plant tissue samples from field and greenhouse experiments were analyzed by x-ray fluorescence spectrometry in pellet form. In sample preparation, the plant tissue was dried at 60°C and ground to pass through a 100 mesh sieve using a spex-mixer mill. A small aluminum cup (Alcoa spec-cap) measuring 3.3 cm in diameter and 0.7 cm in depth was half-filled with boric acid (as a backing) and filled to the brim with ground sample. This was then inserted into a 3.45 cm pellet die and 3800 kg/cm^2 pressure applied. Elements analyzed included Na, K, Ca, Mg, Al, P, Si, S, Mo, Mn, Fe, Cu and Zn.

CORRELATION STUDIES

Soil samples from on-going field and greenhouse experiments were used to study correlation between resin and ammonium acetate extractable nutrients, and between extractable nutrients and nutrient uptake by plant.

A. Field experiment

This experiment was set up to study the relative response of some tropical and temperate legumes to lime treatment on nitrogen deficient Wahiawa soil (Munns and Fox, 1976). $CaCO_3$ was applied in a continuous function design at rates which increased along the plant row from 0 to 22 tons per hectar, producing an average (of all blocks) gradient in soil pH from 4.8 to 7.1. At the low pH levels, elemental sulfur plus

H_2SO_4 were applied to adjust pH with an amount equivalent to 0.02-0.39 kg $CaCO_3$/ha.

Blanket application of fertilizer to blocks at the per hectare rate was as follows: 1340 kg treble superphosphate (268 kg P), 56 kg KCl (29.3 kg K), 31 kg $ZnSO_4 \cdot 2H_2O$ (10.3 kg Zn) and 2.6 kg Na_2MoO_4 (1.2 kg Mo).

P rate was based on phosphate sorption isotherms. Similarly, lime rate was determined from the soil's titration curve with $CaCO_3$, taking bulk density as 1.26 and depth of application of 15 cm.

Legumes inoculated with appropriate Rhizobia, representing 18 species, were grown.

B. Greenhouse experiment

This experiment was designed to study the effect of P source on sudax (Sorghum bicolor x Sorghum sudanensis) yield. The two sources were fused magnesium phosphate (FMP) separated into three particle size fractions (normal size, ns; coarse fraction, cf; fine fraction, ff), and treble superphosphate (TSP) applied to the Halii and Lualualei soils. The normal size (0.2-1.5 mm) was the unsegregated fraction as supplied by the manufacturer; and the coarse and fine fractions were > 0.5 mm and < 0.5 mm respectively. The fertilizer rates were 100, 300 and 800 kg P/ha for Halii, and 50, 100 and 200 kg P/ha for Lualualei. There were three replications in each treatment, and a blanket application of 400 kg N/ha as urea, 300 kg K/ha as KCl, 10 ppm Zn as $ZnSO_4 \cdot 7H_2O$ and 1 ppm B as H_3BO_3. The crop was harvested at the end of the 5th week of growth.

STATISTICAL ANALYSIS

Data analyses were performed with the aid of a computer. Multiple regression analysis was performed using the BMD-02R, Stepwise regression Program (Dixon, 1973), and the Factorial-split Plot Program was used for analysis of variance.

RESULTS AND DISCUSSION

CALIBRATON OF STANDARDS

The relationship between the x-ray intensity and elemental concentration in resin standard is presented in Figures 5, 6 and 7 for Ca, Mg and K. Similar calibration standards were obtained for Na, Al, Mn, Fe, Cu, Zn, P, S, Si and Mo. Because of absorption and enhancement effects the relationship between the fluorescent intensity and concentration of an element in a multi-element system normally deviates from linearity (Jenkins and DeVries, 1970; Liebhafsky et al., 1972; and Bertin, 1973). However, the relationships in the figures mentioned above and those of other standards (not shown here) indicate that absorption and enhancement of secondary x-rays did not greatly affect x-ray intensity measurements in this study. This was probably because: (1) the concentration, and therefore the weight fraction of each element in the standards was low, (2) the resin medium consisted of a framework of very low atomic number elements comprising C, H, O and S for the cation exchange resin; and C, H and N for the anion exchange resin, which made the resin a very low x-ray absorbing medium, and (3) the thickness of the resin disc was within the limits of infinite thickness so that x-ray absorption by sample was practically nil. Law and Campbell (1974) working with ion exchange resin impregnated filter papers, found that the x-ray intensity of an element adsorbed on a resin was only slightly affected by the presence of other elements on the resin. This means inter-element effects due to absorption and enhancement of secondary x-rays are not very important limiting factors in x-ray fluorescence analysis of elements

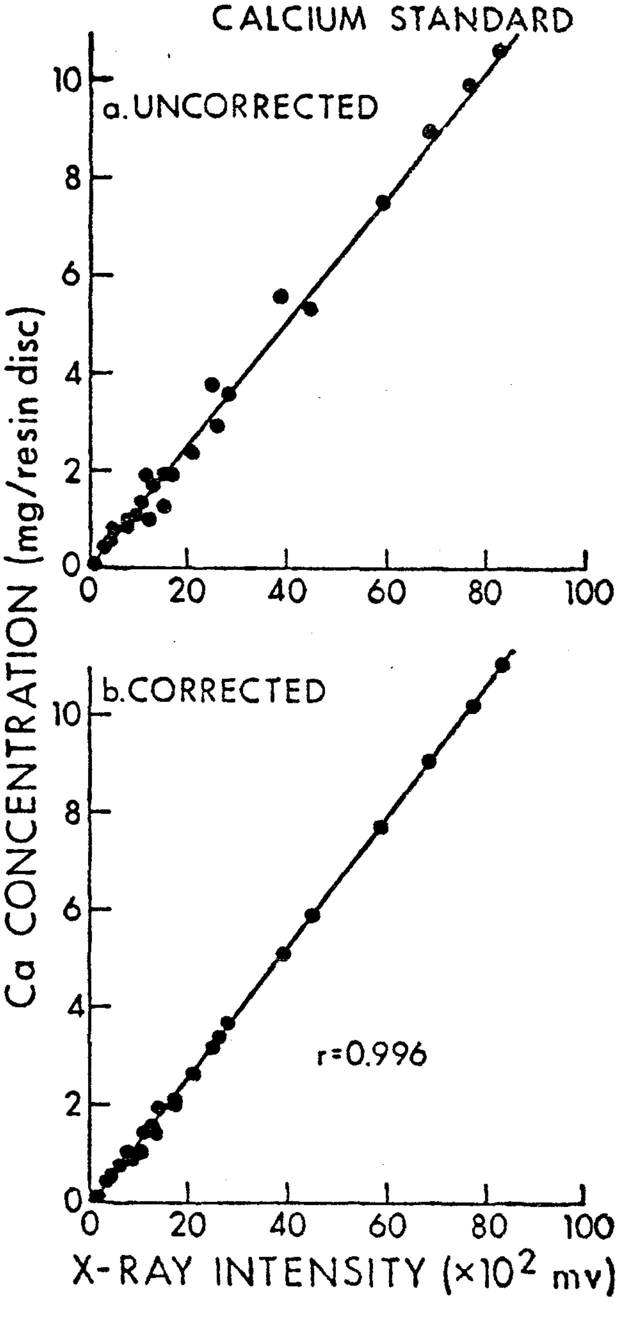

Figure 5. Ca calibration curve.

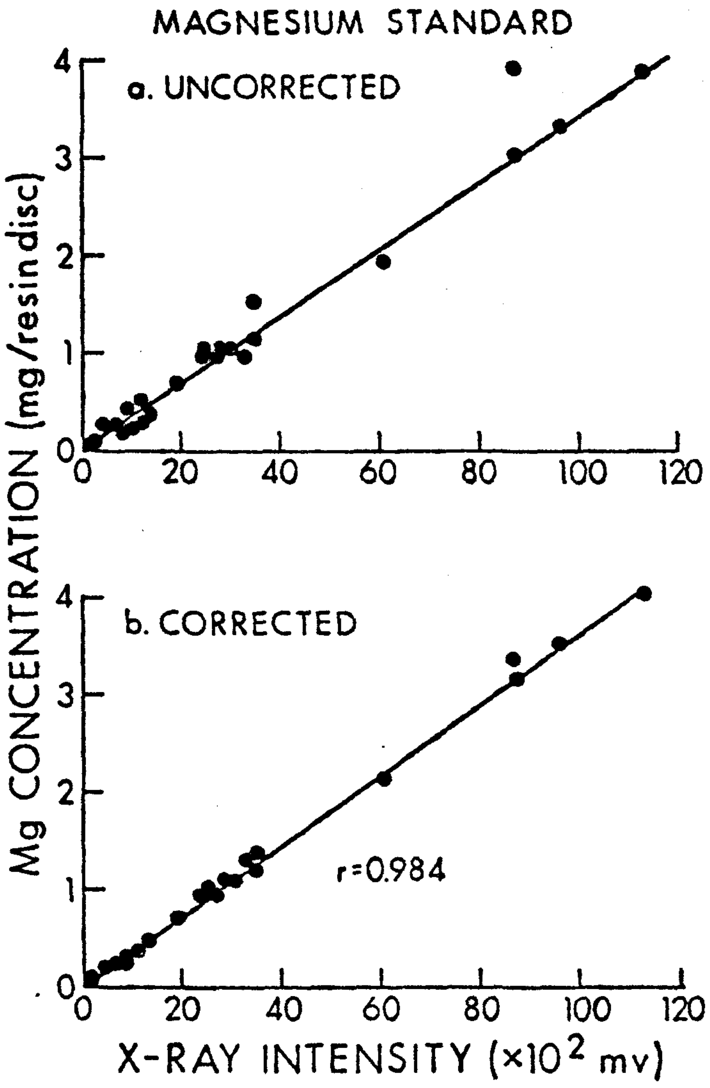

Figure 6. Mg calibration curve.

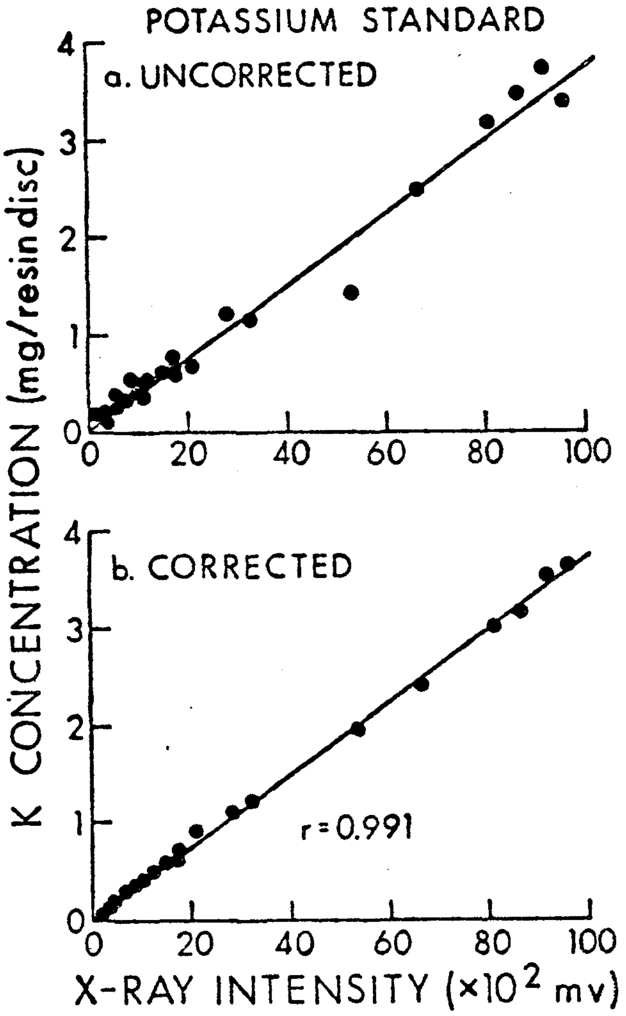

Figure 7. K calibration curve.

adsorbed on ion exchange membrane. Hence, a linear relationship between x-ray intensity and concentration was obtained for the uncorrected data (Figures 5a, 6a and 7a) as well as the corrected data (Figures 5b, 6b and 7b).

METHOD

This study showed that by sandwiching a resin membrane between two permeable paper discs in an extraction cell, plant nutrients in soil can be extracted and analyzed. It has been recognized that plants growing in soil depend on the soil solution concentration for their nutrient requirement (Pearson, 1971; Khasawneh, 1971; and Grimme et al., 1971). Similarly, ion uptake by resin in this study depended upon the soil solution concentration, since there was no direct contact between resin and soil. By serving as a sink the resin simulated the plant root so that more ions were desorbed from the soil into the soil solution. It is believed that nutrients adsorbed by resin reflected the quantity-intensity parameter of the soil nutrient pool.

In most applications of ion exchange resin to soil systems, the soil is always finely ground and mixed with the resin (Wiklander, 1949; Amer et al., 1955; and Cooke and Hislop, 1963). In such an approach the probability of error due to soil contamination is very high. For example, positively charged soil colloids could adhere to cation exchange resin (negatively charged), and so also could negatively charged soil colloids adhere to anion exchange resin (positively charged). Also, the nutrient status estimated from finely ground soil could over-estimate the actual value (Bolton, 1973). Furthermore, a direct contact with soil could damage the resin by soil abrasion (Zunino et al., 1972). The technique developed here utilized soils as they were obtained from the field.

The combined application of ion exchange resin and x-ray fluorescence spectrometry enabled most of the essential plant nutrients to be extracted in one step and analyzed simultaneously.

THE EFFECTS OF SOIL MASS, SOIL-WATER RATIO AND EQUILIBRATION TIME ON CATION ADSORPTION BY ION EXCHANGE RESIN

A. Effect of soil mass and equilibration time.

This experiment was conducted to determine the optimum soil sample size and equilibration time for use in a routine extraction procedure. The results, presented in Figures 8 and 9, and Table 3, show that for the Lualualei and Waimea soils the rate of cation adsorption by resin was quite rapid, approaching equilibrium within 36 hours for all sample sizes. This no doubt was due to the high base content of these soils. In contrasts, the Wahiawa and Paaloa soils (Figure 9) show a gradual and steady increase in total extracted cations even after 60 hours for the 2 and 4 gm samples. A similar trend seems to hold for the Halii and Hilo soils (Table 3).

It was reported by Wiklander (1949) that a gradual increase indicates a slow dissolving process or release of ions from non-exchangeable forms. This seems to explain the results of the Halii, Hilo and Paaloa soils, since these are low base soils high in hydrous oxides of Fe and Al. For the Wahiawa (Figure 9), also a low base soil, resin-extractable Ca continued to be adsorbed from the large samples even after 72 hours. This is believed to be the result of a slow desorption of Ca

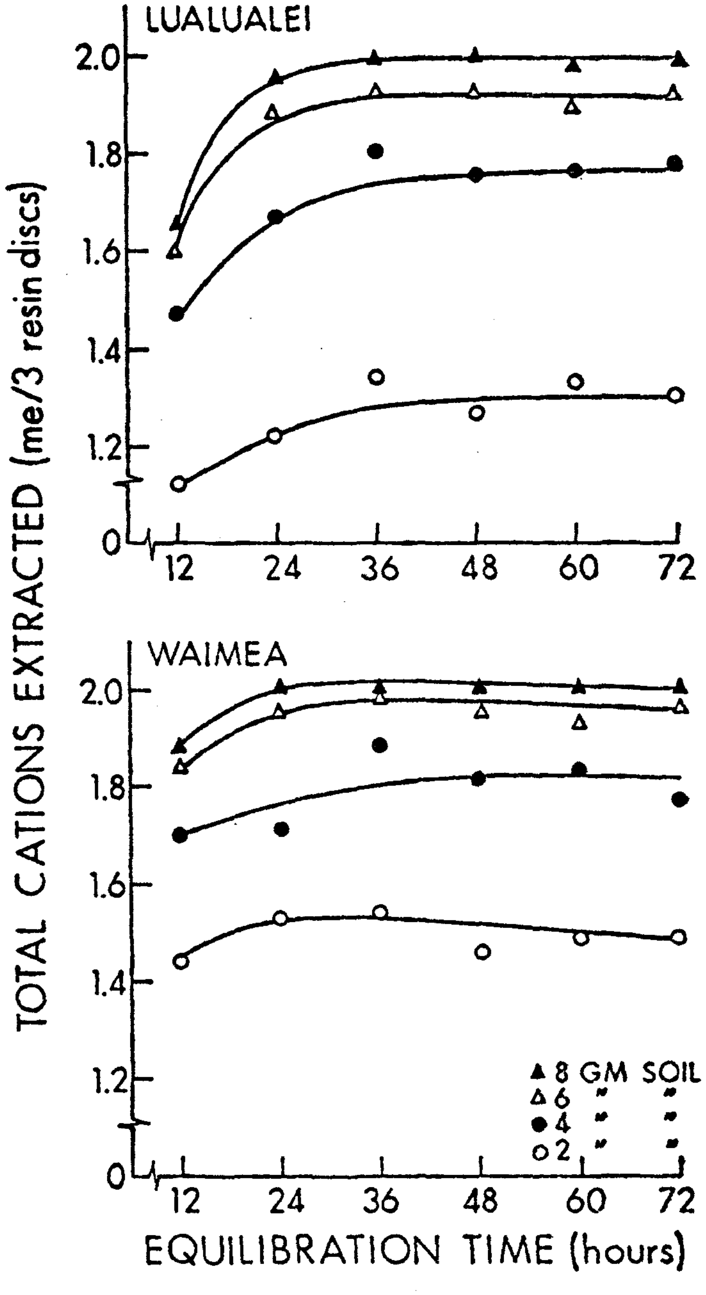

Figure 8. The effect of soil mass and equilibration time on cation adsorption by resin from Lualualei and Waimea soils.

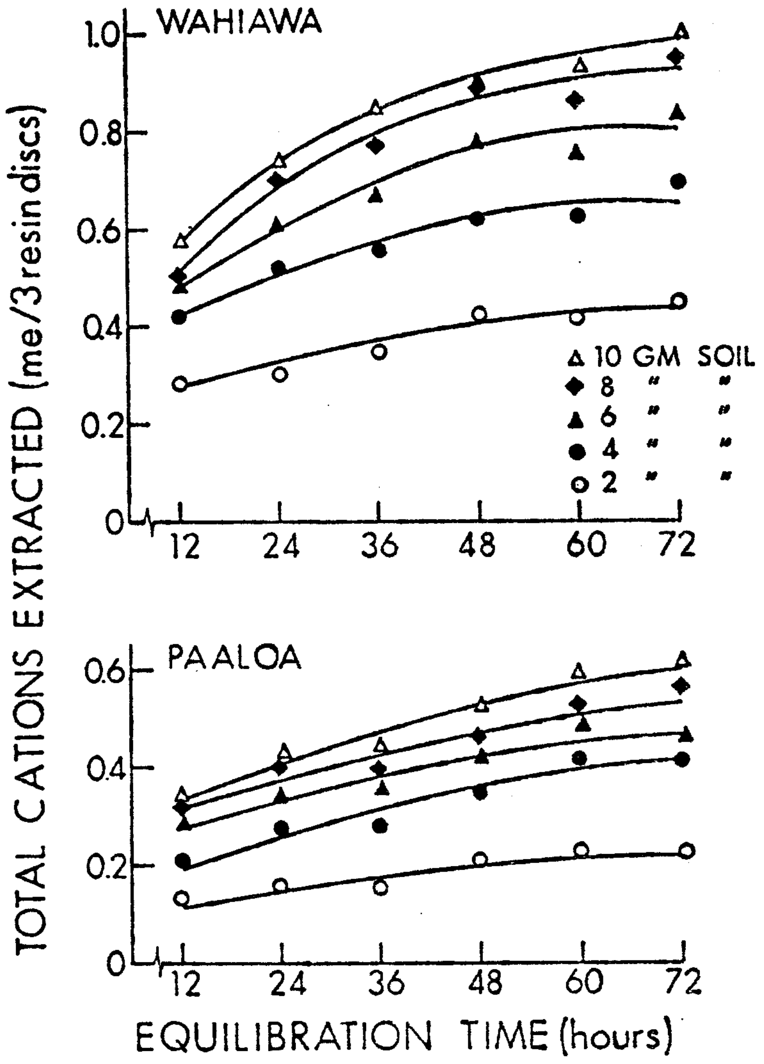

Figure 9. The effect of soil mass and equilibration time on cation adsorption by resin from Wahiawa and Paaloa soils.

Table 3. The effect of Equilibration Time on Total Cations Extracted by Ion Exchange Resin Using Increasing Sample Sizes.

Soil	Equil. Time (hrs)	2	4	6	8	10
		(gm soil)				
		m.e./3 resin discs[1]				
Halii	12	0.46	0.58	0.67	0.77	0.78
	24	0.58	0.75	0.93	1.02	1.13
	36	0.52	0.84	1.03	1.16	1.20
	48	0.58	0.90	1.20	1.17	1.29
	60	0.64	0.99	1.30	1.40	1.49
	72	0.63	1.01	1.28	1.46	1.56
Hilo	12	0.19	0.22	0.22	0.23	0.24
	24	0.23	0.26	0.28	0.27	0.29
	36	0.27	0.33	0.34	0.35	0.38
	48	0.35	0.38	0.37	0.39	0.40
	60	0.38	0.45	0.42	0.46	0.42
	72	0.38	0.47	0.50	0.49	0.46

[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

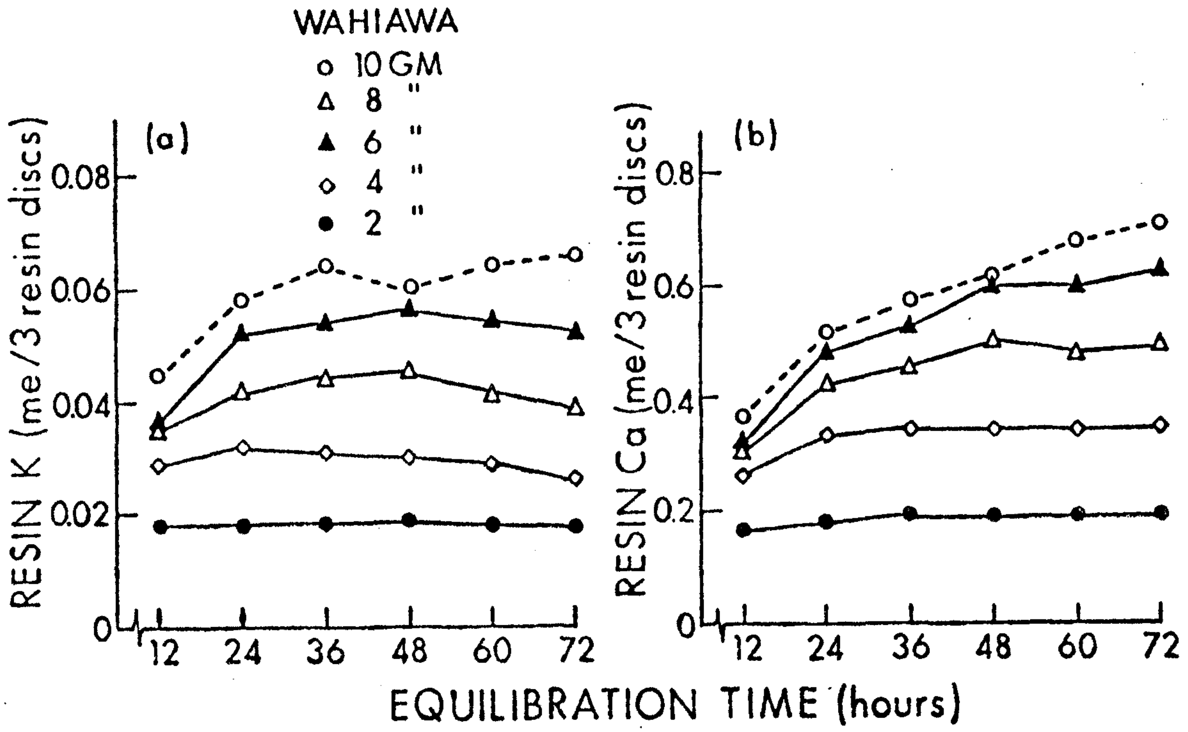

Figure 10. The effect of soil mass and equilibration time on (a) K and (b) Ca adsorption by resin from Wahiawa soil.

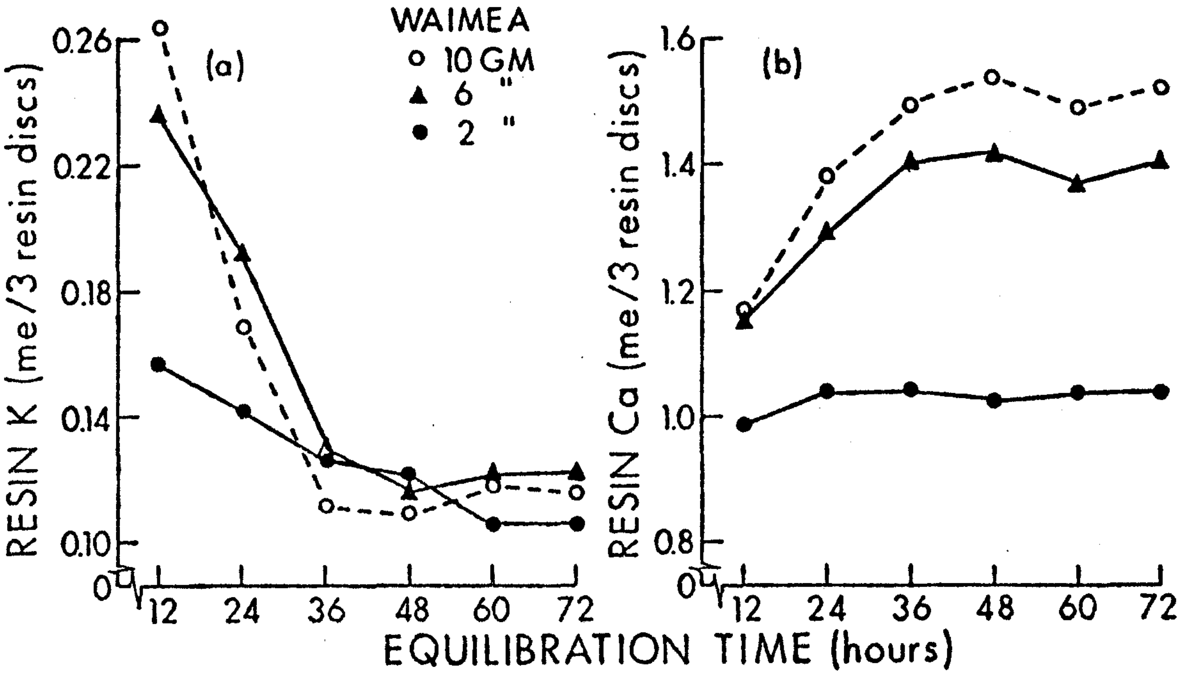

Figure 11. The effect of soil mass and equilibration time on (a) K and (b) Ca adsorption by resin from Waimea soil.

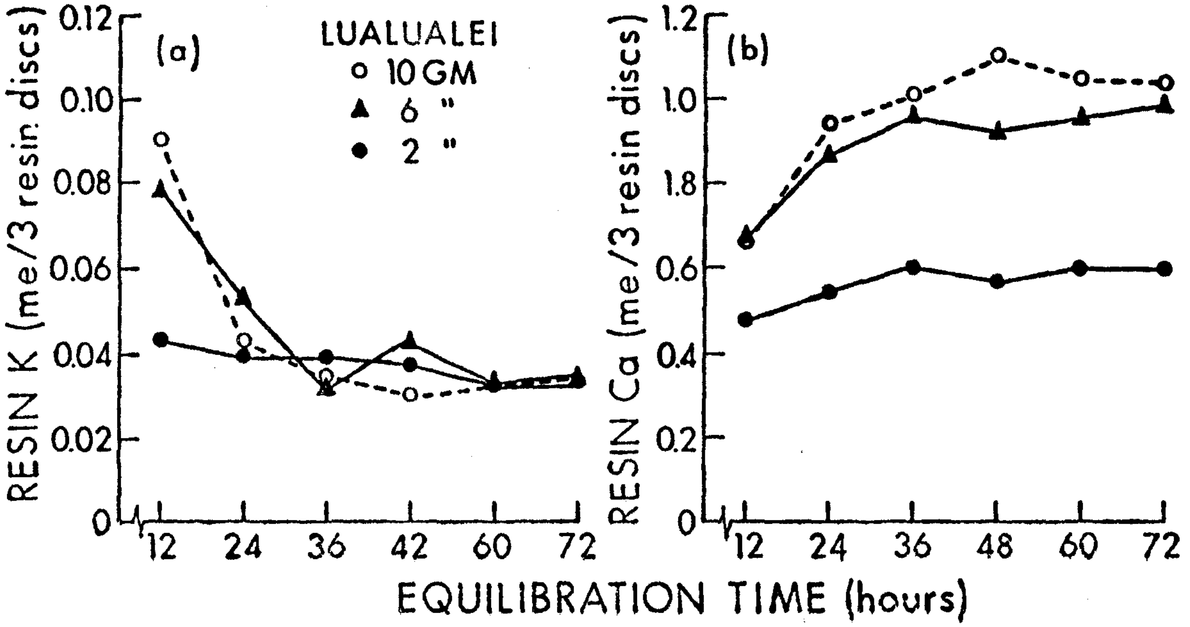

Figure 12. The effect of soil mass and equilibration time on (a) K and (b) Ca adsorption by resin from Lualualei soil.

into the soil solution, since this soil has the capacity to retain Ca. According to Stoop (1974), the Wahiawa soil can "fix" as much as 8% of the Ca added when phosphate fertilizer is not applied and more when it is applied.

Furthermore, mica in the Wahiawa soil serves as a source of K for removal by resin. Mica as a source of non-exchangeable K has been reported by several workers (Barber and Mathews, 1962; Haagsma and Miller, 1963; Waddy and Vimpany, 1970; Bolton, 1973; and Lee and Gibson, 1974). The results for the Wahiawa soil (Figure 9) appear to be related to such a mechanism, since total K extracted increased (Figure 10) with time especially for the large sample sizes. In contrast, K extracted from the Waimea and Lualualei soils (Figures 11 and 12) decreased with time due to competition with Ca and Mg which occurred in high concentration.

For practical reasons and to minimize time dependent adsorption errors, a time of 36 hours and a sample size of 3 gm were selected for routine analysis.

B. Effect of soil-water ratio and equilibration time.

Here, the effects of dilution on the extractability of exchangeable cations from several different soil types by cation exchange resin were studied. The results presented in Figures 13, 14 and 15, for the six soil- show that the total quantity of cations extracted by resin decreased with increasing dilution, irrespective of soil type and equilibration time. This behavior could be attributed to a decrease in the total cation concentration of the equilibrium solution as the soil-water ratio was increased. As Drachev and Aleksandrova (1932) pointed

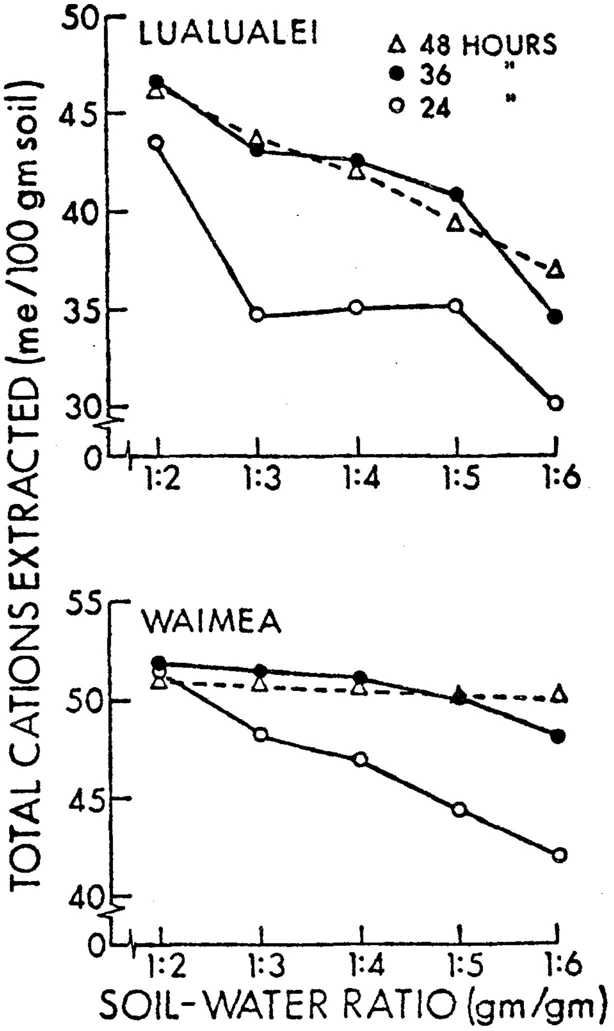

Figure 13. The effect of soil-water ratio and equilibration time on cation adsorption by resin from Lualualei and Waimea soils.

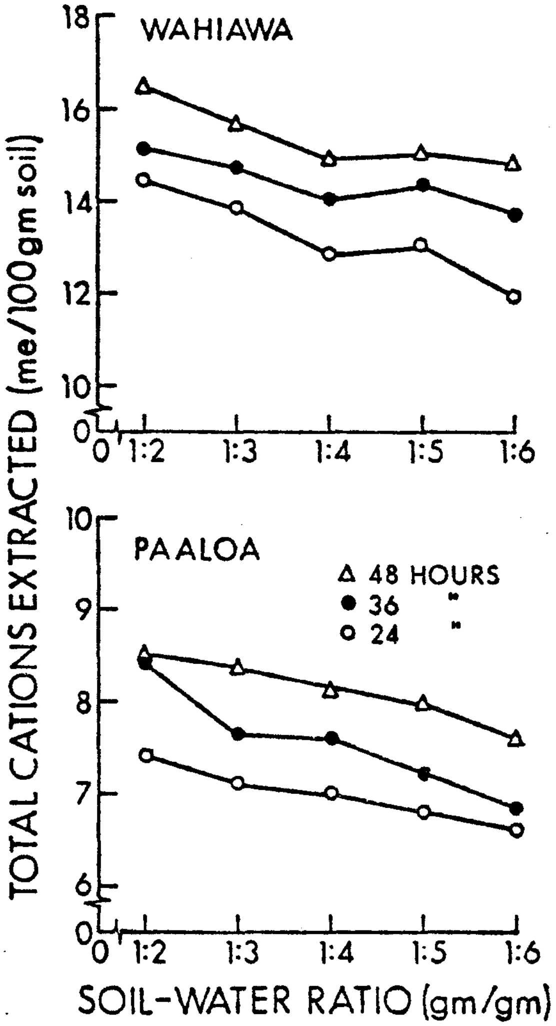

Figure 14. The effect of soil-water ratio and equilibration time on cation adsorption by resin from Wahiawa and Paaloa soils.

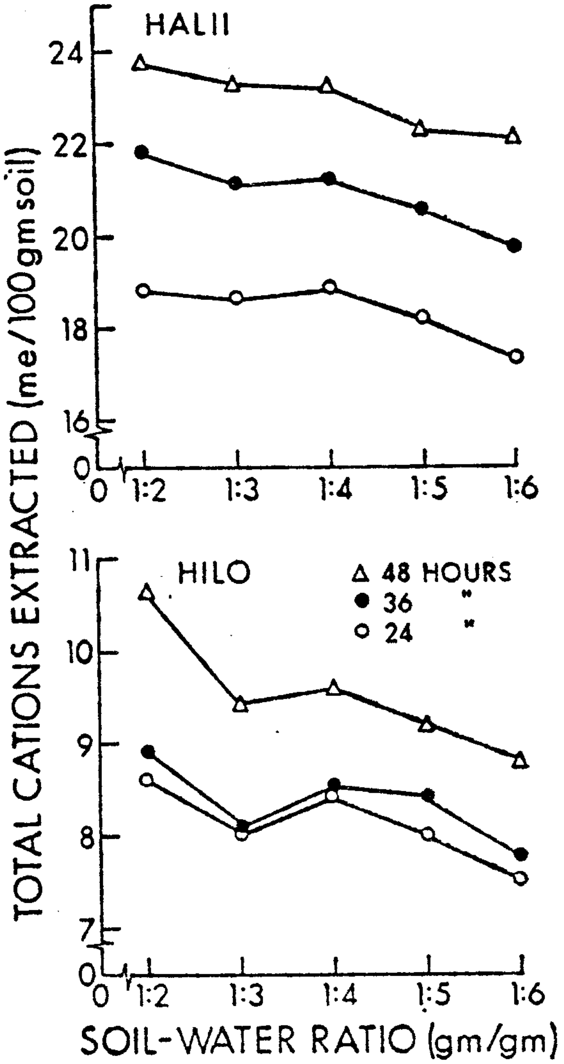

Figure 15. The effect of soil-water ratio and equilibration time on cation adsorption by resin from Halii and Hilo soils.

out, the total electrolyte concentration of the equilibrium soil solution decreases as the total water content of the soil is increased. Thus, experimental results and theory are in agreement, which indicates that the ability of the resin to extract nutrients from soil, as restricted by the technique employed in this study, was dependent on the soil solution concentration. In other words, contact exchange which might have occurred had the resin been placed in direct contact with soil was absent in this system.

Presented in Figures 16, 17 and 18, and in Table 4 are the results of the effects of dilution on individual cations. They show that Al and the divalent cations decreased as K increased with dilution, although Mg increased slightly in both the Waimea and Wahiawa soils. Such an increase in Mg adsorption indicates an increasing Mg concentration in the soil solution, which could result from competition between Ca and Mg for re-adsorption by the soil since the Ca/Mg ratio was very high in these two soils. According to Eaton and Sokoloff (1935) when the soil-water ratio is increased Ca and sometimes Mg decreases, implying that Mg may or may not decrease upon dilution of the soil solution. For the Paaloa, Halii and Hilo soils dilution did not have much effect except on Al. This is not surprising since these are low base soils, high in exchangeable Al. Thus, it may be concluded that soil-water ratios affect cation adsorption by resin but the quantities of the cations in the soil definitely have an overriding influence.

Based on these results 1:3 soil-water ratio was considered suitable for a routine extraction procedure.

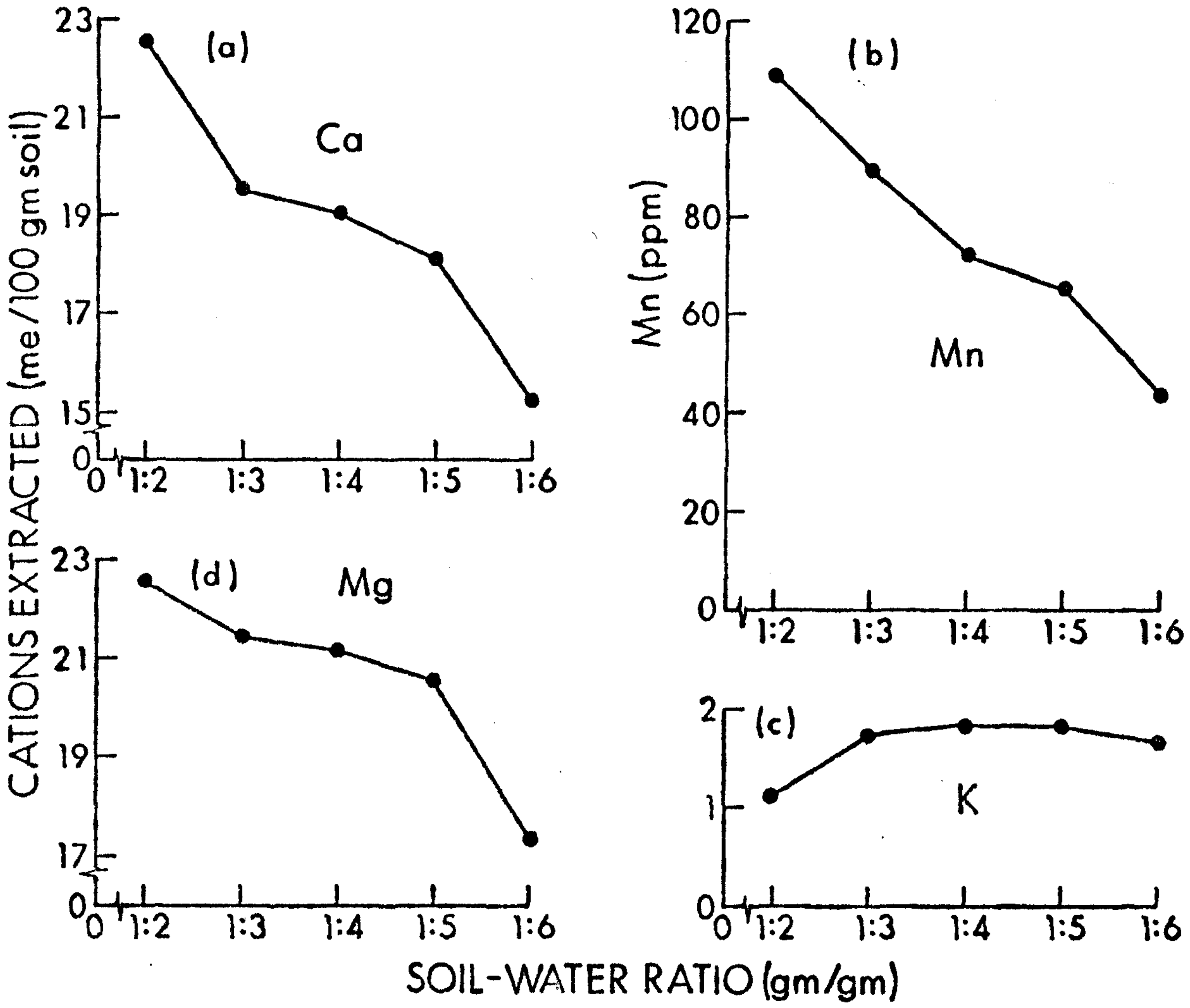

Figure 16. Relationship between soil-water ratio and cations adsorbed by resin from Lualualei soil.

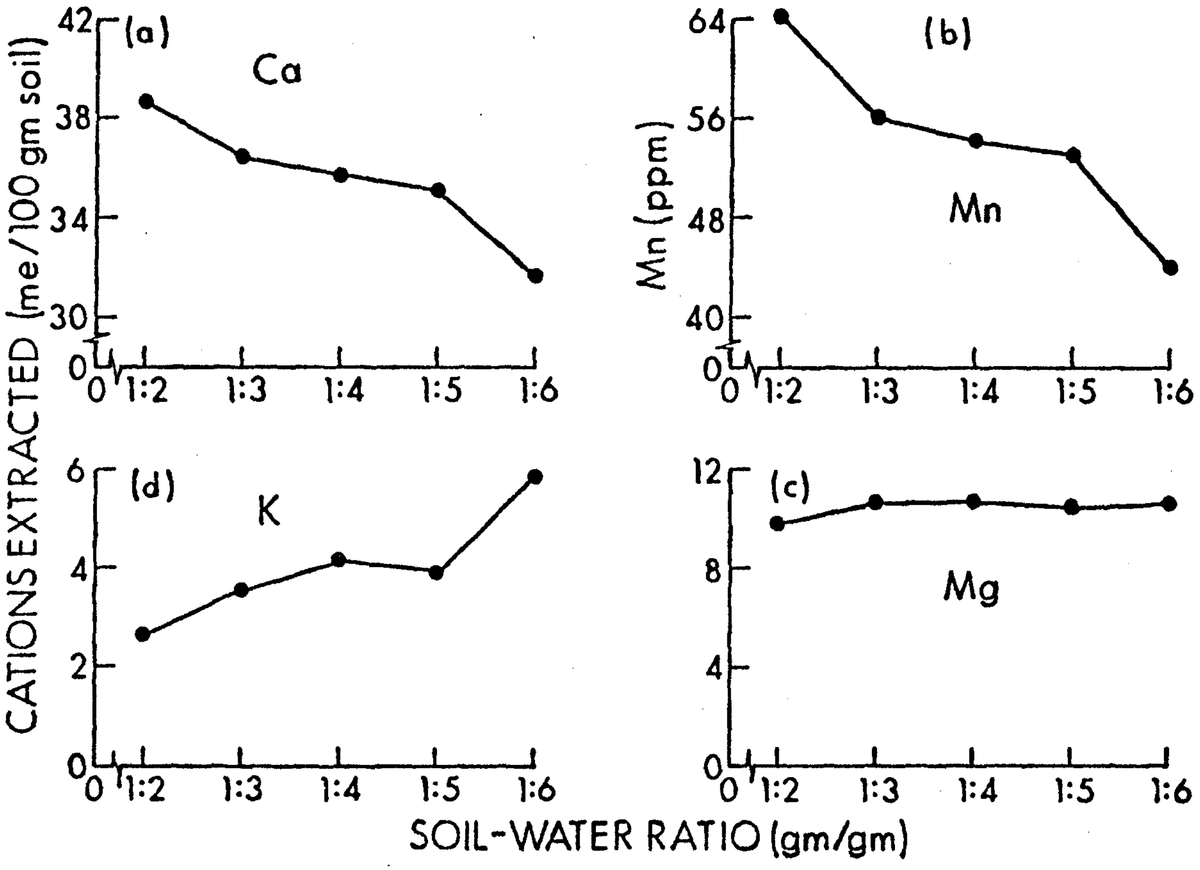

Figure 17, Relationship between soil-water ratio and cations adsorbed by resin from Waimea soil.

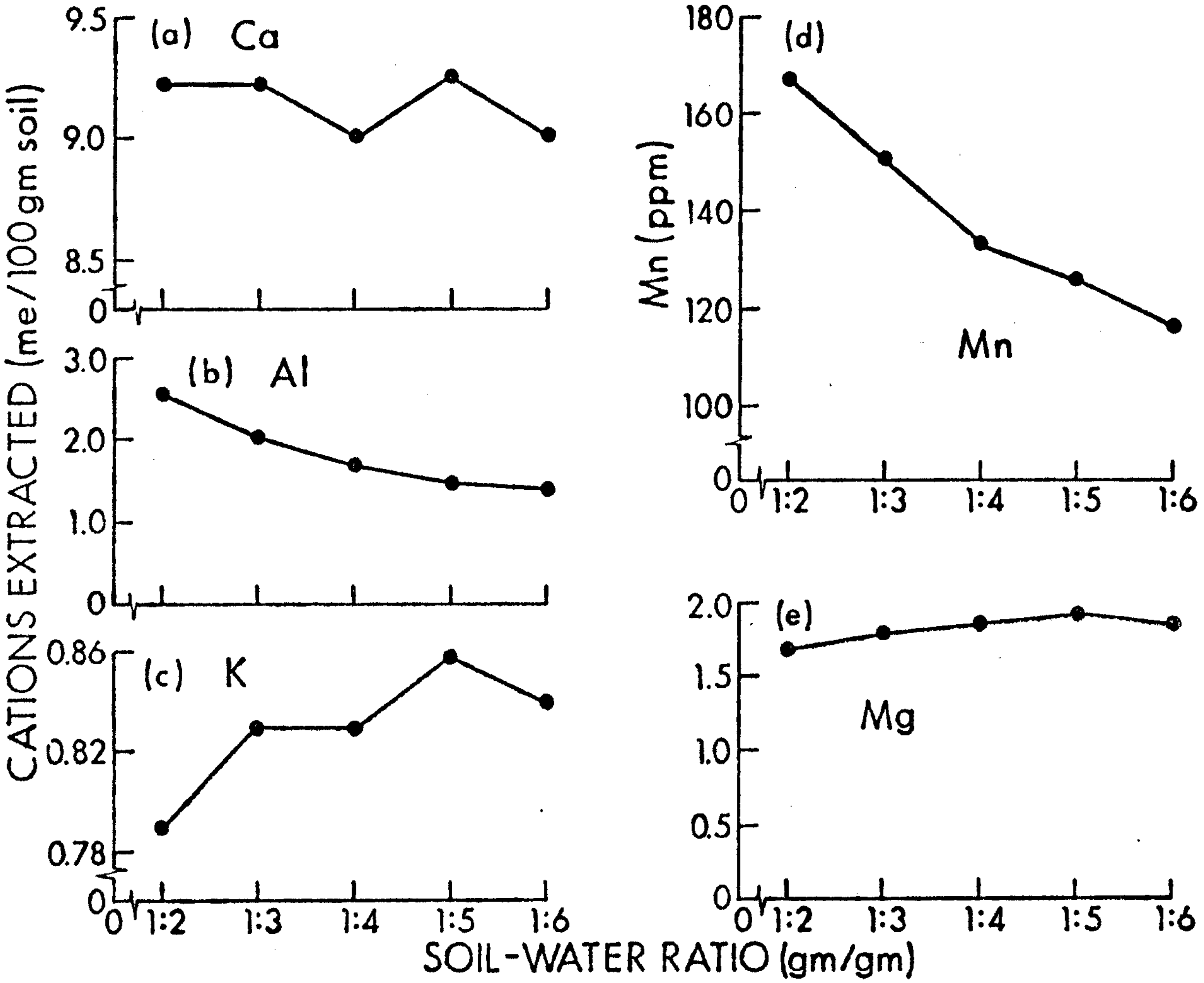

Figure 18. Relationship between soil-water ratio and cations adsorbed by resin from Wahiawa soil.

Table 4. The Effect of Soil-Water Ratio on Cation Extraction by Resin Using 4 gm Soil Equilibrated for 36 Hours.

Soil	Ratio	K	Mg	Ca	Al	Mn
	(gm/gm)	(m.e./100 gm soil)				(ppm)
Halii	1:2	0.17	1.15	0.89	19.44	34
	1:3	0.17	1.02	0.85	18.94	32
	1:4	0.18	1.13	0.95	18.90	33
	1:5	0.18	1.06	0.98	18.19	34
	1:6	0.17	1.12	0.89	17.40	33
Paaloa	1:2	0.23	1.52	2.71	3.78	30
	1:3	0.22	1.42	2.55	3.25	30
	1:4	0.23	1.46	2.53	3.22	30
	1:5	0.23	1.50	2.50	2.83	30
	1:6	0.23	1.50	2.59	2.36	30
Hilo	1:2	0.16	0.34	0.30	7.83	30
	1:3	0.16	0.35	0.35	7.08	30
	1:4	0.16	0.34	0.33	7.52	30
	1:5	0.16	0.37	0.38	7.37	30
	1:6	0.15	0.34	0.30	6.82	30

C. Cation interactions.

1. Effect of soil mass.

The changes in cation extraction with sample size are illustrated in Figures 19, 20 and 21 for the Wahiawa, Waimea and Lualualei soils. Results for the Halii, Paaloa and Hilo soils are given in Table 5. In general, increasing soil mass increased Ca and Mg extraction, sometimes at the expense of K. In neutral soils Mn and Al decreased with increasing soil mass but the reverse is true for acid soils.

For the Wahiawa soil, the large quantity of Ca adsorbed by resin relative to Mg and K was due to lime application which could also explain the decrease in the quantities of Al and Mn extracted.

The Waimea (Typic Eutrandept) and the Lualualei (Typic Chromustert) are high base soils. Based on the results of a neutral normal ammonium acetate extraction, the quantities of Ca, Mg and K in these soils may be described as follows: Ca>> Mg> K for Waimea and Mg> Ca>> K for Lualualei (Table 1). These relationships explain the adsorption of these elements by cation exchange resin.

For the Halii, Paaloa and Hilo soils (Table 5) there was less interaction among cations. Obviously, this was due to the low base status of these soils and the large exchange capacity of the resin relative to their exchangeable base contents.

2. Effect of equilibration time.

Equilibration time as it affected cation extraction by resin is illustrated in Figures 10, 11 and 12. For the Waimea and Lualualei soils, K adsorption decreased as Ca adsorption increased with time due to the greater preference for Ca on the basis of its charge and quantity

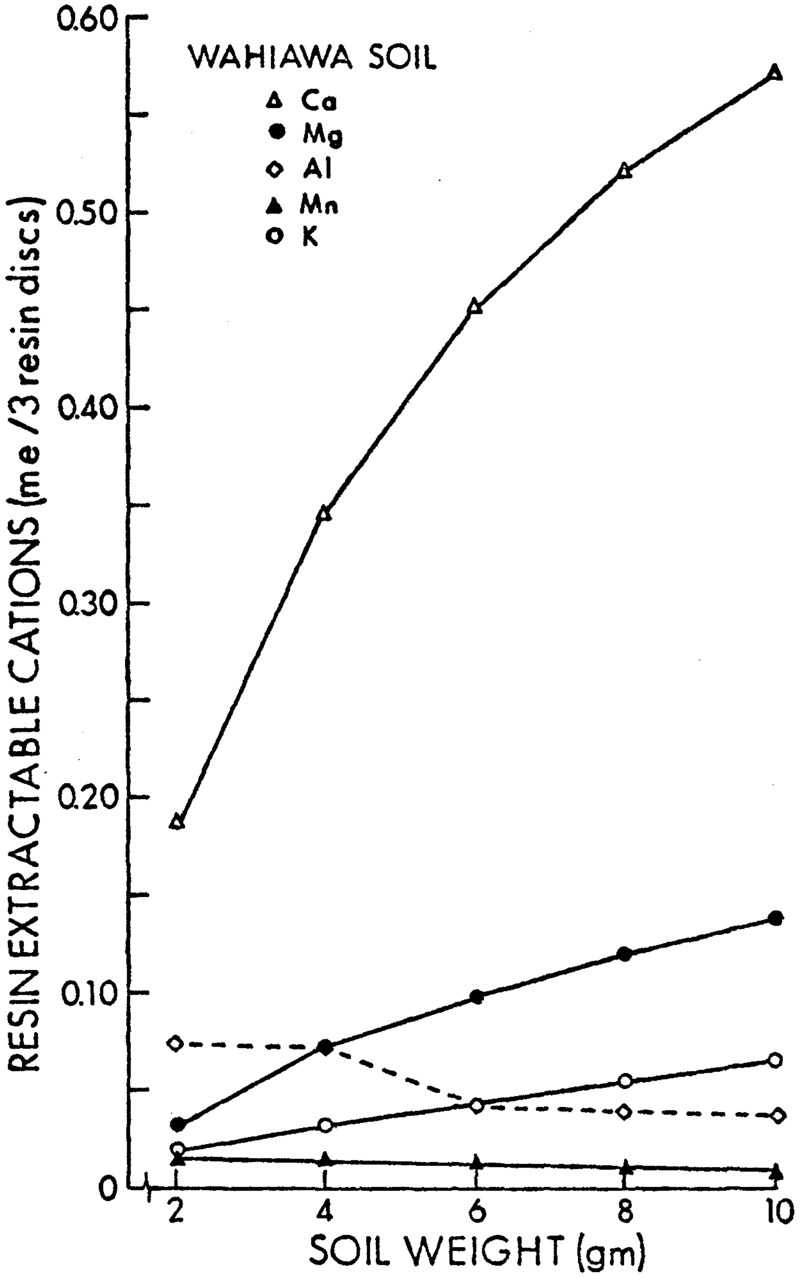

Figure 19. Relationship between soil weight and cations adsorbed by resin from Wahiawa soil equilibrated for 36 hours.

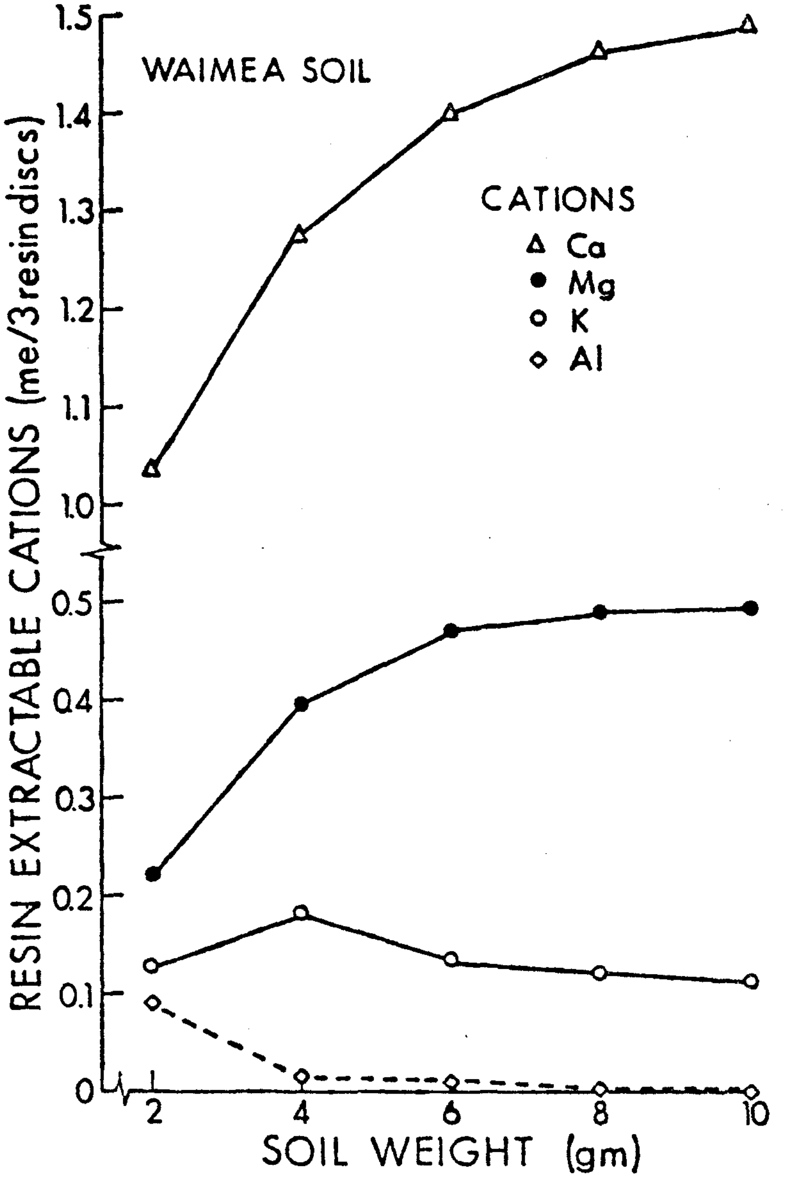

Figure 20. Relationship between soil weight and cations adsorbed by resin from Waimea soil equilibrated for 36 hours.

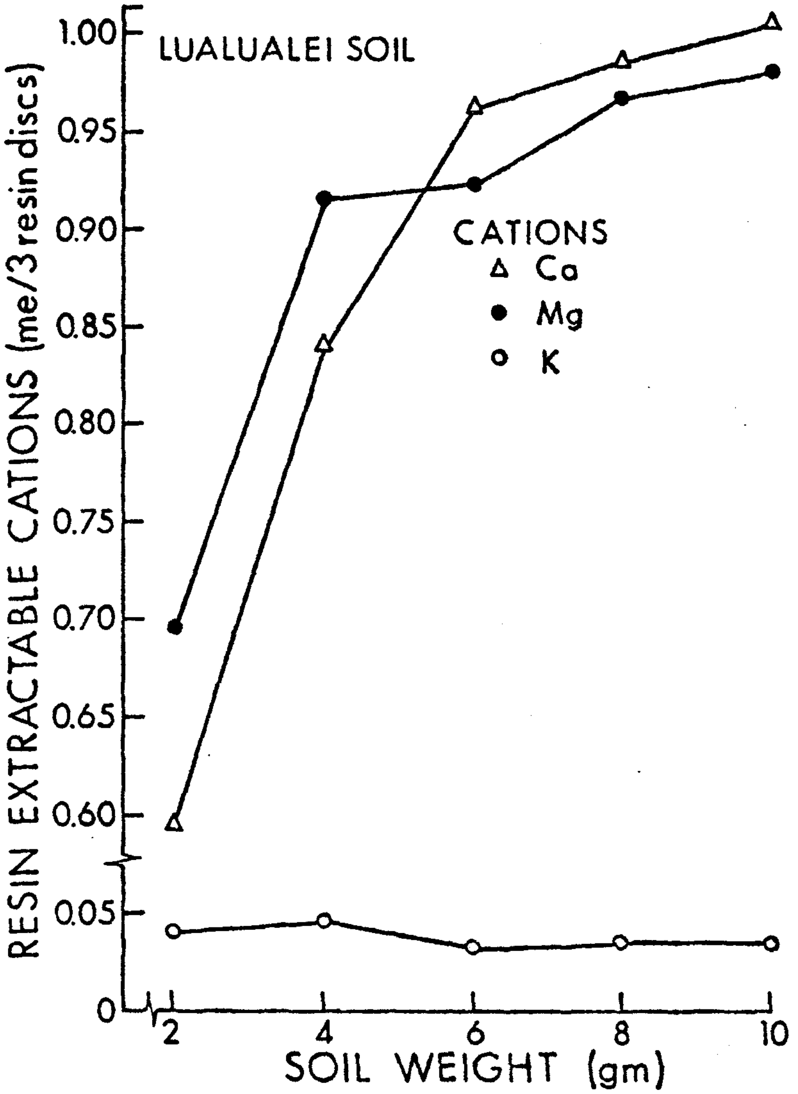

Figure 21. Relationship between soil weight and cations adsorbed by resin from Lualualei soil equilibrated for 36 hours.

Table 5. The Effect of Soil Sample Size on Cation Extraction by Ion Exchange Resin Equilibrated for 36 Hours.

Soil	Soil Wt.	K	Mg	Ca	Al	Mn
	(gm)	(m.e./3 resin discs)[1]				(μg/3 discs)
Halii	2	0.008	0.014	0.024	0.447	86
	4	0.008	0.033	0.048	0.731	99
	6	0.007	0.053	0.066	0.880	113
	8	0.006	0.074	0.086	0.963	122
	10	0.006	0.088	0.100	0.976	138
Paaloa	2	0.010	0.013	0.050	0.048	86
	4	0.013	0.039	0.103	0.094	89
	6	0.015	0.061	0.147	0.103	97
	8	0.018	0.078	0.173	0.080	102
	10	0.022	0.098	0.208	0.067	107
Hilo	2	0.009	0.000	0.009	0.220	97
	4	0.010	0.000	0.016	0.261	103
	6	0.011	0.008	0.027	0.260	113
	8	0.012	0.016	0.034	0.246	117
	10	0.013	0.025	0.041	0.254	121

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

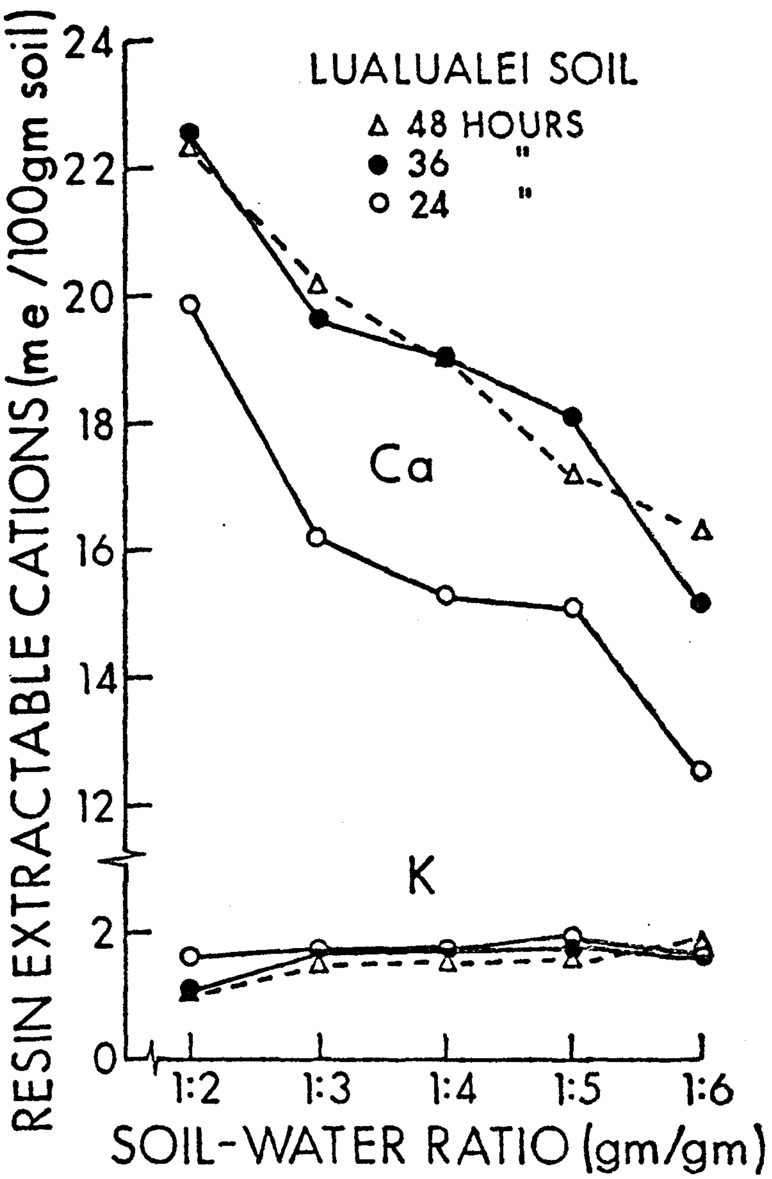

Figure 22. The effect of soil-water ratio and equilibration time on Ca and K adsorption by resin from Lualualei soil.

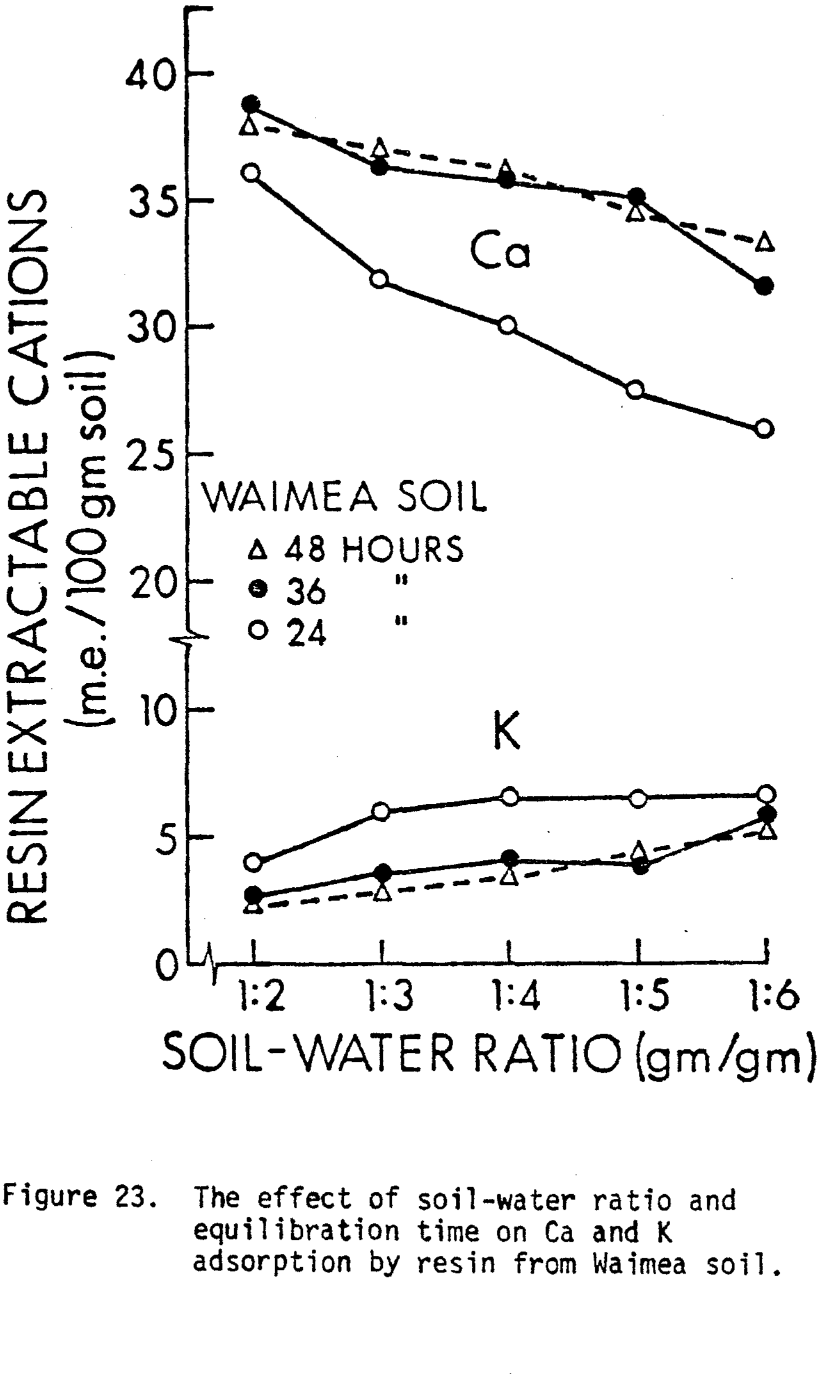

Figure 23. The effect of soil-water ratio and equilibration time on Ca and K adsorption by resin from Waimea soil.

in the soil. However, for the Wahiawa soil both Ca and K increased with time due to reasons previously stated.

The effect of time may also be observed in Figures 22 and 23. Increasing the equilibration time, the quantities of Ca and K extracted also increased irrespective of the soil-water ratio. This suggests that the high quantities of cations extracted at short equilibration times by applying narrow soil-water ratios could also be obtained with wide soil-water ratios and longer equilibration times.

THE EFFECTS OF SOIL MASS, SOIL-WATER RATIO AND EQUILIBRATION TIME ON ANION ADSORPTION BY ION EXCHANGE RESIN

A. Effect of Soil mass and equilibration time.

The results for the effect of soil mass and time are presented in Figure 24 and in Tables 17 to 19 (Appendix II). They show that in general, increasing soil mass and equilibration time increased anion exchange resin-extractable Si, P and S.

1. Silicon

More Si was extracted from the Lualualei soil than from any other soil. This result was primarily caused by the fact that this soil occurs in valley bottoms in arid regions so that the water-soluble Si content of the soil is high. Likewise, the high Si in the Waimea soil can be attributed to its occurrence in low rainfall regions. In contrast, the Halii soil is highly leached due to high rainfall and intensive weathering and as a result has a low Si content. This is in agreement with Cline's (1955) findings that intensive weathering and leaching under high rainfall result in the depletion of Si and bases in Hawaiian soils.

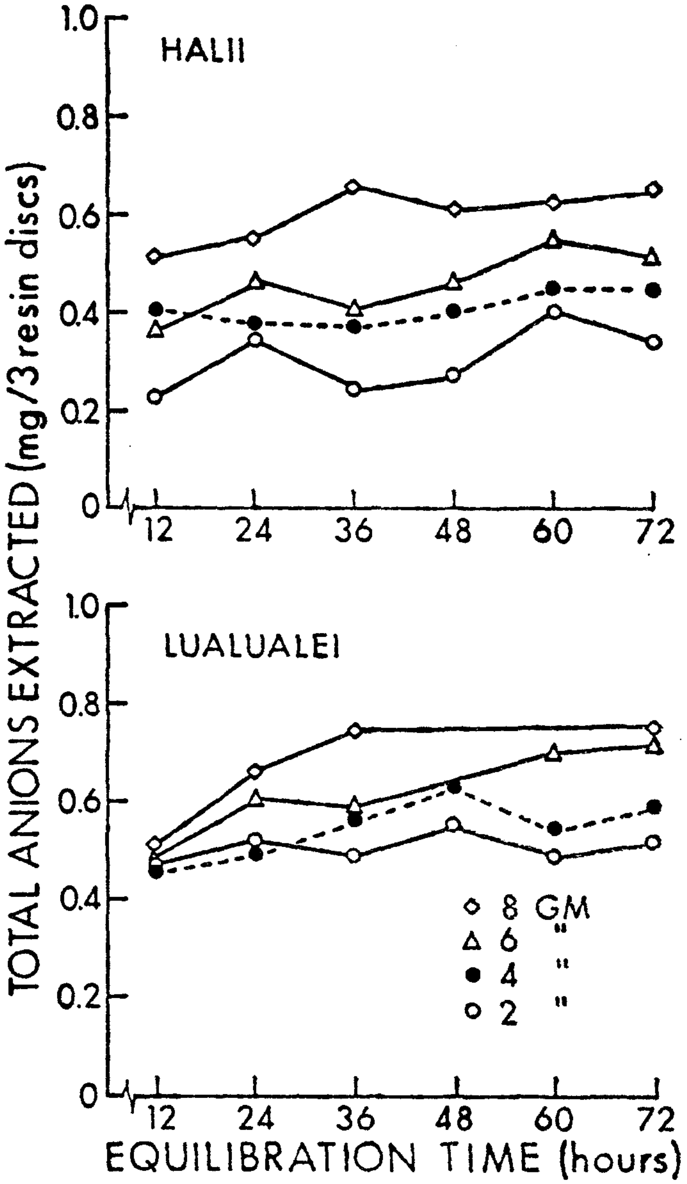

Figure 24. The effect of soil mass and equilibration time on anion adsorption by resin from Halii and Lualualei soils.

However, Si extracted from this soil is believed to be the result of Si desorption due to phosphate application at a rate of 800 kg P/ha. Similarly, the Wahiawa and Paaloa soils had no resin-extractable Si due to their highly weathered nature.

2. Phosphorus

In the Halii soil the high rate of P applied undoubtedly caused P extraction by resin. In the Waimea and Paaloa soils, where no P was applied, the native P was not adsorbed in sufficient quantity to be detected. Similarly, the P content of the Wahiawa soil was very low and was not easily adsorbed by resin. The lack of resin-extractable P in the Lualualei soil is a puzzle since an appreciable amount was extracted by chemical methods (Table 1). However, there was a yield response to P application to this soil, suggesting that low resin-extractable P was not entirely unexpected.

There is usually a good negative correlation between P adsorption in soil and Si solubility. According to Fox (1974), for soils developed from volcanic ash P adsorption is inversely related in Si solubility. This implies that if Al-P or Ca-P interaction and the level of P are not limiting, then the resin would extract more P from soils that contain appreciable amounts of water-soluble Si.

Although time did not permit a more careful testing of resin P extraction, the use of OH^--saturated anion exchange resins appears to hold some promise for improving sensitivity of resin to soil P.

3. Sulfur

SO_4-S extracted by resin exceeded all other nutrients in all soils.

However, it is not clear whether this was due to preference for S by the anion exchange resin, or to high levels of SO_4-S in these soils or to the turbidimetric method used to calibrate S standards. If the latter were the case, then the S concentration in samples could be over-estimated. Hasan et al. (1970) have reported that there is an abundance of adsorbed SO_4-S associated with hydrated Al and Fe oxides in highly weathered Hawaiian soils. These soils are also known to contain high levels of organic S. Thus, it is believed that these two sources might have contributed to the large quantities of SO_4-S adsorbed by resin.

4. Molybdenum

The estimation of Mo was not successful. Perhaps, this was because of the extremely low quantities adsorbed by resin, which were not easily detected by x-ray fluorescence techniques due to background radiation effects, since the Mo line intensity lies at the peak of the bremstrahlung.

For a routine anion extraction procedure, the same soil sample size (3 gm) that was selected for cation extraction was employed together with an equilibration time of 48 hours.

B. Effect of soil-water ratio.

Figures 25 and 26 show the total quantity of anions extracted at different equilibration times plotted as a function of soil-water ratio. The results show a general tendency for the quantity of anions extracted to decrease with increasing dilution.

For individual elements resin adsorption (Appendix II, Tables 20-24) decreased with increasing soil-water ratio in all soils. However, P

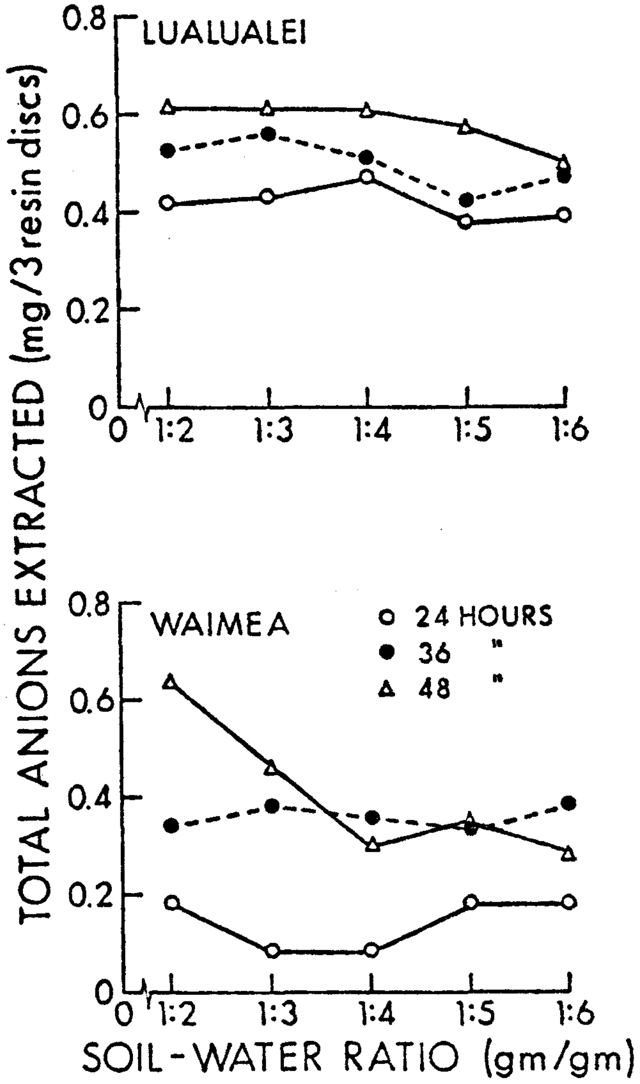

Figure 25. The effect of soil-water ratio and equilibration time on anion adsorption by resin from Lualualei and Waimea soils.

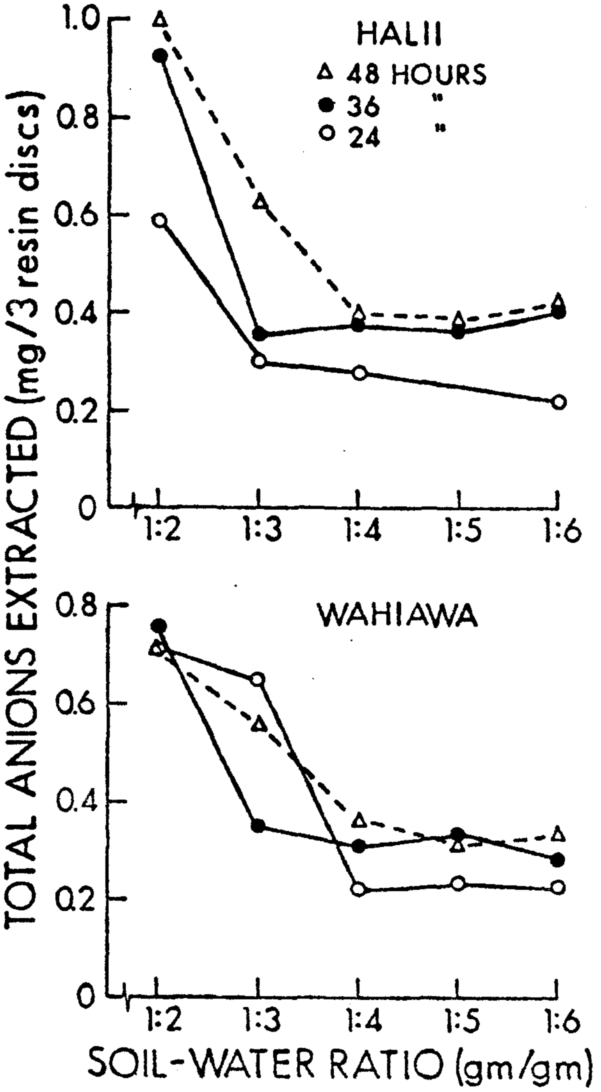

Figure 26. The effect of soil-water ratio and equilibration time on anion adsorption by resin from Halii and Wahiawa soils.

extracted from the Halii soil appeared to increase slightly with dilution. Perhaps this was due to the overriding influence of time. Based on these results 1:5 soil-water ratio (gm/gm) was selected for routine extraction.

C. Anion interactions

There was very little interaction among the anions, except for the tendency of Si adsorption from the Halii soil to decrease with increasing soil sample size and time, whereas P and S extracted increased.

COMPARISON BETWEEN ION EXCHANGE RESIN AND CHEMICAL METHODS IN NUTRIENT EXTRACTION

A. Cations

Correlations between cation exchange resin-extractable K and 1*N* ammonium acetate-extractable K for the Halii and Lualualei soils are given in Figures 27 and 28 respectively. The results show that these two methods were very highly correlated. However, ammonium acetate seemed to extract about twice as much K as the resin extracted from the Lualuelei soil, whereas the same amount was extracted by both methods from the Halii soil. The difference in the quantities extracted could be the result of competition between polyvalent and monovalent cations (Lee and Gibson, 1976). This relationship is very significant because it indicates that resin extraction of an ion depends on the quantity of other ions present in the soil and may represent a more realistic picture of nutrient extraction by plant roots.

Unlike the resin, 1*N* ammonium acetate extracts virtually all exchangeable cations and therefore more cations than would normally be

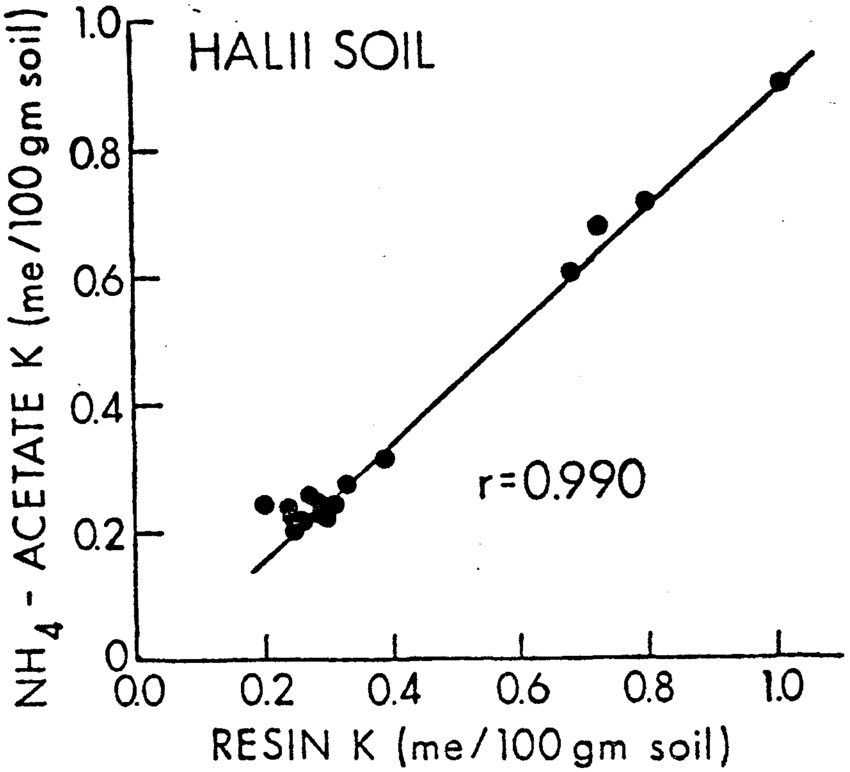

Figure 27. Relationship between K extracted by 1N ammonium acetate and K adsorbed by NH_4-saturated resin from Halii soil.

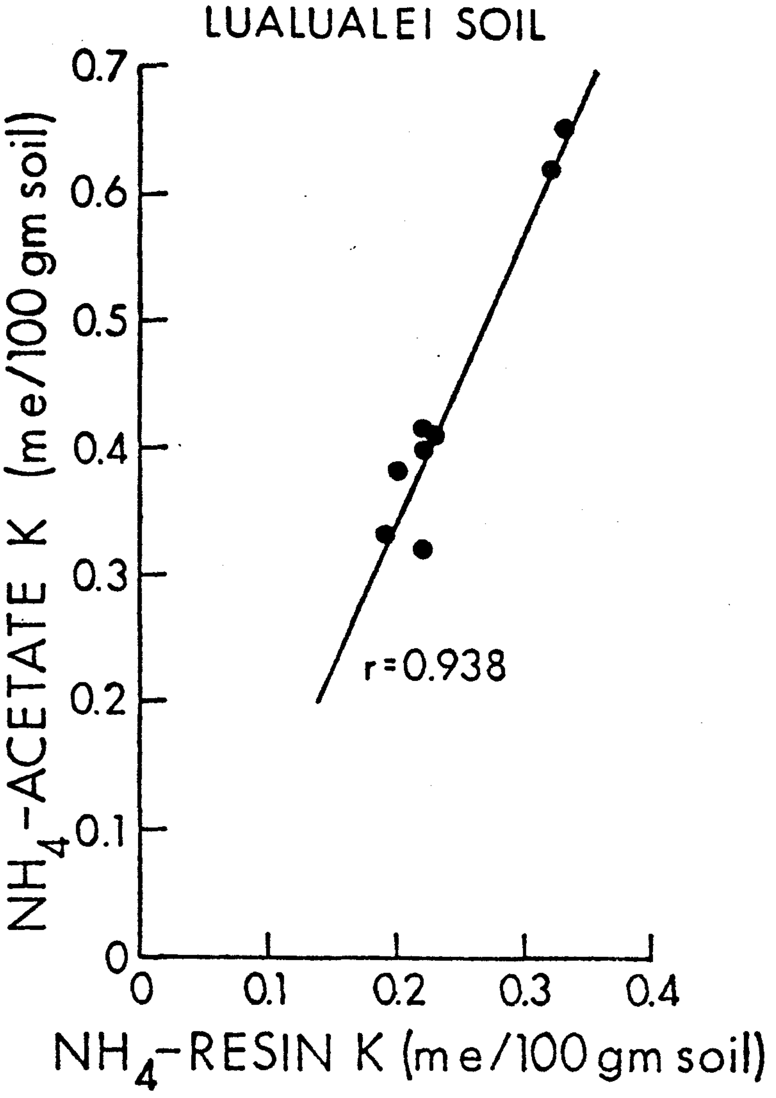

Figure 28. Relationship between K extracted by 1N ammonium acetate and K adsorbed by NH_4-saturated resin from Lualualei soil.

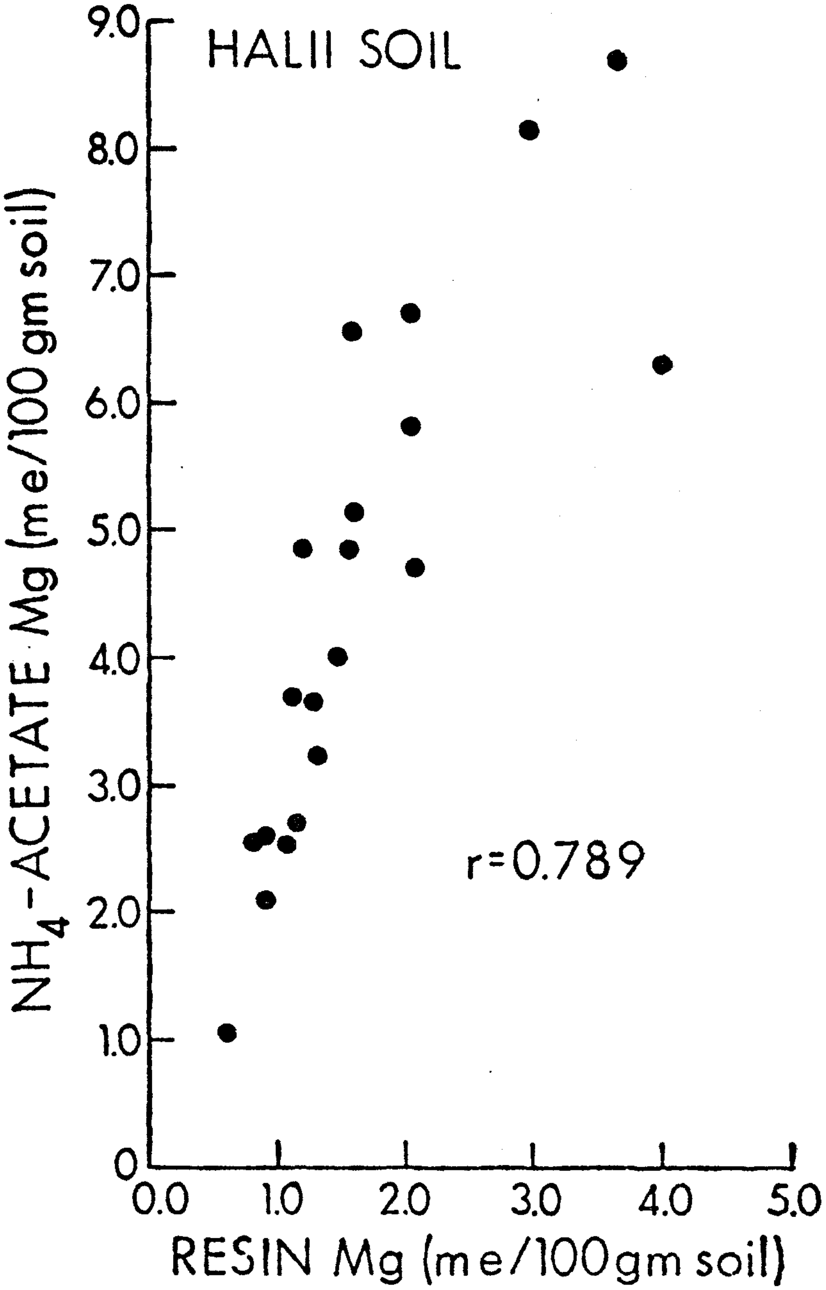

Figure 29. Relationship between Mg extracted by 1N ammonium acetate and Mg adsorbed by NH_4-saturated resin from Halii soil.

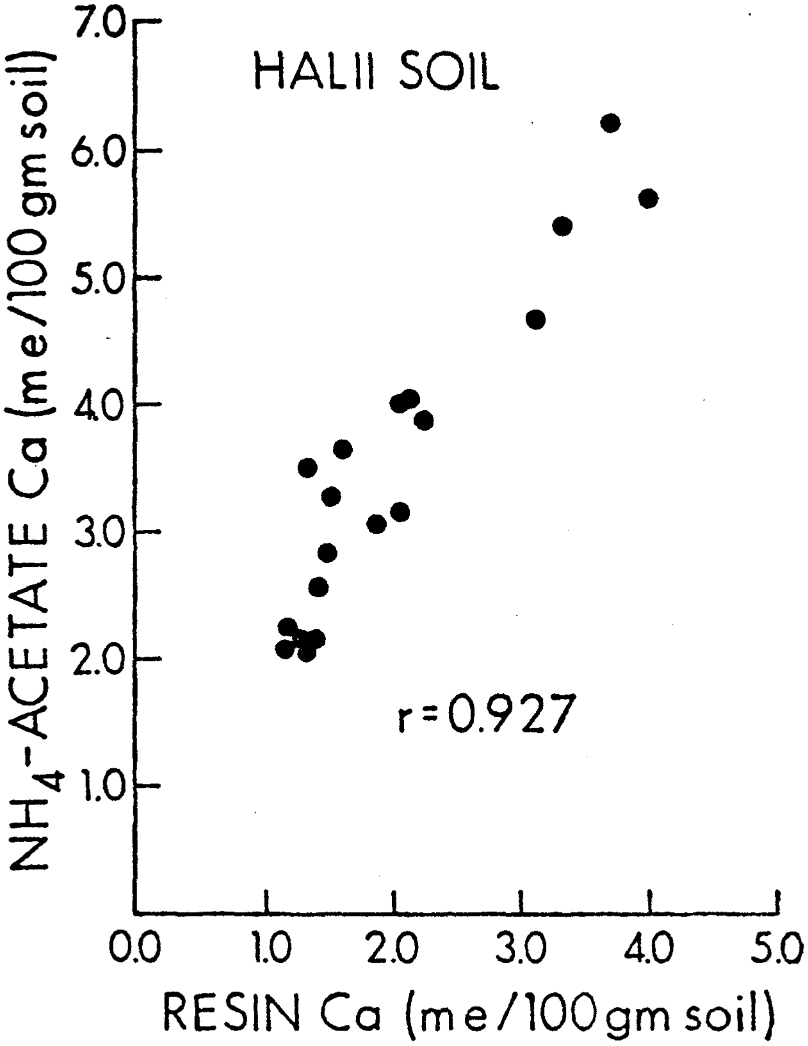

Figure 30. Relationship between Ca extracted by 1N ammonium acetate and Ca adsorbed by NH_4-saturated resin from Halii soil.

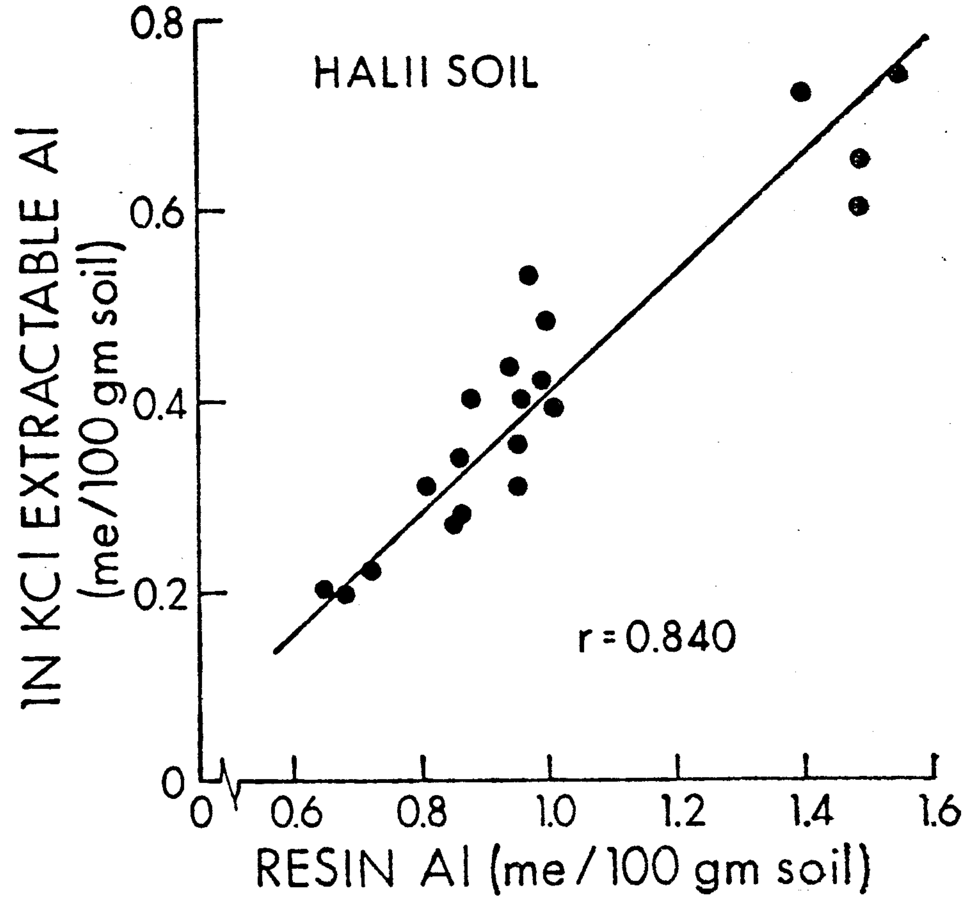

Figure 31. Relationship between Al extracted by 1N KCl and Al adsorbed by NH_4-saturated resin from Halii soil.

available and necessary for the plant (Beckett, 1972); and in addition the acetate anion dissolves organic matter and increases the solubility of non-exchangeable bases (Tucker, 1960).

Other nutrient cations such as Mg and Ca (Figures 29 and 30) show a highly significant correlation between resin and 1N ammonium acetate extraction from the Halii soil, but a poor correlation for the Lualualei soil. This is further indication that the resin method is more selective since it extracts only a portion of the total exchangeable cation. Consequently, while 1N ammonium acetate may extract most if not all the exchangeable nutrients, ion exchange resin extracts only a portion of the nutrient pool. Whether this portion coincides with plant root extraction remains to be seen.

A significant correlation was also obtained for Al estimated by ion exchange resin and 1N KCl (Figure 31). In this case resin extracted more Al than 1N KCl. This result is consistent with that obtained by Amedee and Peech (1976) who showed that a single 1N KCl extraction is not a good measure of the extractable aluminum.

B. Effect of saturating counter-ion species on cation extraction by resin in comparison with 1N ammonium acetate extraction.

An analysis of variance test to determine the difference in the quantities of nutrients estimated by NH_4- and H-saturated cation exchange resin and 1N ammonium acetate was performed on greenhouse and field sample data. The test results (Table 40, Appendix III) including a modified Duncan's (Bayesian) Least Significant Difference test (Table 41, Appendix III) show that a highly significant difference exists between extraction methods for all nutrients estimated in the Lualualei soil.

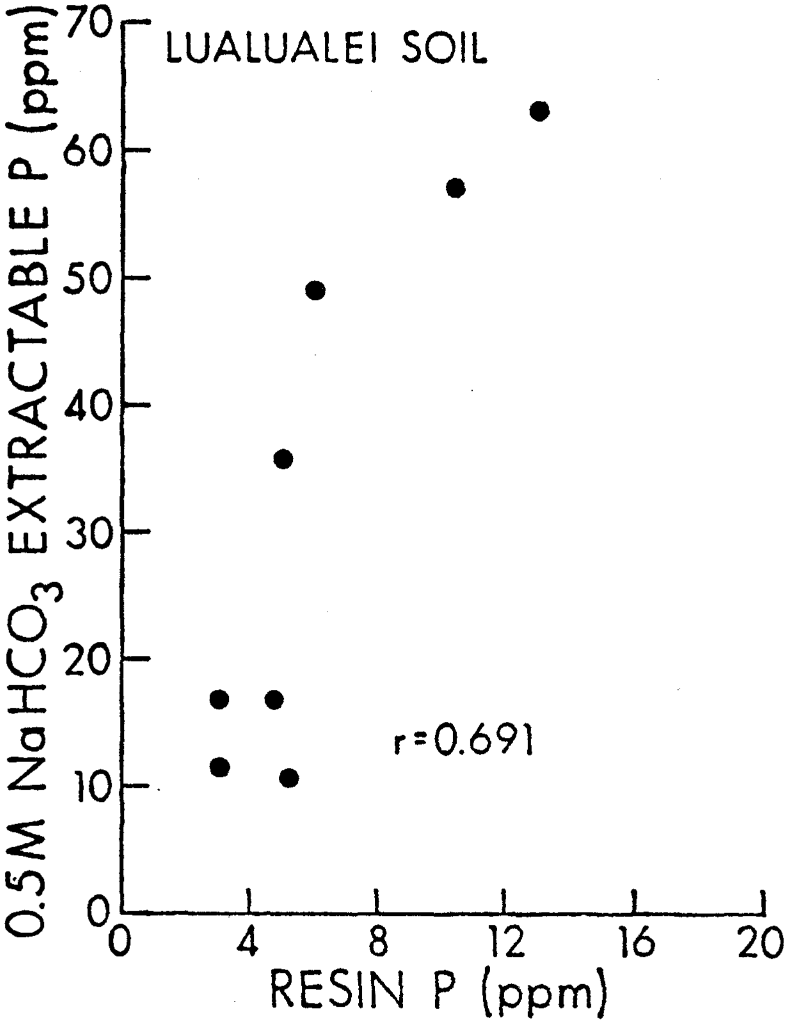

Figure 32. Relationship between P extracted by $0.5M\ NaHCO_3$ and P adsorbed by resin from Lualualei soil.

Similarly, for the Halii soil which was subjected to two extraction methods involving NH_4-saturated resin and 1N ammonium acetate, the results (Table 39, Appendix III) show that all nutrient cations except K were significantly different at the 0.01 level. A highly significant difference (Table 53, Appendix IV) was also obtained for the effect of ion exchange resin saturating counter-ion on the Wahiawa soil.

C. Anions.

The ion exchange resin extraction procedure was marginally successful for the estimation of P. This could be attributed to the fact that P extractable by resin depended on the water-soluble fraction since contact exchange was absent, and P was only sparingly soluble in water.

However, a significant correlation was obtained between resin and chemically extracted P for the Lualualei soil (Table 46, Appendix III). According to the results, resin extracted P was slightly better correlated with P extracted by 0.5 M $NaHCO_3$ (Figure 32) than with P extracted by modified Truog procedure.

An appreciable amount of Si was estimated from the Lualualei soil because of its high Si content, although this amount was very poorly correlated with water-extractable Si.

RELATIONSHIP BETWEEN RESIN EXTRACTION AND NUTRIENT UPTAKE

A. Nutrient uptake by sudax in relation to resin and chemical extraction methods.

A summary of multiple regression equations describing nutrient uptake by sudax in relation to resin and chemical extraction procedures is provided in Tables 42, 44 and 45, Appendix III, for the Halii and

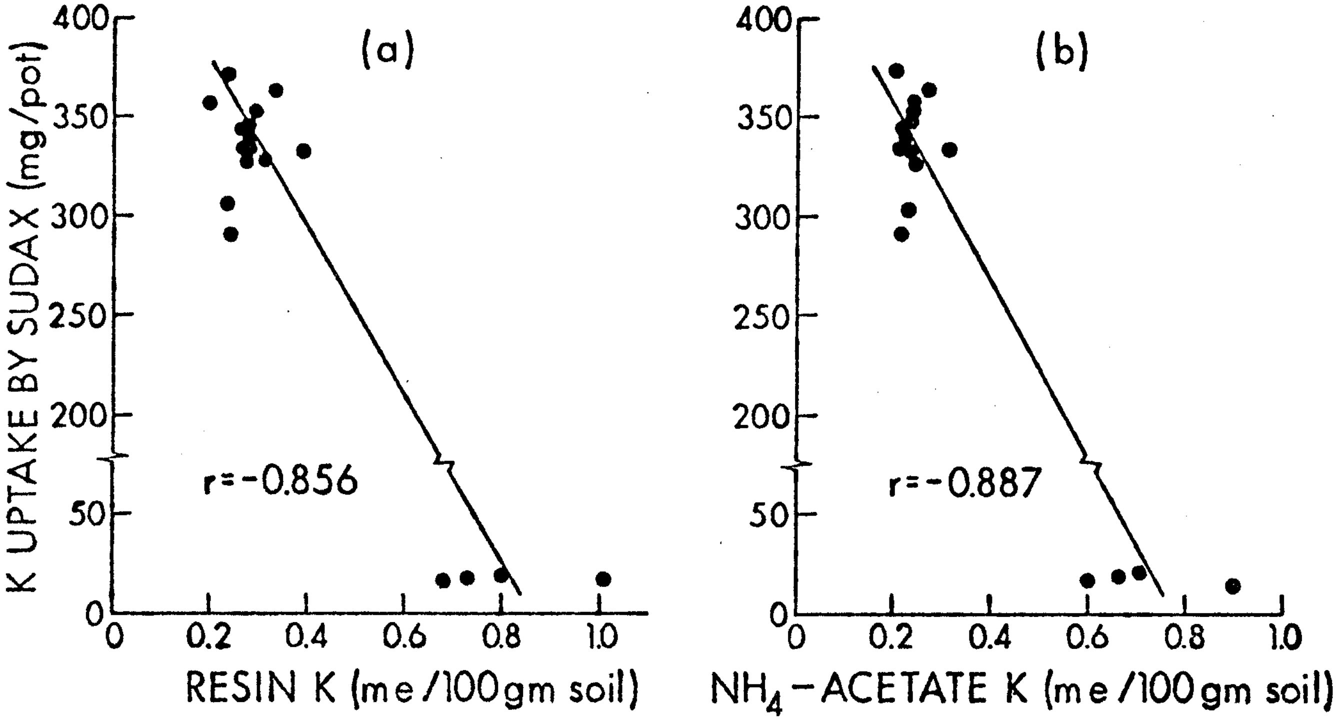

Figure 33. Relationship between K uptake by sudax and K extracted by (a) cation exchange resin and (b) 1N ammonium acetate from Halii soil.

Lualualei soils.

1. K uptake.

Figure 33 shows a highly significant correlation between K uptake by sudax and extractable K in soil, with little or no distinction between extraction methods. In this study extractable K was measured after cropping, which may explain the negative correlation. This seems to suggest soil K depletion due to greater uptake in the higher phosphorus treatments. This result tells us that uptake of a nutrient by plants depends not only on the concentration of the nutrient but also on the vigor of the plant as influenced by all other nutrients.

A correlation between K uptake by plant and soil K extracted by resin has been reported by Salmon (1965). His study showed that the uptake of non-exchangeable K by grass was significantly correlated with H-resin extractable K. Likewise, McLean (1961), and Barber and Mathews (1962) showed that non-exchangeable K adsorbed by resin was significantly correlated with plant uptake.

2. Mg and Ca uptake.

Figures 34 and 35 illustrate correlation between the uptake of Mg and Ca by sudax and extractable Mg and Ca in Halii soil. Resin-extractable Mg was by far better correlated with Mg uptake than 1N ammonium acetate-extractable Mg. At the same time, Ca extracted by the latter was slightly better correlated with uptake. However, based on a stepwise multiple regression analysis (Table 42. Appendix III) Mg and Ca uptake can best be described by the cation ratios $(\sqrt{Ca}/\sqrt[3]{Al})$ and $\sqrt{Ca}/(\sqrt{Ca + Mg} + \sqrt[3]{Al})$ respectively, as predicted by nutrient cations

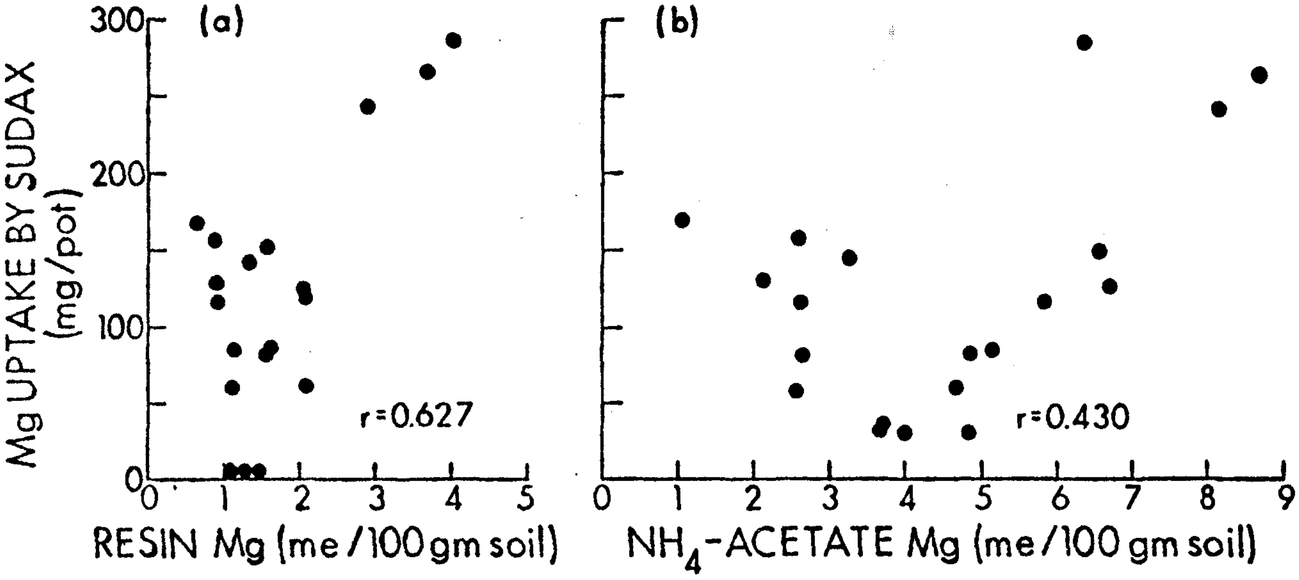

Figure 34. Relationship between Mg uptake by sudax and Mg extracted by (a) cation exchange resin and (b) 1N ammonium acetate from Halii soil.

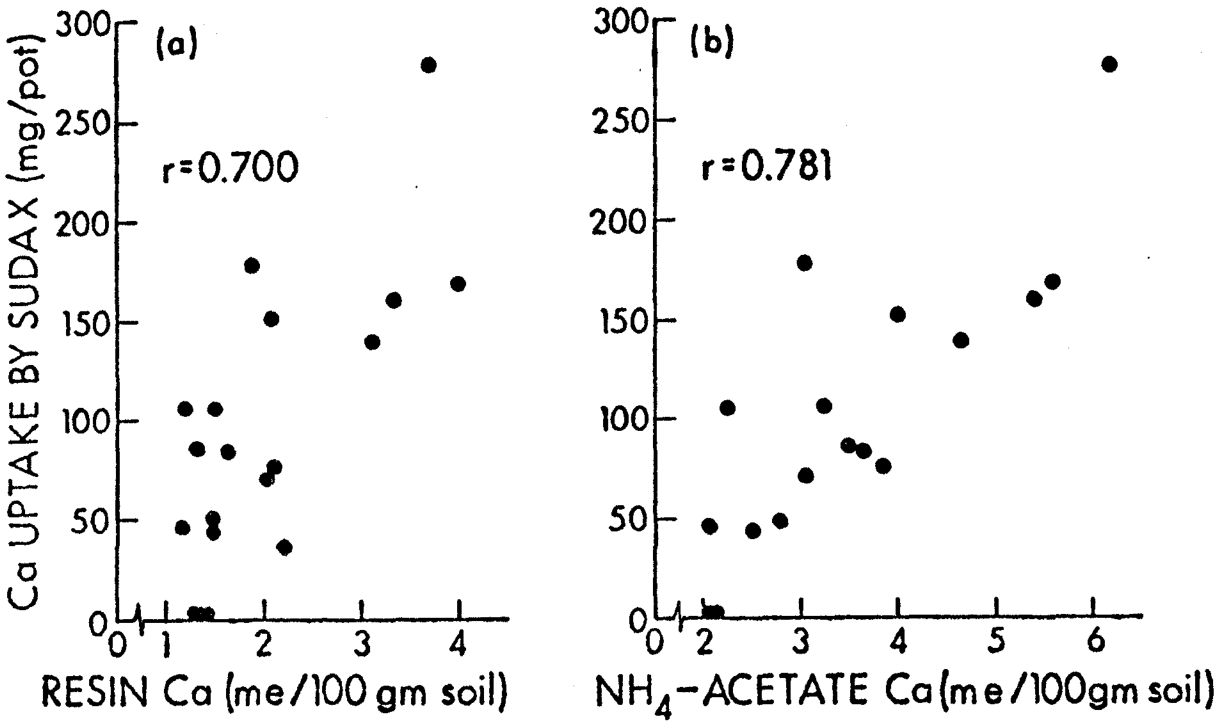

Figure 35. Relationship between Ca uptake by sudax and Ca extracted by (a) cation exchange resin and (b) 1<u>N</u> ammonium acetate from Halii soil.

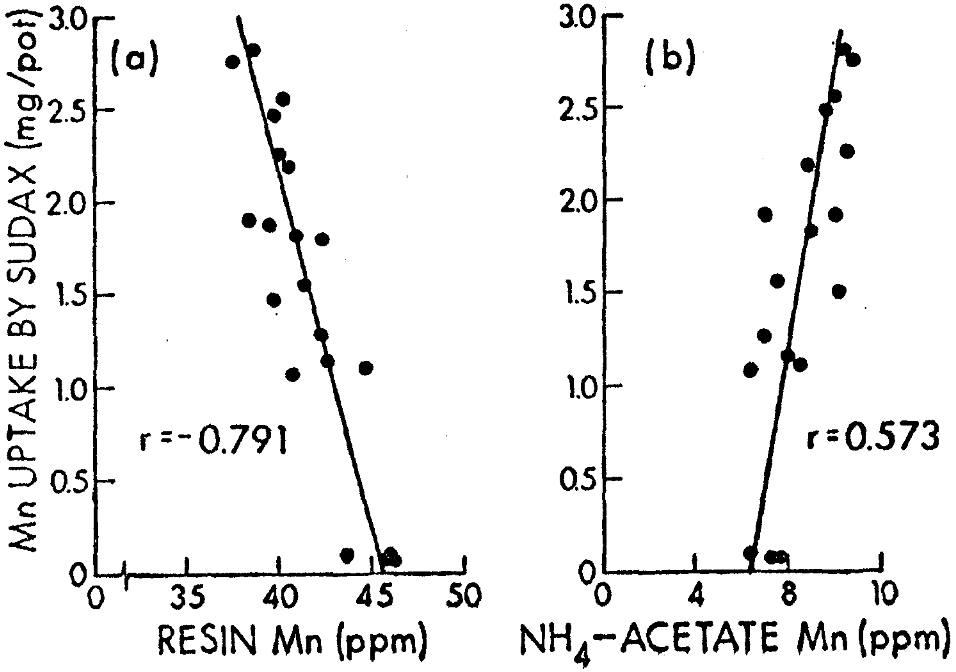

Figure 36. Relationship between Mn uptake by sudax and Mn extracted by (a) cation exchange resin and (b) 1N ammonium acetate from Halii soil.

estimated by both methods.

3. Mn uptake

The relationship between Mn uptake by sudax and extractable Mn in soil is illustrated in Figure 36 for the two extraction procedures. These results show that resin-extractable Mn was significantly negatively correlated with uptake while 1N ammonium acetate extractable Mn was positively correlated. The reason for this trend is not clear but it is recognized that a normal neutral ammonium acetate is not a good procedure for extracting Mn. Furthermore, by the nature of this soil Mn or Al toxicity is more likely to restrict plant growth and reduce uptake than to enhance it. Therefore, the negative relationship between Mn uptake and resin-extractable Mn is more realistic than the positive relationship with 1N ammonium acetate-extractable Mn. Consistent with this, Table 42 (Appendix III) shows that resin-extractable Mn was negatively correlated with yield and positively correlated with Al, which was in turn negatively correlated with yield. From these relationships there is reason to believe that ion exchange resin-extractable Mn correctly quantifies soil Mn with respect to Mn uptake.

Little has been reported on the extraction of plant available Mn by ion exchange resin but the work of Acquaye et al. (1972) and the present study show that cation exchange resin can be used to estimate soil Mn for correlation with plant uptake.

B. Nutrient uptake by tropical legumes in relation to resin-extractable cations

Tables 60 and 62 in Appendix IV show summaries of nutrient uptake by *Leucaena leucocephala* and *Stylosanthes fruticosa* respectively, in relationship to resin-extractable cations. These two legumes, very different in their sensitivities to soil acidity, will be examined with respect to nutrient uptake as a function of liming.

1. Ca uptake

Ca uptake by *Leucaena leucocephala* according to Figure 37, is inversely related to the cation ratio, $K/\sqrt{Ca + Mg}$ (referred to as the cation activity ratio $a_K/\sqrt{a_{Ca} + a_{Mg}}$, or k potential, $p^K - \frac{1}{2}p^{(Ca + Mg)}$). Beckett (1969a) first used this expression to describe the soil solution K intensity, since this was affected by the quantities of Ca and Mg in solution.

In this relationship Ca uptake increases as ($K/\sqrt{Ca + Mg}$) decreases, which corresponds to increasing resin-extractable Ca and soil pH (Table 50, Appendix IV). Similarly, in visualizing uptake as a function of ($\sqrt{Ca + Mg}/K$), (the reciprocal of ($K/\sqrt{Ca + Mg}$)) one may find that Ca uptake increases directly as resin-extractable Ca or lime rate increases. Thus, both of these relationships indicate that Ca uptake by L. leucocephala was in direct response to liming.

The negative correlation between Ca uptake and resin extractable K in the ($K/\sqrt{Ca + Mg}$) is believed to be the effect of one of two factors: First, crop response to liming led to increased plant growth and K uptake which might have resulted in K depletion. Resin extraction was conducted after harvest. Consequently, resin-extractable K decreased as yield and Ca uptake increased. Secondly, competition between Ca and K for exchange sites on the resin probably resulted in decreasing amounts of K adsorbed as Ca adsorption increase with lime treatment.

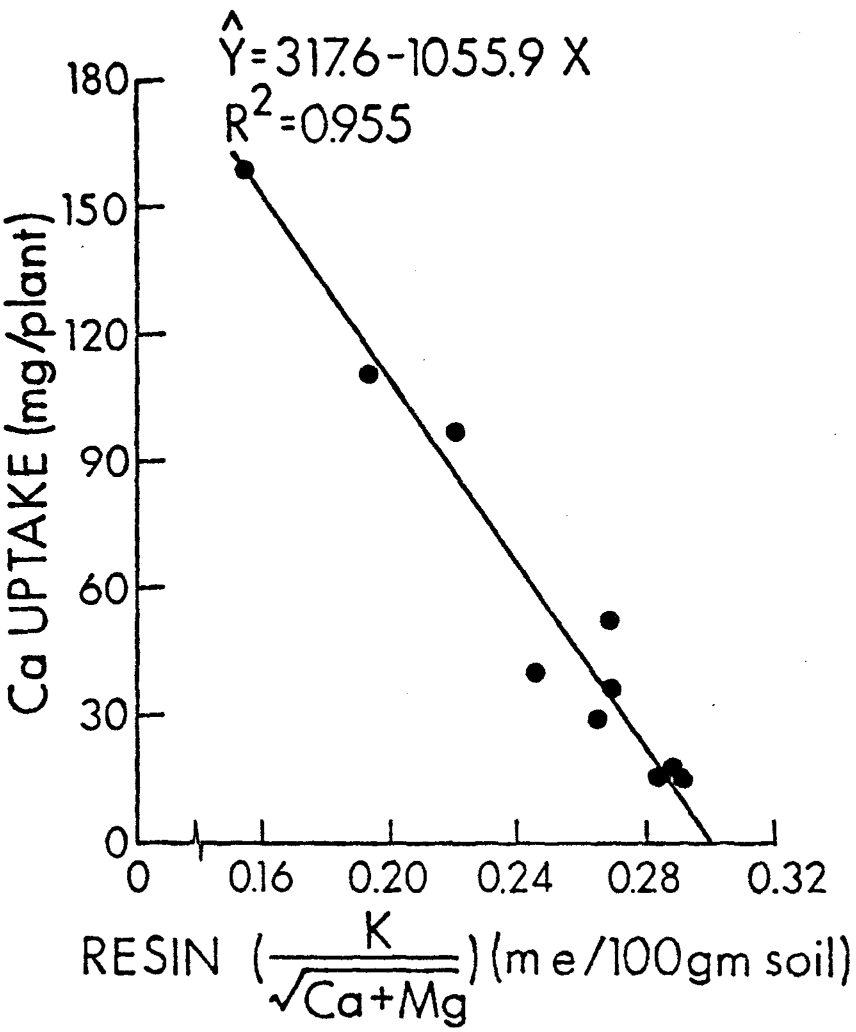

Figure 37. Relationship between Ca uptake by _Leucaena leucocephala_ and resin-extractable $(K/\sqrt{Ca + Mg})$ from Wahiawa soil.

Unlike Leucaena leucocephala, Ca uptake by Stylosanthes fruticosa was found to be dependent on the cation ratio ($\sqrt[3]{Al}/\sqrt{Cu}$), (Table 61, Appendix IV). This relationship is not unexpected because this legume is highly tolerant to Al and is not very responsive to lime treatment.

2. K uptake

The relationship in Figure 38 shows that K uptake by Leucaena leucocephala was also determined by the ($K/\sqrt{Ca + Mg}$) cation ratio. This, as already explained, is related to increased yield due to liming, K depletion and strong preference for Ca over K adsorption by the resin in the high lime treatment.

K uptake by Stylosanthes fruticosa as described by the regression equation in Table 61 (Appendix IV) was related to ($K/\sqrt[3]{Al}$). This suggests some type of interaction between K and Al in the uptake of K. S. fruticosa is not a high yielding legume and does not deplete soil K to the extent of L. leucocephala and the positive relation between resin K and K uptake is maintained.

3. Mn uptake

A major factor which affects Mn uptake by plants is soil pH. However, according to Figure 39 Mn uptake by Leucaena leucocephala was affected by K x Cu interaction. It is not understood whether this was an indirect effect of soil pH or not, but the work of Maas (1967) has shown that K and Cu interfere in the uptake of Mn by plants. Maas (1967) found that K markedly reduced Mn uptake by barley roots. Similarly, Cu was found, along with other polyvalent cations, to inhibit Mn adsorption by plants. In contrast, Mn uptake by Stylosanthes fruticosa appears to depend mostly on the ($K/\sqrt[3]{Al}$) ratio (Table 62, Appendix IV).

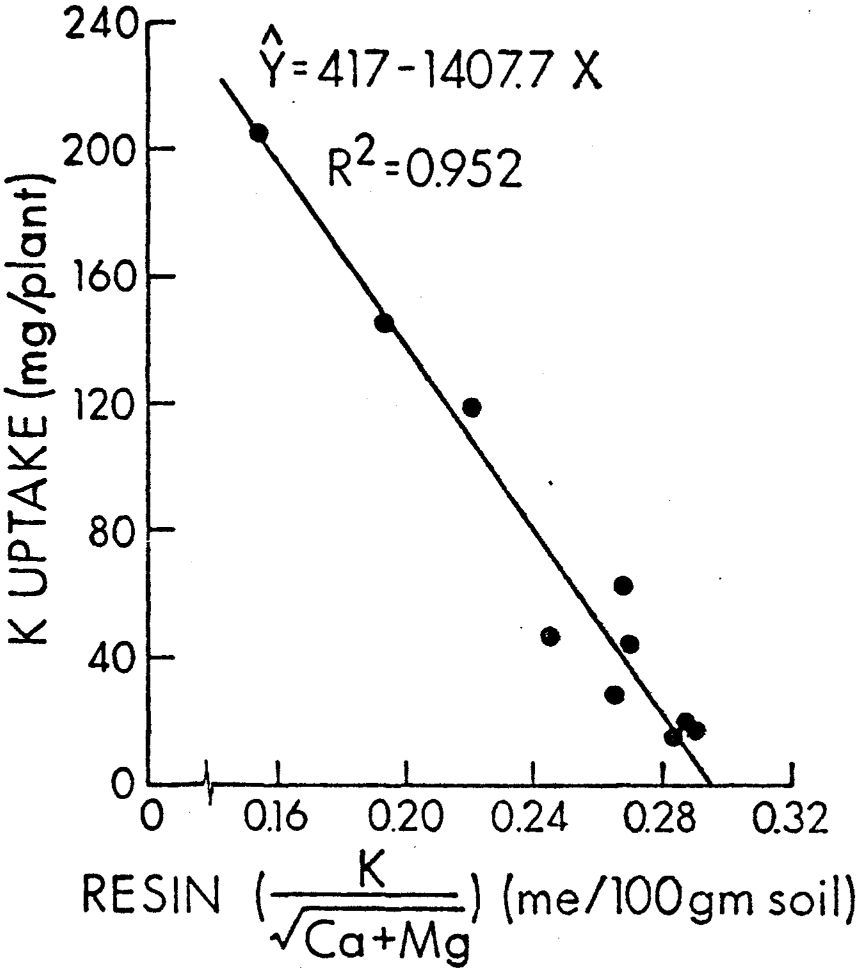

Figure 38. Relationship between K uptake by *Leucaena leucocephala* and resin-extractable $(K/\sqrt{Ca + Mg})$ from Wahiawa soil.

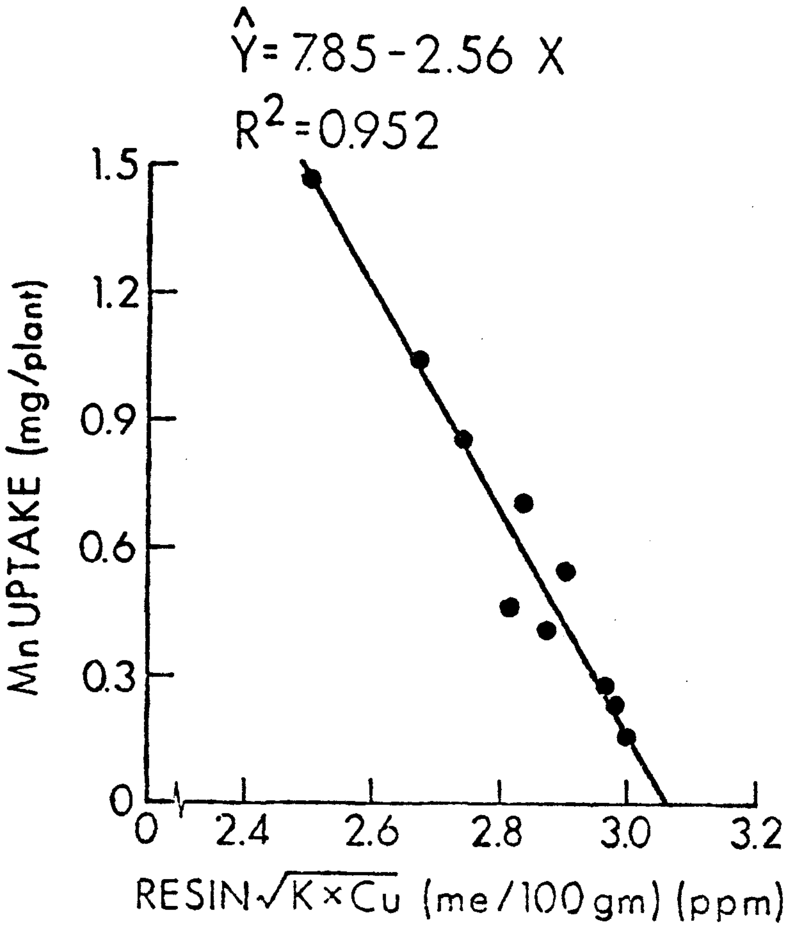

Figure 39. Relationship between Mn uptake by <u>Leucaena leucocephala</u> and resin-extractable ($\sqrt{K \times Cu}$) from Wahiawa soil.

Although the results with L. leucocephala and S. fruticosa are very preliminary, they illustrate the complex nature of nutrient uptake by plants. The results indicate that the uptake of a particular nutrient element depends as much on the concentration of other elements as it does on the concentration of the nutrient element under investigation. In addition these complex relations differ for different crops.

PREDICTION OF YIELD RESPONSE

A. Yield of sudax in relation to extraction methods.

The dry matter yield of sudax (*Sorghum bicolor* x *Sorghum sudanensis*) as predicted for the Halii soil by chemically extractable nutrients (with P included) is given in Table 44 (Appendix III) as follows:

$$\hat{Y} = 8.7 + 0.1\ P - 7.7\ \log_e K - 18.0\ Al$$

$$R^2 = 0.920$$

Extractable P alone accounts for 75% of the yield increase of sudax. A similar relationship holds for the Lualualei soil.

However, it is possible to relate yield response to nutrient cations[10] only. Figures 40 and 41 show that the yield of sudax in Halii soil can be adequately correlated to either resin or neutral normal ammonium acetate-extractable K and Ca, with a slightly better result with ammonium acetate. The yield of sudax in Halii soil is better described by the following equations for the two extraction methods (Table 42, Appendix III).

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[10] Since P extraction by anion exchange resin was not very successful.

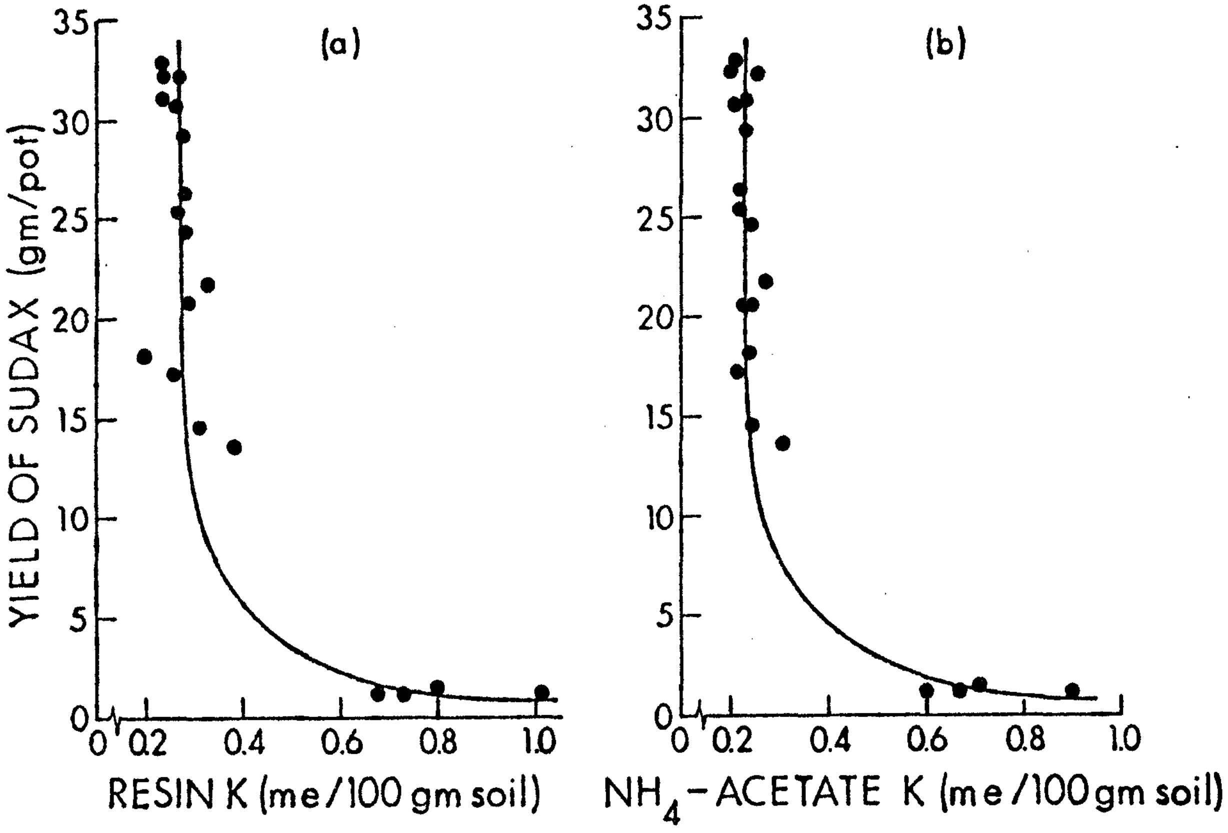

Figure 40. Relationship between the yield of sudax and K extracted by (a) cation exchange resin and (b) 1N ammonium acetate from Halii soil.

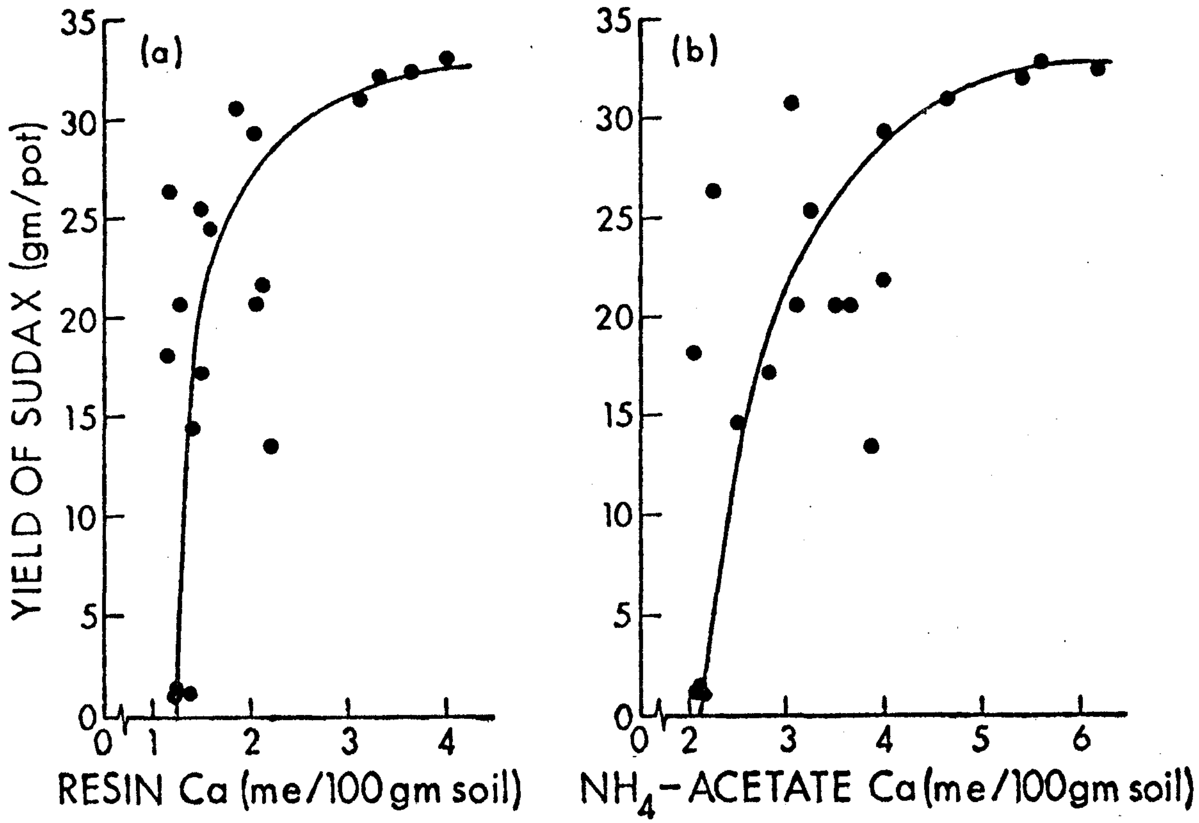

Figure 41. Relationship between the yield of sudax and Ca extracted by (a) cation exchange resin and (b) 1N ammonium acetate from Halii soil.

Resin:

$$\hat{Y} = 39.6 + 3.1(1/K) + 104.6\left(\frac{\sqrt{Ca}}{\sqrt{Ca + Mg} + \sqrt[3]{Al}}\right) - 1.8Mn - 2.9(Ca/Mg)$$

$$R^2 = 0.904$$

Chemical:

1) with four variables in equation:

$$\hat{Y} = -8.7 - 20.3Al + 3.2(1/K) + 42.7\left(\frac{\sqrt{Ca}}{\sqrt{Ca + Mg} + \sqrt[3]{Al}}\right) + 0.1\ (Mg \times Ca)$$

$$R^2 = 0.877$$

2) with five variables in equation:

$$\hat{Y} = -29.4 - 43.4Al + 2.9\ (1/K) + 4.9\left(\frac{\sqrt{Ca}}{\sqrt{Ca + Mg} + \sqrt[3]{Al}}\right)$$

$$+ 0.4(Mg \times Ca) + 91.7\ (\sqrt[3]{Al}/\sqrt{Ca + Mg})$$

$$R^2 = 0.904$$

The above comparison shows that even though the ammonium acetate method correlates better with yield than the ion exchange resin method when single elements are employed, the resin method is superior to ammonium acetate in a multiple regression analysis. The ability of multiple regression analysis to describe yield with a high degree of precision, even when the most limiting nutrient (in this case P) is not considered, is the result of an indirect relationship between the primary causative factor and factors of secondary importance in yield response.

B. Yields of tropical and temperate legumes in relation to resin-extractable cations.

The yields of tropical and temperate legumes are given in Table 55 (Appendix IV) in the order of increasing lime treatment. These results show that legumes like other plant species (Palazzo and Duell, 1974) vary in their response to lime treatments. Andrew and Norris (1961), and Munns and Fox (1976) studied the relative responses of tropical and temperate legumes to lime treatments. They found that tropical legumes are just as responsive to lime as temperate legumes.

Leucaena leucocephala is a tropical legume which is very responsive to lime. According to Table 64 (Appendix IV), the yield of this crop can be predicted by the following equation:

$$\hat{Y} = -1.64 + 0.25\text{pH}^2 - 1.51\text{Fe} + 1.73\sqrt{\text{Ca}}$$

$$R^2 = 0.708$$

The effect of lime application is to raise pH, lower soluble Al and Mn and increase exchangeable Ca. L. leucocephala responds to all variables.

In contrast, Stylosanthes fruticosa is a tropical legume which thrives under acid soil conditions. It did not respond to lime treatment, and in fact, yields were depressed by liming as shown by the yield equation:

$$\hat{Y} = -7652.7 + 6.1\text{Zn} - 84.2\text{pH}^2 + 4522.4\sqrt{\text{pH}} + 16.6(\text{Al} \times \text{Ca}) - 231.8\sqrt{\text{Mg}} + 0.7\text{Mn}$$

$$R^2 = 0.605$$

Resin-extractable Zn, probably pH dependent, appears to affect yield most. Also, yield was inversely related to soil pH (Table 64, Appendix IV). Andrew and Norris (1961), and Munns and Fox (1976) reported the depression of yields of stylosanthes species by liming. The cause of this may be explained from the results of a recent study conducted at CIAT[11] which showed that certain stylosanthes species thrive in high Al

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[11] Centro Internacio de Agricultura Tropical, Cali, Columbia.

environment.

EXTRACTIONS WITH SINGLE AND MULTIPLE RESIN DISCS

The initial extraction procedure was based on three resin discs in order to have a sufficient soil sample size. Any number of discs greater than three was considered too cumbersome and too time consuming. Later, in order to further reduce the time involved in cell assemblage, two and one resin disc-cell combinations were tested, maintaining the same resin-soil ratio.

The results given in Tables 48, 49 and 50 (Appendix IV) show that the quantity of each cation extracted differed for each resin-cell combination. In general, extractions with one resin disc had higher concentrations than extractions with two or three resin discs. This appears to be an effect of the soil sample size and not the resin and suggests that the chances for error are greater with a 1gm sample than with 2 or 3 gm sample. These differences are confirmed by an analysis of variance test (Table 53) and a modified Duncan's (Bayesian) Least Significant Difference test (Table 54) in Appendix IV. Table 54 further shows that for Mg extraction there was no significant difference between all three resin-cell combinations. Similarly, there was no significant difference between two and three resin-cell combinations for Ca and Zn. Multiple regression analysis summarized in Table 65 (Appendix IV) shows that the regression equations describing nutrient uptake by plant in relation to the number of resin discs used differ even though the R^2's are similar.

IMPLICATIONS FOR SOIL TESTING PROGRAMS

The objective of any extraction procedure in soil testing is to remove a fraction of the soil nutrient pool, which correlates with yield and uptake by plant. Most conventional soil testing procedures fulfil this requirement but do not provide information on the interaction of various soil nutrients in the root environment.

Ion exchange resin extraction of a particular nutrient depends on the concentration of other nutrients in the soil as much as it does on the concentration of the nutrient being measured. As a result it is selective, in contrast to the non-selectivity of ammonium acetate which tends to extract all elements that are present as exchangeable ions in the soil. There is good reason to believe that plant response to soil fertilization depends to a large extent on the interaction of soil nutrients. The ion exchange resin method offers an opportunity to study interaction among nutrients and to relate yield response and nutrient uptake to such interactions.

The combined ion exchange resin and x-ray fluorescence method employed in this study has the capacity to analyze as many as 23 elements simultaneously. This unique advantage simplifies sample preparation and shortens the time involved in sample analysis. Moreover, during analysis by x-ray fluorescence spectrometry samples are not consumed and as a result can be stored for re-analysis in the future. This new method can be only as accurate as the chemical method since it relies on calibration standards prepared by the chemical method although it has a much greater precision.

The major disadvantage of the ion exchange resin procedure for soil testing is the need for a costly multichannel analyzer. However, simultaneous analysis of nutrient elements in plant tissue and soil is indispensible for making sound fertilizer and soil management recommendations. But much remains to be done before resin extraction methods can be used on a routine basis.

SUMMARY AND CONCLUSION

A method of soil analysis based on ion exchange resin extraction and x-ray fluorescence analysis of soil nutrients was examined. Sample preparation involved shaking soil and ion exchange resin membrane (3.5 cm diameter) sandwiched between permeable paper discs in a specially designed extraction cell, and freeze-drying the resin discs. By this method all major plant nutrients except B and N, were determined.

To determine optimum conditions for a routine extraction procedure, the effects of soil sample size, soil-water ratio and equilibration time on ion uptake by resin were tested. The results showed that the adsorption of a nutrient by resin was affected by all three factors. For practical reasons, a shaking time of 36 hours, a sample size of 3 gm and a soil-water ratio of 1:3 were selected for routine extraction of cations. Similarly, a shaking time of 48 hours, a sample size of 3 gm and a soil-water ratio of 1:5 were selected for anion extraction.

Using soil samples from a greenhouse pot experiment, ion exchange resin and 1N ammonium acetate extraction methods were compared. These comparisons showed that the degree of correlation between the two methods for a particular nutrient depended on the quantity of the nutrient in the soil. This relationship was explained by reference to the selective adsorption of nutrients by ion exchange resins and the non-selective extraction by 1N ammonium acetate. By means of a multiple regression analysis cations adsorbed by ion exchange resin were found to be superior to those extracted by 1N ammonium acetate in predicting yield response. In a field experiment to study the relative response of tropical and temperate legumes to lime treatment, legume yields were adequately predicted by ion exchange resin-extractable cations.

Based on the results of this study the following conclusions are made:

1) The combined ion exchange resin-x-ray fluorescence approach is a sensitive method for estimating plant nutrients in soil.
2) The quantity of a particular nutrient extracted from soil depends on the nature of the extractant used and the quantity of the nutrient in the soil. The degree of correlation between ion exchange resin and ammonium acetate extraction depends, in addition on the quantity of ions other than the one in question.
3) In general, ion exchange resin-extracted cations correlate better with uptake and yield than 1N ammonium acetate-extracted cations.
4) Ion exchange resin extracts trace elements which frequently contribute significantly to the prediction of yield response.

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APPENDIX I

Cation and Anion Resin Standards

Table 1. Summary of Multiple Linear Regression Analysis of Cation Standards.

Cations	Independent Variables in Multiple Regression Equation						
	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Al	0.04668	0.43623 Al	0.980				
Mg	-0.00683	0.36614 Mg	0.968				
Ca	-0.06973	1.32896 Ca	0.992				
K	0.04019	0.36783 K	0.981				
Mn	0.03993	0.68758 Mn	0.939	0.41516 Mn x Fe	0.959	-0.38824 Mn x Cu	0.976
Fe	0.00432	0.56087 Fe	0.945				
Cu	0.01122	0.42644 Cu	0.949	0.25860 Cu x Fe	0.961	-0.49386 Cu x Mn	0.983
Zn	0.00207	0.49834 Zn	0.943	0.29838 Zn x Fe	0.957	-0.31698 Zn x Cu	0.981

Table 2. Summary of Multiple Linear Regression Analysis of Anion Standards.

	Variables in Multiple Regression Equation						
Anions	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Si	-0.00609	0.09805 Si	0.893	-0.02732 Si x S	0.959	-0.01240 Si x P	0.971
P	0.00015	0.04463 P	0.939	-0.00570 P x S	0.959		
S	0.00198	0.20897 S	0.950	-0.04996 S x Si	0.975		

APPENDIX II

Soil Extraction Data for Determining Soil Mass, Soil-Water Ratio and Equilibration Time.

Table 3. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Lualualei Soil.

Equil. Time	Soil Wt.	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm)	(m.e./3 resin discs)[1]				(µg/3 resin discs)			
12	2	0.043	0.575	0.468	0.0	208	34	63	15
	4	0.069	0.748	0.601	0.0	147	27	60	11
	6	0.079	0.794	0.675	0.0	130	27	61	11
	8	0.084	0.822	0.680	0.0	118	26	59	8
	10	0.090	0.818	0.668	0.0	118	29	61	10
24	2	0.039	0.633	0.543	0.0	292	26	54	8
	4	0.051	0.843	0.748	0.0	195	19	55	6
	6	0.053	0.936	0.872	0.0	176	18	54	5
	8	0.059	0.973	0.889	0.0	136	16	53	3
	10	0.043	0.992	0.940	0.0	110	17	52	3
36	2	0.039	0.695	0.060	0.0	512	40	63	16
	4	0.045	0.915	0.841	0.0	332	28	58	9
	6	0.031	0.922	0.963	0.0	201	18	57	6
	8	0.035	0.968	0.987	0.0	174	17	57	8
	10	0.034	0.981	1.007	0.0	150	17	56	5
48	2	0.037	0.613	0.560	0.0	568	36	63	9
	4	0.045	0.867	0.816	0.0	344	20	56	1
	6	0.044	0.950	0.919	0.0	230	17	56	0
	8	0.031	0.935	1.028	0.0	233	15	56	0
	10	0.030	0.906	1.107	0.0	195	15	54	0
60	2	0.032	0.668	0.602	0.0	649	46	65	8
	4	0.031	0.827	0.882	0.0	421	41	59	2
	6	0.033	0.886	0.958	0.0	250	41	59	1
	8	0.031	0.893	1.036	0.0	206	39	58	0
	10	0.033	0.924	1.039	0.0	143	37	56	0
72	2	0.033	0.651	0.588	0.0	662	40	61	5
	4	0.035	0.946	0.878	0.0	415	38	56	0
	6	0.035	0.902	0.977	0.0	237	35	55	0
	8	0.035	0.940	0.995	0.0	172	35	53	0
	10	0.034	0.938	1.033	0.0	176	34	54	0

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 4. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Wahiawa Soil.

Equil. Time (hrs)	Soil Wt. (gm)	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
		(m.e./3 resin discs)[1]				(µg/3 resin discs)			
12	2	0.018	0.032	0.166	0.028	171	39	73	43
	4	0.029	0.060	0.266	0.022	154	35	71	42
	6	0.035	0.072	0.304	0.028	137	36	69	34
	8	0.036	0.074	0.319	0.019	137	38	70	38
	10	0.044	0.095	0.360	0.023	133	31	68	36
24	2	0.018	0.024	0.180	0.042	355	41	78	66
	4	0.032	0.073	0.340	0.036	352	41	77	83
	6	0.042	0.086	0.422	0.022	298	39	74	86
	8	0.052	0.105	0.483	0.016	249	41	72	73
	10	0.058	0.113	0.511	0.011	217	41	72	67
36	2	0.018	0.031	0.188	0.073	416	40	82	74
	4	0.031	0.072	0.346	0.072	441	42	82	82
	6	0.044	0.098	0.453	0.043	317	44	82	95
	8	0.054	0.120	0.522	0.041	284	42	82	87
	10	0.064	0.138	0.571	0.038	268	41	82	83
48	2	0.019	0.033	0.189	0.113	859	42	82	101
	4	0.030	0.070	0.347	0.113	784	36	84	153
	6	0.045	0.114	0.502	0.083	623	41	82	156
	8	0.056	0.139	0.600	0.063	534	35	81	152
	10	0.058	0.137	0.615	0.044	436	42	80	122
60	2	0.018	0.030	0.186	0.136	910	41	85	95
	4	0.029	0.067	0.344	0.133	931	39	85	157
	6	0.041	0.095	0.477	0.102	807	39	83	180
	8	0.054	0.125	0.580	0.054	622	39	81	160
	10	0.065	0.130	0.675	0.031	497	38	74	133
72	2	0.017	0.028	0.187	0.197	994	42	88	106
	4	0.026	0.067	0.352	0.219	1025	40	92	175
	6	0.039	0.097	0.497	0.168	1005	39	85	204
	8	0.052	0.133	0.627	0.133	864	39	83	207
	10	0.066	0.163	0.706	0.096	783	39	82	209

[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 5. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Waimea Soil.

Equil. Time	Soil Wt.	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm)	(m.e./3 resin discs)[1]				(μg/3 resin discs)			
12	2	0.156	0.287	0.978	0.000	122	16	51	3
	4	0.214	0.383	1.082	0.000	85	16	49	1
	6	0.236	0.428	1.150	0.000	85	15	47	0
	8	0.260	0.432	1.165	0.000	85	15	46	0
	10	0.263	0.433	1.163	0.000	85	15	46	0
24	2	0.141	0.288	1.036	0.049	183	18	54	2
	4	0.186	0.377	1.121	0.006	106	24	54	0
	6	0.192	0.448	1.292	0.006	99	15	47	0
	8	0.194	0.474	1.340	0.009	95	15	47	0
	10	0.168	0.498	1.377	0.004	95	15	46	0
36	2	0.125	0.270	1.037	0.092	260	22	53	6
	4	0.180	0.396	1.280	0.016	142	17	50	0
	6	0.129	0.468	1.401	0.014	101	15	47	0
	8	0.120	0.490	1.466	0.003	87	15	46	0
	10	0.111	0.493	1.493	0.002	87	15	46	0
48	2	0.121	0.253	1.022	0.042	285	23	57	0
	4	0.113	0.361	1.314	0.004	127	14	52	0
	6	0.116	0.394	1.413	0.006	97	13	51	0
	8	0.110	0.403	1.512	0.000	85	10	49	0
	10	0.108	0.423	1.536	0.003	85	8	50	0
60	2	0.105	0.248	1.032	0.081	376	42	60	4
	4	0.120	0.363	1.332	0.000	178	37	56	0
	6	0.121	0.418	1.350	0.000	110	35	54	0
	8	0.125	0.472	1.384	0.000	100	37	54	0
	10	0.118	0.482	1.480	0.000	97	36	54	0
72	2	0.105	0.243	1.035	0.079	396	38	58	0
	4	0.130	0.363	1.286	0.000	167	32	53	0
	6	0.122	0.422	1.396	0.000	145	29	52	0
	8	0.117	0.451	1.411	0.000	132	26	50	0
	10	0.115	0.442	1.503	0.000	129	26	50	0

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 6. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Paaloa Soil.

Equil. Time	Soil Wt.	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm)	(m.e./3 resin discs)[1]				(μg/3 resin discs)			
12	2	0.010	0.019	0.049	0.028	86	55	68	21
	4	0.012	0.046	0.089	0.031	86	56	69	24
	6	0.016	0.076	0.120	0.038	92	54	69	25
	8	0.019	0.091	0.134	0.029	93	50	69	25
	10	0.022	0.103	0.145	0.028	94	52	70	25
24	2	0.011	0.020	0.052	0.056	86	64	70	22
	4	0.013	0.045	0.100	0.080	87	60	70	27
	6	0.016	0.076	0.140	0.070	90	57	69	29
	8	0.019	0.099	0.175	0.067	97	56	70	31
	10	0.022	0.122	0.191	0.050	99	55	69	33
36	2	0.010	0.013	0.050	0.048	86	62	71	24
	4	0.013	0.013	0.103	0.094	89	63	70	28
	6	0.015	0.061	0.147	0.103	97	62	69	34
	8	0.018	0.078	0.173	0.080	102	60	69	34
	10	0.022	0.098	0.208	0.067	107	61	70	37
48	2	0.010	0.024	0.056	0.112	86	86	68	29
	4	0.012	0.053	0.109	0.164	88	83	70	38
	6	0.014	0.077	0.152	0.166	89	80	69	44
	8	0.017	0.097	0.186	0.156	94	80	68	48
	10	0.019	0.121	0.224	0.158	98	74	70	55
60	2	0.007	0.030	0.051	0.156	120	60	35	12
	4	0.010	0.064	0.113	0.215	126	60	36	15
	6	0.013	0.090	0.168	0.206	134	51	37	21
	8	0.015	0.119	0.203	0.189	136	48	33	21
	10	0.018	0.147	0.264	0.195	138	43	34	28
72	2	0.006	0.031	0.052	0.151	125	67	37	11
	4	0.009	0.061	0.110	0.225	134	69	38	13
	6	0.012	0.089	0.163	0.220	136	65	35	19
	8	0.015	0.128	0.216	0.210	120	40	30	16
	10	0.017	0.143	0.263	0.211	145	54	36	32

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 7. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Halii Soil.

Equil. Time	Soil Wt.	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm)	(m.e./3 resin discs)[1]				(µg/3 resin discs)			
12	2	0.008	0.018	0.031	0.383	86	51	71	36
	4	0.009	0.033	0.051	0.464	96	51	72	56
	6	0.009	0.060	0.067	0.510	108	47	70	69
	8	0.010	0.088	0.082	0.559	122	47	70	79
	10	0.011	0.097	0.091	0.541	131	49	72	86
24	2	0.008	0.008	0.024	0.392	86	48	71	35
	4	0.008	0.032	0.042	0.566	90	54	73	54
	6	0.008	0.053	0.063	0.707	101	51	71	69
	8	0.008	0.073	0.080	0.744	115	53	74	82
	10	0.007	0.094	0.093	0.841	127	46	72	98
36	2	0.008	0.014	0.024	0.447	86	54	72	39
	4	0.008	0.033	0.048	0.731	99	51	71	59
	6	0.007	0.053	0.066	0.880	113	57	71	79
	8	0.006	0.074	0.086	0.963	122	49	70	91
	10	0.006	0.088	0.100	0.976	138	52	72	111
48	2	0.008	0.006	0.022	0.436	86	60	73	36
	4	0.008	0.028	0.044	0.716	95	53	72	58
	6	0.007	0.062	0.070	0.961	111	53	73	80
	8	0.007	0.073	0.081	0.891	121	53	73	91
	10	0.006	0.082	0.096	1.023	134	54	72	108
60	2	0.006	0.023	0.016	0.586	110	48	37	26
	4	0.007	0.041	0.037	0.900	116	50	37	49
	6	0.008	0.066	0.060	1.157	132	53	35	68
	8	0.009	0.081	0.078	1.219	158	64	35	88
	10	0.007	0.076	0.087	1.312	189	45	35	84
72	2	0.006	0.023	0.016	0.581	119	58	37	21
	4	0.007	0.043	0.038	0.912	135	65	37	45
	6	0.009	0.058	0.058	1.266	151	68	37	69
	8	0.008	0.073	0.072	1.290	180	64	37	84
	10	0.007	0.064	0.082	1.401	195	57	36	75

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 8. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Cations from Hilo Soil.

Equil. Time	Soil Wt.	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm)	(m.e./3 resin discs)[1]				(μg/3 resin discs)			
12	2	0.009	0.000	0.008	0.145	89	51	72	19
	4	0.010	0.001	0.016	0.156	90	50	73	18
	6	0.011	0.011	0.022	0.142	96	52	75	21
	8	0.012	0.018	0.031	0.134	94	58	72	19
	10	0.013	0.025	0.034	0.129	99	53	72	19
24	2	0.009	0.000	0.006	0.179	94	59	75	18
	4	0.010	0.001	0.015	0.198	97	57	75	19
	6	0.011	0.010	0.025	0.191	101	59	76	20
	8	0.012	0.018	0.031	0.172	100	58	75	20
	10	0.012	0.022	0.036	0.175	102	57	73	17
36	2	0.009	0.000	0.009	0.220	97	60	75	18
	4	0.010	0.000	0.016	0.261	103	58	74	17
	6	0.011	0.008	0.027	0.260	113	62	75	21
	8	0.012	0.016	0.034	0.246	117	60	76	20
	10	0.013	0.025	0.041	0.254	121	60	77	21
48	2	0.009	0.000	0.011	0.292	122	65	76	20
	4	0.009	0.002	0.018	0.313	138	63	75	20
	6	0.010	0.009	0.027	0.291	127	68	78	21
	8	0.012	0.015	0.037	0.290	124	60	76	18
	10	0.012	0.022	0.041	0.288	131	64	77	19
60	2	0.005	0.005	0.003	0.357	144	40	43	7
	4	0.007	0.011	0.013	0.404	147	27	41	6
	6	0.008	0.020	0.022	0.390	145	30	38	6
	8	0.009	0.026	0.032	0.410	148	32	43	6
	10	0.010	0.036	0.042	0.392	150	30	37	6
72	2	0.005	0.004	0.003	0.367	148	40	40	6
	4	0.006	0.010	0.014	0.408	153	31	42	6
	6	0.007	0.020	0.024	0.420	147	35	42	7
	8	0.009	0.029	0.034	0.406	150	29	40	7
	10	0.010	0.036	0.041	0.400	152	33	40	6

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[1] 3 cation resin discs have a combined total exchange capacity of 2.1 milliequivalents.

Table 9. The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Lualualei Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	1.60	21.79	19.84	0.00	69.9	9.9	16.0	2.3
	1:3	1.66	18.27	16.19	0.00	44.9	10.0	16.0	2.6
	1:4	1.76	17.90	15.28	0.00	46.5	9.8	16.3	3.1
	1:5	1.90	18.10	15.06	0.00	41.9	10.7	17.5	3.7
	1:6	1.65	15.17	12.45	0.00	33.7	10.7	16.4	2.9
36	1:2	1.13	22.52	22.51	0.00	108.4	9.7	15.4	2.2
	1:3	1.68	21.42	19.54	0.00	89.2	10.0	15.9	2.6
	1:4	1.76	21.12	19.03	0.00	72.4	9.8	15.8	2.3
	1:5	1.81	20.46	18.08	0.00	65.4	9.9	16.8	3.1
	1:6	1.63	17.31	15.18	0.00	42.6	10.8	16.2	2.6
48	1:2	1.11	22.50	22.30	0.00	149.8	10.1	16.0	3.5
	1:3	1.52	21.60	20.19	0.00	118.0	10.2	16.2	2.7
	1:4	1.62	20.75	19.04	0.00	105.1	11.0	17.0	3.5
	1:5	1.78	19.85	17.23	0.00	85.6	10.5	17.1	3.1
	1:6	1.79	18.79	16.34	0.00	73.3	11.3	17.3	3.4

Table 10. The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Wahiawa Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	0.83	2.02	9.16	1.78	122.0	11.3	21.3	29.4
	1:3	0.83	2.10	9.10	1.22	93.6	11.2	19.7	23.4
	1:4	0.79	2.00	8.53	1.00	85.5	11.2	19.7	22.0
	1:5	0.84	1.98	8.93	0.78	79.3	11.2	19.6	21.1
	1:6	0.79	1.67	8.39	0.67	72.0	11.2	19.3	19.9
36	1:2	0.79	1.71	9.20	2.53	166.7	13.0	22.6	36.8
	1:3	0.83	1.81	9.23	2.05	151.2	12.9	22.5	34.7
	1:4	0.83	1.85	8.99	1.67	132.9	12.2	22.1	30.7
	1:5	0.86	1.96	9.25	1.47	126.0	12.7	22.1	31.2
	1:6	0.84	1.85	9.03	1.39	116.0	12.6	22.0	28.2
48	1:2	0.76	1.90	9.10	3.72	204.2	12.7	22.9	39.5
	1:3	0.77	1.83	9.01	3.25	177.5	12.7	22.6	36.8
	1:4	0.77	1.83	8.75	2.69	171.1	12.7	22.6	36.5
	1:5	0.78	1.85	9.04	2.61	159.8	12.3	22.6	35.0
	1:6	0.80	1.94	9.09	2.19	143.5	13.1	22.5	32.9

Table 11. The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Waimea Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	4.01	10.23	36.04	0.97	42.8	7.6	14.0	0.0
	1:3	5.92	9.92	31.63	0.58	35.3	7.6	14.1	0.6
	1:4	6.55	9.79	30.05	0.39	31.8	7.6	14.3	0.3
	1:5	6.42	9.71	27.65	0.36	29.5	7.7	14.8	0.9
	1:6	6.52	9.12	25.93	0.14	27.6	7.6	14.7	0.8
36	1:2	2.56	9.62	38.64	0.53	64.4	7.6	14.8	0.0
	1:3	3.48	10.67	36.41	0.47	55.9	7.9	14.4	0.0
	1:4	4.05	10.69	35.73	0.39	53.6	7.6	14.2	0.0
	1:5	3.77	10.44	35.08	0.33	51.0	8.1	15.0	0.0
	1:6	5.81	10.46	31.58	0.22	43.5	8.0	14.6	0.0
48	1:2	2.56	9.58	37.73	0.83	70.4	7.3	13.9	0.0
	1:3	2.80	10.21	36.79	0.64	59.4	7.6	14.2	0.0
	1:4	3.43	10.52	35.94	0.61	59.8	7.7	14.5	0.0
	1:5	4.38	10.56	34.51	0.44	52.9	7.7	14.4	0.0
	1:6	5.26	10.80	33.25	0.31	49.6	7.8	14.9	0.0

Table 12. The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Paaloa Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	0.25	1.73	2.71	2.56	29.9	3.9	7.9	1.2
	1:3	0.24	1.58	2.69	2.42	29.9	4.1	7.9	1.4
	1:4	0.24	1.54	2.59	2.50	29.9	3.2	7.9	1.4
	1:5	0.24	1.60	2.78	2.03	29.9	3.0	7.9	1.1
	1:6	0.24	1.64	2.50	2.10	29.9	3.0	7.9	1.1
36	1:2	0.23	1.52	2.71	3.78	29.9	4.9	7.9	1.2
	1:3	0.22	1.42	2.55	3.25	29.9	3.7	7.9	1.5
	1:4	0.23	1.46	2.53	3.22	29.9	3.2	7.9	1.6
	1:5	0.23	1.50	2.50	2.83	29.9	3.7	7.9	1.2
	1:6	0.23	1.50	2.59	2.36	29.9	3.5	7.9	1.5
48	1:2	0.24	1.50	2.78	3.78	29.9	5.6	7.9	1.4
	1:3	0.23	1.44	2.73	3.86	29.9	5.5	7.9	1.6
	1:4	0.23	1.54	2.74	3.42	29.9	4.9	7.9	1.5
	1:5	0.23	1.58	2.81	3.19	29.9	4.6	7.9	1.3
	1:6	0.23	1.52	2.60	3.00	29.9	3.9	7.9	1.4

Table 13: The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Halii Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	0.17	1.04	0.91	16.36	32.4	3.3	7.8	3.3
	1:3	0.17	1.10	1.00	16.19	32.4	3.0	7.9	6.8
	1:4	0.18	1.12	0.99	16.36	33.0	3.0	7.8	3.9
	1:5	0.19	1.12	0.95	15.81	33.0	3.0	7.9	5.2
	1:6	0.18	1.12	0.94	14.89	31.8	3.0	7.7	3.1
36	1:2	0.17	1.15	0.89	19.44	33.5	3.0	7.9	4.1
	1:3	0.17	1.02	0.85	18.94	32.3	3.1	7.7	3.2
	1:4	0.18	1.13	0.95	18.90	33.4	3.0	7.9	4.7
	1:5	0.18	1.06	0.98	18.19	33.5	3.1	7.8	4.4
	1:6	0.17	1.12	0.89	17.40	33.0	3.0	7.7	3.6
48	1:2	0.17	1.00	0.86	21.61	36.4	4.1	7.9	4.6
	1:3	0.17	1.10	0.90	20.97	35.2	3.7	7.8	4.7
	1:4	0.17	1.10	0.90	20.97	34.6	3.4	7.9	3.6
	1:5	0.17	1.02	0.91	20.00	34.1	3.2	7.9	4.3
	1:6	0.17	1.15	0.95	19.78	33.6	3.0	7.6	3.4

Table 14. The Effect of Equilibration Time and Soil-Water Ratio on Ion Exchange Resin Extraction of Cations from Hilo Soil.

Equil. Time	Ratio	K	Mg	Ca	Al	Mn	Fe	Cu	Zn
(hrs)	(gm/gm)	(m.e./100gm soil)				(ppm)			
24	1:2	0.16	0.32	0.33	7.60	29.9	3.0	7.9	0.0
	1:3	0.16	0.36	0.35	6.95	29.9	3.0	7.9	0.0
	1:4	0.16	0.31	0.33	7.42	29.9	3.0	7.9	0.0
	1:5	0.16	0.31	0.33	7.02	29.9	3.0	7.9	0.0
	1:6	0.15	0.33	0.33	6.56	29.9	3.0	7.9	0.0
36	1:2	0.16	0.34	0.30	7.83	30.1	3.2	7.9	0.0
	1:3	0.16	0.35	0.35	7.08	29.9	3.9	7.9	0.0
	1:4	0.16	0.34	0.33	7.52	29.9	3.1	7.9	0.0
	1:5	0.16	0.37	0.38	7.37	29.9	3.2	7.9	0.0
	1:6	0.15	0.34	0.30	6.82	29.9	3.2	7.9	0.0
48	1:2	0.16	0.26	0.30	9.77	29.9	3.1	7.9	0.0
	1:3	0.16	0.31	0.28	8.47	29.9	3.4	7.9	0.0
	1:4	0.16	0.34	0.40	8.57	29.9	4.2	7.9	0.0
	1:5	0.16	0.35	0.33	8.21	29.9	3.2	7.9	0.0
	1:6	0.16	0.31	0.33	7.82	29.9	3.0	7.9	0.0

Table 15: The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Anions.

Soil	Equil. Time (hrs)	Soil Wt. (gm)	Si	P	S
			(μg/ 3 resin discs)[1]		
Halii	12	2	0	0	223
		4	0	0	401
		6	0	4	360
		8	0	3	507
		10	1	4	551
	24	2	0	3	338
		4	4	8	357
		6	0	0	470
		8	3	10	537
		10	6	2	572
	36	2	7	4	228
		4	0	9	352
		6	7	7	397
		8	11	9	645
		10	13	5	577
	48	2	27	37	301
		4	19	28	354
		6	7	17	444
		8	9	26	571
		10	8	17	716
	60	2	19	23	359
		4	4	16	436
		6	20	19	520
		8	4	23	599
		10	7	42	873
	72	2	17	26	296
		4	12	11	416
		6	2	19	489
		8	9	28	614
		10	7	62	814

[1] 3 anion resin discs have a combined total exchange capacity of 1.4 milliequivalents.

Table 16. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Anions.

Soil	Equil. Time (hrs)	Soil Wt. (gm)	Si	P	S
			(μg/3 resin discs)[1]		
Lualualei	12	2	48	0	413
		4	72	0	389
		6	110	0	358
		8	122	0	379
		10	114	0	325
	24	2	84	0	439
		4	142	0	342
		6	149	0	451
		8	178	0	492
		10	161	0	585
	36	2	85	0	401
		4	171	0	391
		6	179	0	409
		8	163	0	587
		10	169	0	500
	48	2	150	0	401
		4	195	0	437
		6	250	0	278
		8	279	0	321
		10	234	0	350
	60	2	230	0	246
		4	265	0	279
		6	232	0	468
		8	236	0	374
		10	246	0	389
	72	2	201	6	316
		4	210	6	378
		6	228	5	484
		8	209	20	523
		10	220	0	540

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[1] 3 anion resin discs have a combined total exchange capacity of 1.4 milliequivalents.

Table 17. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Anions.

Soil	Equil. Time (hrs)	Soil Wt. (gm)	Si	P	S
			(μg/3 resin discs)[1]		
Waimea	12	2	0	0	160
		4	0	0	142
		6	11	0	265
		8	2	0	265
		10	3	0	322
	24	2	12	0	279
		4	12	0	299
		6	8	0	682
		8	0	0	332
		10	8	0	454
	36	2	6	0	198
		4	8	0	370
		6	14	0	565
		8	11	0	481
		10	5	0	618
	48	2	4	0	261
		4	2	0	294
		6	7	0	513
		8	3	0	287
		10	9	0	352
	60	2	3	0	192
		4	14	0	536
		6	21	0	535
		8	9	0	499
		10	11	0	666
	72	2	24	0	362
		4	21	0	364
		6	0	0	446
		8	5	0	421
		10	0	0	538

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[1] 3 anion resin discs have a combined total exchange capacity of 1.4 milliequivalents.

Table 18. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Anions.

Soil	Equil. Time (hrs)	Soil Wt. (gm)	Si	P	S
			(μg/3 resin discs)		
Wahiawa	12	2	0	0	229
		4	0	0	113
		6	0	0	200
		8	0	0	191
		10	0	0	214
	24	2	0	0	293
		4	0	0	458
		6	0	0	351
		8	0	0	287
		10	0	0	207
	36	2	0	0	323
		4	0	0	461
		6	0	0	327
		8	0	0	330
		10	0	0	742
	48	2	0	0	324
		4	0	0	114
		6	0	0	238
		8	0	0	369
		10	0	0	194
	60	2	0	0	322
		4	0	0	286
		6	0	0	485
		8	0	0	613
		10	0	0	539
	72	2	0	0	360
		4	0	0	409
		6	0	0	305
		8	0	0	414
		10	0	0	765

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[1] 3 anion resin discs have a combined total exchange capacity of 1.4 milliequivalents.

Table 19. The Effect of Equilibration Time and Soil Sample Size on Ion Exchange Resin Extraction of Anions.

Soil	Equil. Time (hrs)	Soil Wt. (gm)	Si	P	S
			(μg/3 resin discs)		
Paaloa	12	2	0	0	121
		4	0	0	190
		6	0	0	229
		8	0	0	319
		10	0	0	419
	24	2	0	0	293
		4	0	0	374
		6	0	0	681
		8	0	0	399
		10	0	0	449
	36	2	0	0	405
		4	0	0	428
		6	0	0	668
		8	0	0	514
		10	0	0	551
	48	2	0	0	219
		4	0	0	446
		6	0	0	406
		8	0	0	269
		10	0	0	514
	60	2	0	0	197
		4	0	0	614
		6	0	0	601
		8	0	0	765
		10	0	0	964
	72	2	0	0	343
		4	0	0	489
		6	0	0	868
		8	0	0	671
		10	0	0	993

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[1] 3 anion resin discs have a combined total exchange capacity of 1.4 milliequivalents.

Table 20. The Effect of Equilibration Time and Soil-Water Ratio on Anion Extraction by Ion Exchange Resin Using 4 gm Soil.

Soil	Equil. Time	Ratio	Si	P	S
	(hrs)	(gm/gm)	(μg/gm soil)		
Halii	24	1:2	0.0	1.8	143
		1:3	0.0	3.2	72
		1:4	0.0	1.5	68
		1:5	0.0	1.8	92
		1:6	0.0	1.5	54
	36	1:2	3.2	4.8	227
		1:3	1.2	2.5	85
		1:4	0.0	8.0	89
		1:5	2.0	6.5	82
		1:6	0.0	6.8	95
	48	1:2	4.0	6.2	240
		1:3	3.0	6.5	147
		1:4	0.0	3.5	95
		1:5	2.0	3.5	89
		1:6	0.0	7.5	112

Table 21. The Effect of Equilibration Time and Soil-Water Ratio on Anion Extraction by Ion Exchange Resin Using 4 gm Soil.

Soil	Equil. Time (hrs)	Ratio (gm/gm)	Si	P	S
			(μg/gm soil)		
Lualualei	24	1:2	25	0	80
		1:3	53	0	54
		1:4	31	0	87
		1:5	19	0	75
		1:6	37	0	59
	36	1:2	32	0	98
		1:3	37	0	103
		1:4	36	0	90
		1:5	33	0	72
		1:6	24	0	92
	48	1:2	44	0	110
		1:3	50	0	103
		1:4	49	0	103
		1:5	46	0	97
		1:6	37	0	88

Table 22. The Effect of Equilibration Time and Soil-Water Ratio on Anion Extraction by Ion Exchange Resin Using 4 gm Soil.

Soil	Equil. Time (hrs)	Ratio (gm/gm)	Si	P	S
			(μg/gm soil)		
Waimea	24	1:2	5.0	0.0	37
		1:3	6.2	0.0	13
		1:4	9.0	0.0	10
		1:5	4.5	0.0	37
		1:6	4.2	0.0	37
	36	1:2	1.0	0.0	83
		1:3	3.5	0.0	92
		1:4	1.2	0.0	87
		1:5	0.5	0.0	84
		1:6	4.5	0.0	93
	48	1:2	2.0	0.0	157
		1:3	0.8	0.0	113
		1:4	1.5	0.0	73
		1:5	2.2	0.0	86
		1:6	2.0	0.0	68

Table 23. The Effect of Equilibration Time and Soil-Water Ratio on Anion Extraction by Ion Exchange Resin Using 4 gm Soil.

Soil	Equil. Time (hrs)	Ratio (gm/gm)	Si	P	S
			(μg/gm soil)		
Wahiawa	24	1:2	0	0	179
		1:3	0	0	162
		1:4	0	0	55
		1:5	0	0	58
		1:6	0	0	105
	36	1:2	0	0	190
		1:3	0	0	87
		1:4	0	0	79
		1:5	0	0	82
		1:6	0	0	70
	48	1:2	0	0	117
		1:3	0	0	141
		1:4	0	0	89
		1:5	0	0	80
		1:6	0	0	85

Table 24. The Effect of Equilibration Time and Soil-Water Ratio on Anion Extraction by Ion Exchange Resin Using 4 gm Soil.

Soil	Equil. Time	Ratio	Si	P	S
	(hrs)	(gm/gm)	(μg/gm soil)		
Paaloa	24	1:2	0	0	149
		1:3	0	0	158
		1:4	0	0	105
		1:5	0	0	83
		1:6	0	0	67
	36	1:2	0	0	152
		1:3	0	0	101
		1:4	0	0	119
		1:5	0	0	82
		1:6	0	0	51
	48	1:2	0	0	130
		1:3	0	0	132
		1:4	0	0	155
		1:5	0	0	109
		1:6	0	0	89

APPENDIX III

Greenhouse Experiment: Soil, Yield and Plant Tissue Data and Multiple Linear Regression Analysis.

Table 25. Greenhouse Experiment: Cation Extraction from Halii Soil by NH_4-saturated Cation Exchange Resin. Rep. I

P applied		Mg	Al	K	Ca	Mn	Fe	Cu	Zn
Form[1]	kg/ha	m.e./100 gm				ppm			
FMP (cf)	0	0.91	1.44	0.66	1.08	45.6	4.5	10.0	7.7
	100	1.33	1.01	0.26	1.44	42.5	4.6	10.2	4.3
	300	1.54	0.97	0.33	1.53	42.2	5.1	10.0	2.7
	800	2.45	0.73	0.23	2.68	41.4	6.3	10.0	1.7
FMP (ns)	0	1.16	1.37	0.64	1.14	44.4	5.4	9.8	7.3
	100	1.69	1.28	0.64	2.36	48.0	4.3	9.7	2.0
	300	1.92	0.74	0.26	2.38	41.2	4.3	9.7	2.0
	800	3.14	0.64	0.25	2.61	39.6	4.3	8.7	1.4
FMP (ff)	0	1.18	1.61	1.17	1.15	46.0	5.7	9.5	5.9
	100	1.53	0.85	0.31	1.26	41.2	4.4	9.9	2.2
	300	2.06	0.85	0.31	2.05	41.4	4.8	9.7	1.7
	800	4.35	0.69	0.24	4.46	40.4	5.2	9.2	2.2
TSP	0	1.05	1.74	0.65	1.16	43.8	4.3	8.7	8.3
	100	0.89	0.99	0.31	0.89	40.0	4.3	9.1	1.8
	300	0.68	0.91	0.27	1.06	39.1	4.3	9.1	2.8
	800	0.87	0.94	0.27	1.94	39.0	4.1	9.2	3.2
TSP + Si	100	1.06	1.05	0.31	1.27	39.8	4.5	9.0	2.1
	300	0.96	0.95	0.35	2.06	38.7	4.3	8.7	1.8
	800	0.72	0.86	0.26	4.36	37.6	4.5	8.7	1.5
TSP + Mg	300	1.05	0.95	0.25	1.58	40.0	4.3	9.3	4.2

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[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 26. Greenhouse Experiment: Cation Extraction from Halii Soil by NH_4-saturated Cation Exchange Resin.

Rep. II

P applied		Mg	Al	K	Ca	Mn	Fe	Cu	Zn
Form[1]	kg/ha	m.e./100 gm				ppm			
FMP (cf)	0	1.15	1.33	0.65	1.06	44.8	5.5	9.5	5.8
	100	1.96	1.07	0.24	1.75	43.5	5.5	9.4	3.6
	300	1.49	0.72	0.25	1.66	41.5	5.3	9.4	1.7
	800	2.95	0.74	0.24	3.04	40.4	4.7	9.2	1.6
FMP (ns)	0	1.27	1.35	0.86	1.39	47.2	5.1	10.4	8.1
	100	1.92	0.98	0.29	2.03	44.2	4.5	9.5	3.8
	300	2.27	0.79	0.39	2.22	40.3	4.5	8.9	1.3
	800	4.44	0.62	0.32	4.30	41.1	4.3	8.8	1.7
FMP (ff)	0	1.60	1.07	1.45	1.62	46.8	4.4	9.2	6.6
	100	1.57	0.93	0.30	1.43	42.8	4.5	9.4	2.1
	300	2.45	0.82	0.29	2.15	41.7	4.7	9.2	1.5
	800	3.99	0.68	0.25	3.90	40.5	4.4	9.2	1.5
TSP	0	0.86	1.39	1.04	1.21	43.6	4.6	8.7	6.1
	100	1.21	1.04	0.27	1.37	40.9	5.8	9.5	4.2
	300	1.00	0.94	0.28	1.37	39.5	4.3	8.7	1.6
	800	0.77	0.93	0.26	1.92	38.7	4.3	8.9	1.8
TSP + Si	100	1.10	0.98	0.27	1.28	40.0	4.3	8.9	2.0
	300	0.82	0.79	0.24	1.89	38.5	4.4	8.6	1.3
	800	0.52	0.91	0.24	3.17	37.4	4.3	8.6	1.3
TSP + Mg	300	1.15	0.95	0.26	1.44	39.6	4.3	9.3	2.2

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[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 27. Greenhouse Experiment: Cation Extraction from Halii Soil by NH_4-saturated Cation Exchange Resin. Rep. III

P Applied		Mg	Al	K	Ca	Mn	Fe	Cu	Zn
Form[1]	kg/ha	(m.e./100 gm)				(ppm)			
FMP (cf)	0	1.47	1.70	0.73	1.68	46.2	4.5	9.8	11.6
	100	1.53	1.17	0.28	1.23	41.5	5.0	9.5	1.6
	300	1.61	0.75	0.27	1.66	39.1	4.3	8.7	1.3
	800	3.38	0.68	0.26	3.59	40.7	4.5	8.9	1.7
FMP (ns)	0	1.26	1.76	0.68	1.41	45.7	5.3	10.2	10.9
	100	2.60	0.84	0.23	2.22	41.3	4.8	9.2	2.3
	300	1.89	1.06	0.35	1.81	45.1	4.3	9.1	3.5
	800	3.36	0.68	0.24	2.97	40.0	4.4	8.9	1.8
FMP (ff)	0	1.55	1.53	0.67	1.48	45.2	4.6	9.8	6.9
	100	1.50	0.87	0.32	1.50	42.6	5.3	9.7	3.4
	300	1.61	0.91	0.26	1.91	40.4	4.6	9.7	2.0
	800	3.72	0.68	0.24	3.58	37.9	4.3	8.8	1.7
TSP	0	1.42	1.51	0.72	1.49	43.4	4.3	9.7	7.7
	100	1.15	0.87	0.33	1.30	40.5	4.3	8.9	2.2
	300	1.04	1.11	0.29	1.09	39.4	4.7	9.9	2.2
	800	0.85	0.99	0.26	0.67	38.2	4.4	8.7	1.5
TSP + Si	100	1.22	0.85	0.28	1.33	38.9	4.3	8.7	1.6
	300	0.90	1.11	0.25	2.19	37.7	4.7	8.6	1.5
	800	0.54	0.77	0.22	3.47	37.5	4.3	8.3	1.4
TSP + Mg	300	1.74	0.93	0.31	1.49	40.3	4.4	9.4	2.1

[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 28. Greenhouse Experiment: Cation Extraction from Lualualei Soil by NH_4-saturated Cation Exchange Resin.

P applied		Mg	Al	K	Ca	Mn	Fe	Cu	Zn
Form[1]	kg/ha	m.e./100 gm				ppm			
Rep. I									
FMP	0	21.20	0.86	0.41	21.99	39.1	4.3	8.3	0.8
	50	20.66	0.85	0.18	21.75	38.8	4.2	8.3	0.9
	100	18.93	0.86	0.24	19.27	39.1	4.3	8.3	1.2
	200	19.30	0.71	0.18	20.03	38.0	3.8	8.3	1.2
TSP	0	20.23	0.84	0.26	21.29	38.9	4.3	8.3	1.0
	50	19.78	0.87	0.20	20.74	39.0	4.3	8.4	1.3
	100	20.76	0.84	0.22	20.96	37.9	4.3	8.3	0.8
	200	18.60	0.92	0.19	19.24	39.1	4.1	8.3	1.4
Rep. II									
FMP	0	18.99	0.79	0.27	20.03	38.2	4.2	8.3	1.2
	50	17.62	0.89	0.20	17.56	38.7	4.2	8.3	0.9
	100	20.56	0.96	0.23	21.20	38.8	3.9	8.3	1.3
	200	19.03	0.71	0.19	20.40	38.9	4.3	8.3	0.8
TSP	0	22.09	0.57	0.41	20.06	38.9	4.9	8.3	0.9
	50	18.17	0.93	0.23	20.59	39.6	4.2	8.4	1.3
	100	19.85	0.81	0.24	20.52	39.1	4.3	8.4	1.1
	200	20.30	0.73	0.19	21.22	39.9	4.3	8.3	1.1
Rep. III									
FMP	0	20.67	0.82	0.29	22.63	38.4	4.3	8.3	0.9
	50	18.33	0.96	0.23	18.55	38.7	4.2	8.3	1.2
	100	20.77	1.02	0.19	21.53	38.0	4.1	8.3	1.1
	200	18.92	0.71	0.29	19.21	38.3	4.1	8.3	0.4
TSP	0	20.86	0.92	0.33	22.11	38.3	4.1	8.3	0.6
	50	19.21	0.82	0.27	19.36	39.7	4.3	8.4	0.9
	100	19.14	0.69	0.21	20.20	38.9	4.3	8.4	0.7
	200	19.80	0.72	0.18	20.92	37.9	4.3	8.3	1.2

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[1] FMP = Fused Magnesium Phosphate; TSP = Treble Superphosphate

Table 29. Greenhouse Experiment: Cation Extraction from Lualualei Soil by H-saturated Cation Exchange Resin.

P applied		Mg	Al	K	Ca	Mn	Fe	Cu	Zn
Form[1]	kg/ha	m.e./100 gm				ppm			
Rep. I									
FMP	0	26.26	0.30	0.62	29.31	173.5	4.0	10.7	2.1
	50	25.16	0.01	0.31	26.99	124.4	3.9	10.6	1.5
	100	26.08	0.47	0.36	28.60	163.3	3.5	10.6	1.3
	200	27.44	0.46	0.24	30.50	125.0	4.0	10.6	1.7
TSP	0	27.76	0.11	0.34	30.81	154.7	0.3	8.7	0.0
	50	25.70	0.15	0.30	29.31	149.3	3.2	9.6	0.4
	100	25.25	0.23	0.35	27.55	128.0	2.1	8.7	0.0
	200	23.83	0.47	0.29	27.26	119.7	1.9	9.4	0.7
Rep. II									
FMP	0	26.37	0.06	0.41	28.01	121.2	4.0	10.2	2.0
	50	24.90	0.24	0.33	26.86	132.0	4.0	10.6	2.1
	100	25.56	0.14	0.40	26.82	149.3	3.9	10.6	2.1
	200	26.55	0.39	0.27	29.50	122.3	4.0	10.6	1.7
TSP	0	28.39	0.53	0.55	31.87	183.8	1.8	8.9	0.7
	50	25.37	0.26	0.36	27.81	131.4	3.4	9.4	0.4
	100	25.71	0.36	0.35	27.65	136.5	1.5	8.6	0.0
	200	24.79	0.28	0.30	27.82	173.4	3.3	9.1	0.0
Rep. III									
FMP	0	28.09	0.39	0.36	32.10	166.1	1.3	9.2	0.2
	50	25.46	0.31	0.35	27.44	124.4	0.8	8.9	0.6
	100	25.65	0.12	0.31	27.82	119.0	1.5	9.3	1.7
	200	26.25	0.36	0.44	29.13	121.5	1.3	9.5	1.3
TSP	0	27.04	0.02	0.49	29.64	110.7	0.0	7.6	0.0
	50	25.45	0.45	0.39	27.68	129.9	1.4	9.1	0.0
	100	25.58	0.35	0.32	29.22	133.8	2.2	9.4	0.0
	200	25.86	0.25	0.28	28.22	132.6	1.8	9.1	0.0

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[1] FMP = Fused Magnesium Phosphate; TSP = Treble Superphosphate

Table 30. Greenhouse Experiment: Anion Extraction from Lualualei Soil by Anion Exchange Resin.

	P Applied		Si	P	S
	Form[1]	kg/ha	(ppm)		
Rep. I	FMP	0	21.9	4.7	16.6
		50	28.9	6.2	13.7
		100	25.5	2.3	21.9
		200	50.6	7.7	5.7
	TSP	0	31.0	8.1	15.4
		50	30.7	2.5	0.0
		100	25.9	5.1	3.7
		200	41.4	9.7	16.5
Rep. II	FMP	0	16.4	2.7	0.0
		50	27.0	4.6	0.0
		100	29.9	6.6	10.1
		200	39.8	10.1	18.3
	TSP	0	24.9	2.8	7.2
		50	25.4	5.8	17.8
		100	26.1	4.2	0.0
		200	22.2	19.4	28.6
Rep. III	FMP	0	12.9	1.8	0.0
		50	25.9	3.2	0.0
		100	19.6	6.2	8.0
		200	21.2	13.5	26.3
	TSP	0	33.1	5.3	22.8
		50	20.9	1.0	0.0
		100	27.2	8.8	6.4
		200	33.2	9.8	0.0

[1] FMP = Fused Magnesium Phosphate; TSP = Treble Superphosphate.

Table 31. Greenhouse Experiment: Chemical Analysis of Halii Soil. Rep. I

P applied		pH 1:1	Al	Mg	K	Ca	P	Si	Mn	Fe	Cu	Zn
Form[1]	kg/ha	H_2O	m.e./100gm				ppm					
FMP (cf)	0	4.18	0.64	4.17	0.60	1.88	20	3.8	6.8	6.8	8.8	3.0
	100	4.93	0.45	4.69	0.21	2.81	55	3.3	7.3	7.5	8.5	4.3
	300	4.97	0.28	6.56	0.25	3.44	62	4.0	9.3	3.0	7.8	5.3
	800	5.53	0.21	7.29	0.22	3.69	136	8.3	10.0	2.5	6.8	3.3
FMP (ns)	0	4.23	0.52	3.13	0.60	1.88	25	4.5	7.8	8.8	6.5	4.5
	100	4.34	0.48	4.69	0.56	3.63	50	4.4	7.0	18.8	9.0	3.3
	300	5.10	0.33	6.25	0.21	4.25	60	3.9	8.8	5.0	8.3	4.0
	800	5.67	0.20	9.38	0.22	5.00	125	8.6	11.0	4.5	9.0	3.0
FMP (ff)	0	4.01	0.78	3.65	1.01	1.88	25	4.3	6.5	7.8	7.5	3.5
	100	4.95	0.42	4.38	0.24	2.63	35	2.7	6.5	6.3	9.8	6.0
	300	5.13	0.38	6.04	0.26	3.13	54	4.8	7.3	5.8	8.0	2.5
	800	5.85	0.18	6.25	0.19	5.94	115	2.5	10.8	2.0	8.8	4.5
TSP	0	4.07	0.72	3.33	0.55	1.88	15	3.8	5.0	8.5	9.3	3.8
	100	4.60	0.50	2.60	0.23	1.75	70	3.4	7.0	7.5	8.8	4.0
	300	4.86	0.36	3.13	0.19	2.00	80	2.7	7.0	4.5	7.3	2.5
	800	5.02	0.28	1.56	0.21	3.63	150	3.0	7.8	6.5	7.3	2.0
TSP + Si	100	5.02	0.30	2.60	0.24	2.81	82	3.3	9.3	4.5	6.5	1.5
	300	4.98	0.30	2.08	0.28	4.06	100	4.3	10.0	6.0	7.3	2.3
	800	5.35	0.27	1.04	0.22	6.38	145	5.9	10.3	8.8	7.3	2.0
TSP + Mg	300	4.73	0.43	3.13	0.20	3.44	70	2.7	11.0	5.5	7.5	2.8

[1] FMP = Fused Magnesium Phosphate; cf = coarse fraction (> 0.5mm); ns = normal size (unsegregated fraction); ff = fine fraction (< 0.5 mm); TSP = Treble Superphosphate.

Table 32. Greenhouse Experiment: Chemical Analysis of Halii Soil.
Rep. II

P applied		pH 1:1	Al	Mg	K	Ca	P	Si	Mn	Fe	Cu	Zn
Form[1]	kg/ha	H_2O	m.e./100gm				ppm					
FMP (cf)	0	4.60	0.48	5.21	0.56	2.19	20	3.7	7.5	6.5	10.0	3.0
	100	4.45	0.42	5.00	0.19	2.81	60	3.5	8.5	2.5	8.3	3.0
	300	5.11	0.26	6.35	0.21	3.75	68	3.9	9.3	4.0	8.0	4.3
	800	5.53	0.20	6.77	0.25	4.88	140	7.6	6.3	3.8	6.8	2.5
FMP	0	4.11	0.63	4.17	0.79	2.13	20	6.3	6.5	5.0	8.3	3.5
	100	4.75	0.34	4.17	0.22	4.06	55	3.0	9.8	6.5	9.3	5.0
	300	4.96	0.30	7.29	0.34	4.06	45	3.9	7.8	6.3	7.5	3.5
	800	5.40	0.18	7.81	0.30	5.94	130	7.6	9.3	3.8	7.8	2.5
FMP (ff)	0	4.28	0.64	4.17	1.90	2.38	22	3.4	7.8	8.0	7.5	3.5
	100	5.02	0.35	5.21	0.22	2.50	40	3.3	7.5	5.3	8.5	2.8
	300	5.02	0.20	6.25	0.24	3.25	56	4.4	8.0	5.0	8.8	3.3
	800	5.68	0.10	5.94	0.22	5.63	135	5.2	10.0	2.5	9.0	5.3
TSP	0	4.03	0.73	3.95	0.96	2.19	25	3.3	8.3	7.5	9.3	5.3
	100	4.63	0.52	2.40	0.22	2.25	55	2.6	6.8	7.5	8.8	4.0
	300	4.77	0.39	2.08	0.24	2.50	72	2.8	5.8	3.8	7.3	4.0
	800	5.02	0.30	4.06	0.21	2.08	148	3.0	13.5	5.5	7.5	2.5
TSP + Si	100	4.88	0.45	2.92	0.19	2.50	88	3.3	9.8	5.0	7.0	2.0
	300	5.16	0.30	2.29	0.19	3.75	115	3.8	10.3	7.5	7.0	3.0
	800	5.24	0.24	1.56	0.20	5.63	172	4.7	10.3	6.0	6.8	3.8
TSP + Mg	300	4.64	0.50	2.92	0.20	3.13	82	2.5	10.5	6.0	6.5	3.0

[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (> 0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (< 0.5mm); TSP = Treble Superphosphate.

Table 33. Greenhouse Experiment: Chemical Analysis of Halii Soil. Rep. III

P applied		pH 1:1	Al	Mg	K	Ca	P	Si	Mn	Fe	Cu	Zn
Form[1]	kg/ha	H_2O	m.e./100gm				ppm					
FMP (cf)	0	4.53	0.68	5.21	0.64	2.38	30	3.8	8.5	7.5	9.5	4.3
	100	5.06	0.31	5.73	0.23	2.88	54	3.3	8.3	3.5	8.0	3.5
	300	5.36	0.38	6.77	0.25	3.75	74	5.8	8.3	2.8	7.3	6.8
	800	5.57	0.25	10.41	0.22	5.31	145	9.6	10.5	4.0	7.3	3.0
FMP	0	4.07	0.80	3.65	0.61	2.19	25	3.4	5.0	10.0	7.5	4.3
	100	5.27	0.62	5.21	0.16	3.88	50	5.3	8.8	7.0	8.5	3.5
	300	4.45	0.38	6.56	0.27	3.75	70	3.4	10.5	5.5	9.0	2.5
	800	5.64	0.23	8.85	0.22	5.31	120	8.3	9.8	3.5	8.3	6.8
FMP (ff)	0	4.12	0.75	4.17	0.61	2.19	20	4.1	7.8	8.3	8.0	2.0
	100	4.90	0.42	5.00	0.25	2.50	52	3.3	7.0	5.3	8.5	3.0
	300	5.28	0.26	5.21	0.22	3.00	45	4.4	7.5	3.8	8.5	4.3
	800	5.72	0.10	6.77	0.21	5.25	110	6.2	8.0	3.8	10.0	5.5
TSP	0	4.11	0.77	3.75	0.61	2.19	22	3.4	8.5	7.0	9.0	5.5
	100	4.70	0.58	2.60	0.27	2.19	68	2.5	5.5	2.5	7.5	3.5
	300	4.95	0.50	2.60	0.27	2.19	68	2.6	8.5	3.8	7.3	2.5
	800	5.08	0.48	2.08	0.21	3.44	156	3.0	9.8	5.0	7.3	1.3
TSP + Si	100	4.90	0.44	2.50	0.23	5.25	70	3.2	11.5	5.5	6.5	2.5
	300	5.15	0.32	1.88	0.22	4.13	90	3.4	10.0	7.0	7.3	3.3
	800	5.18	0.30	0.52	0.19	6.57	165	4.4	11.8	6.5	7.3	3.3
TSP + Mg	300	4.89	0.36	3.65	0.25	3.25	75	3.1	10.0	5.8	7.3	2.3

[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 34. Greenhouse Experiment: Chemical Analysis of Lualualei Soil.

P Applied		pH 1:1	Mg	K	Ca	P[2]	P[3]	Si	Mn	Fe	Cu	Zn
Form[1]	kg/ha	H_2O	m.e./100gm			ppm						
Rep. I												
FMP	0	7.02	33.33	0.83	23.75	50	10	8.0	12.5	1.8	8.3	1.3
	50	7.61	35.42	0.35	23.13	55	15	6.6	11.0	1.0	7.5	1.8
	100	7.68	31.35	0.42	22.50	70	35	7.1	26.5	0.8	7.5	3.0
	200	7.88	32.81	0.30	24.25	110	60	6.6	11.3	1.0	8.0	2.5
TSP	0	7.43	33.33	0.47	23.75	45	12	7.6	8.8	2.0	8.0	2.3
	50	7.51	28.13	0.35	22.50	65	20	6.4	13.0	1.0	8.0	3.0
	100	7.48	25.52	0.39	22.13	80	42	6.4	10.0	2.0	7.3	3.0
	200	7.47	29.17	0.31	22.81	120	65	6.9	15.0	1.8	6.5	7.5
Rep. II												
FMP	0	7.33	31.25	0.45	23.13	45	15	7.1	9.5	1.0	7.3	2.0
	50	7.48	34.90	0.37	21.88	72	14	6.4	11.3	0.8	6.8	4.5
	100	7.64	32.40	0.44	21.88	75	40	7.1	24.0	1.5	8.3	3.3
	200	7.64	31.25	0.32	23.25	125	56	7.3	11.0	0.8	8.0	3.5
TSP	0	6.95	32.81	0.86	24.06	40	10	9.0	8.8	1.5	7.3	4.0
	50	7.53	30.21	0.41	22.81	74	18	5.7	10.8	1.3	7.0	2.3
	100	7.47	25.52	0.44	22.88	100	60	7.3	20.0	0.5	6.8	3.8
	200	7.39	30.21	0.36	23.56	110	60	7.1	41.3	2.5	7.5	4.3
Rep. III												
FMP	0	7.16	34.38	0.58	23.44	60	10	8.5	8.5	2.5	7.3	1.5
	50	7.55	34.38	0.42	23.13	64	20	6.9	12.3	0.8	7.5	3.0
	100	7.81	32.29	0.35	22.56	70	32	5.9	15.0	0.8	8.0	3.0
	200	7.61	33.33	0.33	23.38	115	55	7.1	12.3	0.5	8.0	2.3
TSP	0	7.27	31.25	0.63	23.44	62	10	9.7	8.3	8.3	2.5	7.5
	50	7.48	29.17	0.47	23.13	66	14	5.9	11.0	0.5	7.8	2.5
	100	7.54	26.04	0.39	22.25	84	45	6.4	15.0	1.3	7.5	3.8
	200	7.43	30.21	0.33	22.50	140	64	6.9	13.8	2.0	7.5	5.3

[1] FMP = Fused Magnesium Phosphate; TSP = Treble Superphosphate

[2] Modified Truog reagent extractable P.

[3] 0.5M $NaHCO_3$ extractable P.

Table 35. Greenhouse Experiment: Plant Tissue Analysis and Yield of Sudax Grown in Halii Soil.
Rep I.

P Applied		Yield	Mg	K	Ca	Si	P	S	Mn
Form[1]	kg/ha	(gm/pot)	percent						ppm
FMP (cf)	0	1.00	0.29	1.78	0.20	1.09	0.07	0.13	92
	100	16.00	0.50	1.85	0.30	0.93	0.10	0.09	76
	300	24.52	0.65	1.50	0.38	0.95	0.10	0.10	91
	800	31.70	0.78	1.06	0.45	1.15	0.12	0.10	81
FMP (ns)	0	1.06	0.29	1.56	0.22	1.19	0.06	0.15	105
	100	9.20	0.34	3.07	0.22	0.73	0.12	0.09	73
	300	24.14	0.62	1.53	0.38	0.96	0.09	0.09	101
	800	31.95	0.87	1.00	0.51	1.31	0.12	0.09	83
FMP (ff)	0	0.80	0.31	1.88	0.23	1.23	0.08	0.14	96
	100	15.25	0.63	2.09	0.35	0.97	0.13	0.11	120
	300	21.92	0.63	1.70	0.39	1.25	0.09	0.10	100
	800	32.70	0.89	0.94	0.52	1.33	0.12	0.09	88
TSP	0	1.20	0.32	1.71	0.23	0.98	0.06	0.13	103
	100	17.80	0.32	2.11	0.29	0.51	0.09	0.09	72
	300	32.10	0.47	1.06	0.43	0.39	0.10	0.08	79
	800	32.12	0.51	1.00	0.59	0.41	0.15	0.09	106
TSP + Si	100	22.00	0.40	1.49	0.41	0.52	0.08	0.07	74
	300	29.65	0.39	1.10	0.45	0.40	0.07	0.06	61
	800	34.10	0.51	1.18	0.85	0.76	0.17	0.11	99
TSP + Mg	300	27.35	0.53	1.45	0.37	0.40	0.11	0.09	96

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[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (> 0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (< 0.5mm); TSP = Treble Superphosphate.

Table 36. Greenhouse Experiment: Plant Tissue Analysis and Yield of Sudax Grown in Halii Soil.

Rep. II

P applied		Yield	Mg	K	Ca	Si	P	S	Mn
Form[1]	kg/ha	(gm/pot)	percent						ppm
FMP (cf)	0	1.10	0.30	1.42	0.16	1.23	0.06	0.14	64
	100	16.60	0.44	2.14	0.25	0.88	0.11	0.11	61
	300	22.58	0.58	1.59	0.34	0.82	0.10	0.09	79
	800	28.60	0.82	1.01	0.45	1.11	0.11	0.08	70
FMP (ns)	0	1.20	0.29	1.57	0.22	1.04	0.06	0.12	101
	100	17.10	0.42	2.29	0.23	0.81	0.11	0.10	71
	300	21.20	0.61	1.76	0.37	1.15	0.10	0.11	77
	800	33.65	0.81	1.01	0.48	1.16	0.12	0.08	75
FMP (ff)	0	1.05	0.30	1.17	0.17	1.16	0.06	0.14	61
	100	14.30	0.44	2.41	0.25	1.05	0.12	0.11	64
	300	17.80	0.47	1.96	0.30	0.99	0.09	0.07	60
	800	31.45	0.88	0.87	0.50	1.45	0.13	0.08	69
TSP	0	1.02	0.31	1.62	0.23	1.05	0.06	0.15	121
	100	19.10	0.32	1.85	0.24	0.54	0.08	0.09	53
	300	21.30	0.42	1.56	0.36	0.36	0.10	0.09	68
	800	30.40	0.50	1.25	0.58	0.38	0.17	0.11	87
TSP + Si	0	19.30	0.37	1.62	0.40	0.52	0.08	0.08	81
	100	28.90	0.47	1.18	0.54	0.55	0.10	0.08	69
	300	30.85	0.54	1.14	0.97	0.77	0.16	0.10	80
TSP + Mg	300	23.60	0.59	1.29	0.45	0.45	0.11	0.09	100

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[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 37. Greenhouse Experiment: Plant Tissue Analysis and Yield of Sudax Grown in Halii Soil.
Rep. III

P Applied		Yield	Mg	K	Ca	Si	P	S	Mn
Form[1]	kg/ha	(gm/pot)	percent						ppm
FMP (cf)	0	1.05	0.28	1.36	0.15	1.15	0.06	0.14	66
	100	18.02	0.55	1.83	0.30	0.87	0.12	0.10	62
	300	26.08	0.62	1.19	0.31	0.91	0.10	0.08	55
	800	32.40	0.75	0.89	0.44	0.97	0.11	0.08	62
FMP (ns)	0	1.00	0.31	1.62	0.19	1.24	0.07	0.15	75
	100	14.40	0.54	2.27	0.32	0.89	0.12	0.12	101
	300	19.72	0.48	1.75	0.28	0.75	0.10	0.08	67
	800	30.50	0.80	1.05	0.50	1.17	0.12	0.09	82
FMP (ff)	0	1.10	0.30	1.35	0.18	1.19	0.06	0.15	62
	100	14.00	0.60	2.26	0.30	1.15	0.14	0.12	75
	300	22.00	0.60	1.52	0.34	1.15	0.09	0.08	65
	800	34.10	0.84	0.85	0.52	1.26	0.11	0.08	69
TSP	0	1.20	0.29	1.69	0.16	1.26	0.06	0.16	61
	100	17.48	0.32	1.97	0.24	0.50	0.08	0.09	52
	300	25.52	0.43	1.35	0.39	0.37	0.10	0.09	65
	800	29.56	0.52	1.12	0.57	0.42	0.16	0.08	83
TSP + Si	100	20.42	0.45	1.77	0.43	0.69	0.10	0.09	61
	300	29.22	0.48	1.14	0.56	0.59	0.10	0.09	66
	800	31.92	0.51	1.14	0.85	0.67	0.16	0.10	75
TSP + Mg	300	25.30	0.60	1.27	0.42	0.51	0.11	0.09	70

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[1] FMP = Fused Magnesium Phosphate, cf = coarse fraction (>0.5mm), ns = normal size (unsegregated fraction), ff = fine fraction (<0.5mm); TSP = Treble Superphosphate.

Table 38. Greenhouse Experiment: Plant Tissue Analysis and Yield of Sudax Grown in Lualualei Soil

P Applied		Yield	Mg	K	Ca	Si	P	S	Mn
Form[1]	kg/ha	(gm/pot)	percent						ppm
Rep. I									
FMP	0	21.30	0.38	3.37	0.28	1.53	0.11	0.13	27
	50	31.30	0.56	2.92	0.36	1.52	0.15	0.13	38
	100	34.10	0.54	2.52	0.39	1.54	0.15	0.12	41
	200	37.52	0.60	2.52	0.40	1.45	0.18	0.12	41
TSP	0	18.90	0.41	3.54	0.32	1.72	0.12	0.15	30
	50	34.00	0.52	2.68	0.37	1.40	0.14	0.12	39
	100	39.88	0.55	2.44	0.39	1.29	0.14	0.12	43
	200	45.70	0.61	2.10	0.42	1.35	0.17	0.11	41
Rep. II									
FMP	0	21.95	0.45	3.46	0.30	1.69	0.13	0.13	31
	50	30.50	0.53	2.56	0.36	1.59	0.14	0.11	37
	100	32.70	0.59	2.86	0.41	1.55	0.17	0.13	44
	200	37.75	0.61	2.65	0.45	1.51	0.17	0.12	44
TSP	0	20.95	0.42	3.42	0.29	1.58	0.13	0.13	27
	50	32.25	0.51	2.81	0.39	1.60	0.14	0.13	38
	100	42.02	0.53	2.29	0.36	1.30	0.14	0.11	37
	200	38.60	0.66	2.45	0.47	1.40	0.18	0.12	55
Rep. III									
FMP	0	18.38	0.46	3.55	0.33	1.63	0.14	0.15	33
	50	22.90	0.49	3.39	0.36	1.43	0.16	0.16	46
	100	27.90	0.58	3.21	0.37	1.35	0.18	0.14	47
	200	37.22	0.59	2.46	0.44	1.40	0.17	0.12	46
TSP	0	16.00	0.41	3.51	0.31	1.64	0.13	0.13	30
	50	38.90	0.52	2.41	0.39	1.49	0.13	0.11	40
	100	38.65	0.56	2.42	0.42	1.38	0.14	0.12	48
	200	41.15	0.60	2.34	0.45	1.32	0.17	0.12	49

[1] FMP = Fused Magnesium Phosphate; TSP = Treble Superphosphate

Table 39: Analysis of Variance for Resin and Chemical Methods of Nutrient Extraction from Halii Soil.

Source of Variation	d.f.	Mg	K	Ca	Mn
		(Mean Squares)			
Replication	2	0.31	0.0414	0.008	1.28
Whole plot					
P source	2	42.92**	0.0063	10.009**	18.04**
P rate	3	1.04**	0.9985**	16.184**	5.85*
Source x Rate	6	8.73**	0.0079	2.387**	2.40
Error a	22	0.16	0.0259	0.209	1.83
Sub - Plot					
Extraction method[1]	1	97.63**	0.0690**	35.252**	19025.50**
Method x Source	2	8.57**	0.0003	0.727**	30.79**
Method x Rate	3	0.43	0.0017**	1.190**	63.51**
Method x Source x Rate	6	1.93**	0.0003	0.177	2.01
Error b	18	0.33	0.0001	0.091	3.04
Total	65				

[1] Extraction method includes only NH_4-resin and 1N NH_4OAc

* Significant at 5% level.

** Significant at 1% level.

Table 40. Analysis of Variance for Resin and Chemical Methods of Nutrient Extraction from Lualualei Soil.

Source of Variation	d.f.	Mg	K	Ca	P	Mn
		(Mean Squares)				
Replication	2	0.3	0.0024	1.30	59.8	271.8
<u>Whole Plot</u>						
P source	1	27.8**	0.0005	0.16	295.7*	44.5
P rate	3	14.0**	0.1363**	10.17**	6157.5**	114.0
Source x Rate	3	5.7*	0.0015	1.58	99.8	226.4
Error a	14	1.31	0.0175	1.18	36.2	214.0
<u>Sub-Plot</u>						
Extraction Method[1]	2	789.6**	0.2378**	423.08**	32532.5**	104132.5**
Method x P source	2	29.7**	0.0012	0.22	42.9	16.8
Method x P rate	6	5.6**	0.0109**	1.57	1187.0**	255.4
Method x Source x Rate	6	3.9**	0.0002	1.17	29.3	70.3
Error b	32	0.54	0.0015	0.77	38.0	134.6
Total	71					

[1] Extraction method includes NH_4- and H-resin, and 1<u>N</u> NH_4OAc for the cations; and anion exchange resin, 0.5M $NaHCO_3$ and modified Truog procedure for P.

* Significant at 5% level.

** Significant at 1% level.

Table 41. Greenhouse Experiment: Relationship Between Extraction Methods and Quantity of Cations Extracted from Lualualei Soil.[1]

	Mg	K	Ca	Mn
	(m.e./100gm soil)			(ppm)
Extraction method		Means[2]		
Chemical	31.19	0.44	22.96	38.7
H-resin	26.02	0.36	28.66	138.6
NH_4-resin	19.74	0.24	20.47	14.2

[1] Modified Duncan's (Bayesian) Least Significance Difference test.

[2] All means for extraction methods within an element are significantly different at 5% probability level.

Table 42. Summary of Multiple Regression Analysis of Yield and Nutrient Uptake by Sudax (*Sorghum bicolor* x *Sorghum sudanensis*) in Relation to Nutrients Extracted by Resin and Chemical Methods from Halii Soil.

Dependent Variable	Extraction Method	Independent Variables in Multiple Regression Equation									
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Yield	NH_4-resin	39.6	3.1 (1/K)	0.76	104.6 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.83	-1.8 Mn	0.87	-2.9 Ca/Mg	0.90		
	Chemical	-29.4	-43.4 Al	0.72	2.9 (1/K)	0.83	46.9 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.87	0.4 Mg x Ca	0.88	91.7 $\sqrt[3]{Al}/\sqrt{Ca+Mg}$	0.90
Uptake Mg	NH_4-resin	854.5	190.8 $\sqrt{Ca}/\sqrt[3]{Al}$	0.72	-41.6 $\sqrt{K \times Ca}$	0.84	-34.2 $\sqrt{Ca}$	0.86	-140.5 $\sqrt{Mn}$	0.87	-16.7 Ca/Mg	0.89
	Chemical	175.2	51.2 $\sqrt{Ca}/\sqrt[3]{Al}$	0.79	-45.1 $\log_e K$	0.85	4.7 Mg x Ca	0.88	-93.5 $\sqrt{Ca+Mg} + \sqrt[3]{Al}$	0.90		
K	NH_4-resin	-2076.5	-177.1 $\log_e K$	0.80	-1195.7 Al	0.82	3384.3 $\sqrt[3]{Al}$	0.87				
	Chemical	985.7	-92.1 $\log_e K$	0.82	393.2 K x Ca	0.84	-88.6 Ca	0.88	-1663.4 $\sqrt{K}$	0.90		

Table 42. (Continued) Summary of Multiple Regression Analysis of Yield and Nutrient Uptake by Sudax(*Sorghum bicolor* x *Sorghum sudanensis*) in Relation to Nutrients Extracted by Resin and Chemical Methods from Halii Soil.

Dependent Variable	Extraction Method	Independent Variables in Multiple Regression Equation										
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Ca	NH_4-resin	708.7	798.0 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.78	-155.4 $\sqrt{Mn}$	0.91						
	Chemical	600.7	543.0 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.75	-202.7 $\sqrt[3]{Al}$	0.82	91.2 Mn	0.84	-490.2 $\sqrt{Mn}$	0.86		
P	NH_4-resin	65.0	139.6 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.67	-9.6 $\log_e$ K	0.82	-18.6 $\sqrt{Mn}$	0.84				
	Chemical	-27.5	72.4 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.59	-24.5 Al	0.74	-7.5 $\log_e$ K	0.78	1.5 Mn	0.80		
Mn	NH_4-resin	1.8	-0.6 $\log_e$ K	0.64	8.9 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.77	-0.1 Mn	0.79	-0.2 Ca/Mg	0.81		
	Chemical	-1.7	-1.4 $\log_e$ K	0.61	0.6 K x Ca	0.76	2.4 $\frac{\sqrt{Ca}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.77	-1.0 Al	0.78		

Table 43. Correlation Coefficients[1] among Yield, Nutrient Uptake and Tissue Analysis of Sudax (*Sorghum bicolor* x *Sorghum sudanensis*) and Nutrients Extracted by Resin and Chemical Methods from Halii Soil.

		NH_4-RESIN					CHEMICAL					
		Al	Mg	K	Ca	Mn	Al	Mg	K	Ca	Mn	P
Yield		-0.84	0.31	-0.79	0.69	-0.85	-0.85	0.12	-0.80	0.71	0.57	0.87
Uptake	Mg	-0.81	0.63	-0.65	0.76	-0.85	-0.85	0.43	-0.64	0.81	0.51	0.81
	K	-0.81	0.13	-0.86	0.31	-0.71	-0.73	0.04	-0.89	0.46	0.43	0.58
	Ca	-0.65	0.15	-0.60	0.70	-0.81	-0.72	-0.09	-0.60	0.78	0.62	0.93
	P	-0.73	0.23	-0.69	0.67	-0.79	-0.77	0.03	-0.69	0.74	0.62	0.93
	S	-0.82	0.26	-0.79	0.60	-0.83	-0.81	0.10	-0.80	0.71	0.59	0.85
	Si	-0.79	0.75	-0.59	0.80	-0.52	-0.84	0.57	-0.58	0.82	0.39	0.66
	Mn	-0.78	0.25	-0.73	0.59	-0.79	-0.78	0.08	-0.74	0.69	0.57	0.83
Tissue	Mg	-0.77	0.75	-0.58	0.70	-0.49	-0.78	0.62	-0.56	0.74	0.38	0.61
	K	0.31	-0.24	0.15	-0.48	0.49	0.40	-0.10	0.13	-0.49	-0.42	-0.61
	Ca	-0.58	0.04	-0.55	0.64	-0.80	-0.64	-0.19	-0.55	0.73	0.60	0.89
	P	-0.59	0.12	-0.60	0.53	-0.58	-0.60	-0.02	-0.61	0.59	0.50	0.76
	S	0.74	-0.24	0.73	-0.31	0.64	0.74	-0.10	0.75	-0.45	-0.33	-0.59
	Si	0.12	0.60	0.36	0.31	0.47	0.04	0.63	0.40	0.17	-0.23	-0.27
	Mn	0.10	-0.11	0.15	0.002	0.06	0.15	-0.08	0.17	-0.004	-0.01	-0.04
Chemical	Al	0.84	-0.45	0.71	-0.64	0.62						
	Mg	-0.33	0.79	-0.09	0.35	0.19						
	K	0.72	-0.18	0.99	-0.30	0.75						
	Ca	-0.65	0.56	-0.46	0.93	-0.47						
	Mn	-0.45	0.12	-0.39	0.43	-0.48						
	P	-0.66	0.23	-0.60	0.68	-0.73						
NH_4-Resin	Al	1.00	-0.47	0.70	-0.55	0.68						
	Mg		1.00	-0.20	0.67	0.003						
	K			1.00	-0.33	0.74						
	Ca				1.00	-0.35						
	Mn					1.00						

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[1] r for significance at 0.05 probability with 58 d.f.=0.255

Table 44. Summary of Multiple Regression Analysis of Yield and Nutrient Uptake by Sudax (*Sorghum bicolor* x *Sorghum sudanensis*) in Relation to Nutrients Extracted by Chemical Method from Halii Soil.

Dependent Variable	Independent Variables in Multiple Regression Equation								
	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Yield	8.7	0.1 P	0.75	-7.7 $\log_e K$	0.89	-18.0 Al	0.92		
Uptake Mg	-90.7	28.7 $\sqrt{Ca}/\sqrt[3]{Al}$	0.79	-38.3 $\log_e K$	0.85	2.2 Mg x Ca	0.88	0.6 P	0.91
K	985.7	-92.1 $\log_e K$	0.82	393.2 K x Ca	0.84	-88.6 Ca	0.88	-1663.4 $\sqrt{K}$	0.90
Ca	-162.4	1.1 P	0.86	330.4 $\dfrac{\sqrt{Ca}}{\sqrt{Ca+Mg}+\sqrt[3]{Al}}$	0.91				
P	-7.5	0.3 P	0.86	-7.6 $\log_e K$	0.90				
Mn	-1.4	0.009 P	0.69	-1.4 $\log_e K$	0.80	0.5 K x Ca	0.82		

Table 45. Summary of Multiple Regression Analysis of Yield and Nutrient Uptake by Sudax (*Sorghum bicolor* x *Sorghum sudanensis*) in Relation to Nutrients Extracted by Resin and Chemical Methods from Lualualei Soil.

Dependent Variable	Extraction Method	Independent Variables in Multiple Regression Equation												
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Yield	NH_4-resin	-698.1	-18.9 log K	0.40	-1.8 Ca^2	0.46	71.5 Ca	0.60						
	H-resin	117.6	-3.8 Mg	0.39	-11.0 log K	0.54	0.02 (P x Si)	0.59						
	Chemical	130.6	0.2 P	0.60	-3.2 Si	0.78	-12.3 $\sqrt{Ca + Mg}$	0.87						
Uptake Mg	NH_4-resin	-1318.6	-207.5 log K	0.49	105.9 P	0.59	-5.0 (Ca x P)	0.65	0.44 Mn^2	0.67	25.7 Mg	0.73		
	H-resin	732.1	-86.1 log K	0.41	-26.2 Mg	0.60	0.2 (P x Si)	0.70						
	Chemical	97.2	1.5 P	0.71	-26.3 Si	0.84	0.22 (Si x Mn)	0.88	166.2 Ca/Mg	0.90				
K	NH_4-resin	-478.4	-356.4 log K	0.48	-0.6 Mn^2	0.51								
	H-resin	1247.0	-250.7 log K	0.36	-1.0 Mg^2	0.55								
	Chemical	2587.1	-49.3 log K	0.54	20418.8 $K/\sqrt{Ca + Mg}$	0.68	-80.1 Si	0.78	0.2 (P x Si)	0.84	0.4 (Si x Mn)	0.87	-3094.3 $\sqrt{K}$	0.88
Ca	NH_4-resin	-812.1	-128.2 log K	0.44	68.0 P	0.55	-3.1 (Ca x P)	0.62	0.3 Mn^2	0.65	13.5 Mg	0.69		
	H-resin	415.8	0.5 (P x Si)	0.38	-0.4 Mg^2	0.62	-124.3 K^2	0.66	-9.3 $\sqrt{P \times Si}$	0.69				
	Chemical	240.1	1.1 P	0.73	-16.6 Si	0.86	-3.2 Mg	0.90	-0.1 (Si x Mn)	0.92				

Table 45. (Continued) Summary of Multiple Regression Analysis of Yield and Nutrient Uptake by Sudax (*Sorghum bicolor* x *Sorghum sudanensis*) in Relation to Nutrients Extracted by Resin and Chemical Methods from Lualualei Soil.

Dependent Variables	Extraction Method		Independent Variables in Multiple Regression Equation											
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Mn	NH_4-resin	0.2	-1.2 log K	0.48	0.2 P	0.61	-0.2 $\sqrt{Ca \times P}$	0.67						
	H-resin	4.0	-0.004 Mg^2	0.39	-0.002 (P x Si)	0.62	-1.9 K^2	0.68						
	Chemical	0.6	0.01 P	0.68	-0.20 Si	0.84	0.02 Mn	0.90	1.5 Ca/Mg	0.93				
P	NH_4-resin	76.4	-39.9 log K	0.51	0.6 (P x Si)	0.64	-92.4 Ca/Mg	0.68						
	H-resin	90.6	0.1 (P x Si)	0.44	-0.1 Mg^2	0.64	-23.2 log K	0.71						
	Chemical	47.7	0.4 P	0.77	-5.7 Si	0.88	0.4 Mn	0.91						
Si	NH_4-resin	-7251.5	-909.5 $\sqrt{K}$	0.39	0.6 Mn^2	0.50	-19.0 Ca^2	0.56	744.9 Ca	0.66				
	H-resin	1532.6	-50.7 Mg	0.36	-144.6 log K	0.51	0.03 (Si x Mn)	0.57						
	Chemical	991.5	2.1 P	0.52	-46.7 Si	0.74	-6.7 (Ca + Mg)	0.77						
S	NH_4-resin	5.5	-21.2 log K	0.51	5.7 P	0.55	-0.3 (Ca x P)	0.60						
	H-resin	107.6	-44.5 $\sqrt{K}$	0.42	-0.1 Mg^2	0.60	0.2 (P x Si)	0.64						
	Chemical	-76.5	0.2 P	0.59	-30.6 Si	0.84	-0.9 $\sqrt{Ca + Mg}$	0.88	145.3 $\sqrt{Si}$	0.90				

Table 46. Correlation Coefficients[1] among Yield, Nutrient Uptake and Tissue Analysis of Sudax (*Sorghum bicolor* x *Sorghum sudanensis*), and Nutrients Extracted by Resin and Chemical Methods from Lualualei Soil.

		NH_4-RESIN							CHEMICAL							
		Mg	K	Ca	P	S	Si	Mn	Mg	K	Ca	P^2	P^3	Si	Mn
Yield		-0.38	-0.62	-0.34	0.41	0.01	0.38	0.17	-0.59	-0.67	-0.44	0.78	0.71	-0.60	0.38
Uptake	Mg	-0.36	-0.69	-0.29	0.54	0.10	0.41	0.13	-0.50	-0.72	-0.38	0.84	0.77	-0.57	0.43
	K	-0.30	-0.68	-0.24	0.38	-0.02	0.32	0.13	-0.49	-0.70	-0.42	0.68	0.61	-0.72	0.37
	Ca	-0.38	-0.65	-0.30	0.56	0.13	0.39	0.16	-0.52	-0.70	-0.37	0.86	0.76	-0.56	0.45
	P	-0.35	-0.69	-0.29	0.58	0.13	0.46	0.05	-0.40	-0.74	-0.31	0.88	0.82	-0.53	0.47
	S	-0.36	-0.71	-0.27	0.45	0.02	0.35	0.11	-0.52	-0.74	-0.43	0.77	0.68	-0.68	0.41
	Si	-0.47	-0.62	-0.40	0.39	0.07	0.39	0.27	-0.49	-0.67	-0.41	0.72	0.64	-0.63	0.38
	Mn	-0.35	-0.69	-0.27	0.59	0.10	0.30	0.12	-0.52	-0.72	-0.40	0.83	0.72	-0.59	0.52
Tissue	Mg	-0.33	-0.79	-0.23	0.62	0.16	0.35	0.02	-0.24	-0.80	-0.33	0.79	0.71	-0.56	0.53
	K	0.44	0.58	0.42	-0.39	-0.04	-0.37	-0.20	0.56	0.63	0.47	-0.75	-0.66	0.56	-0.39
	Ca	-0.40	-0.70	-0.23	0.68	0.26	0.33	0.12	-0.31	-0.76	-0.29	0.85	0.71	-0.51	0.50
	P	-0.22	-0.66	-0.15	0.59	0.20	0.37	-0.19	0.06	-0.68	-0.09	0.72	0.68	-0.33	0.45
	S	0.26	0.24	0.36	-0.20	-0.05	-0.30	-0.22	0.53	0.29	0.35	-0.51	-0.48	0.29	-0.24
	Si	0.03	0.44	0.11	-0.31	0.15	-0.16	0.13	0.57	0.44	0.40	-0.62	-0.57	0.43	-0.31
	Mn	-0.32	-0.72	-0.21	0.61	0.12	0.13	0.02	-0.27	-0.73	-0.35	0.69	0.55	-0.57	0.57
Chemical	Mg	0.04	0.21	-0.01	-0.05	0.16	-0.08	-0.15							
	K	0.61	0.94	0.32	-0.41	0.01	-0.36	0.12							
	Ca	0.30	0.45	0.22	0.15	0.33	0.11	0.03							
	P^2	-0.34	-0.55	-0.19	0.66	0.19	0.50	-0.09							
	P^3	-0.22	-0.42	-0.15	0.69	0.24	0.49	-0.04							
	Si	0.55	0.69	0.38	-0.08	0.24	-0.04	-0.12							
	Mn	0.00	-0.29	0.00	0.52	0.40	-0.08	0.46							
NH_4-Resin	Mg	1.00	0.49	0.75	-0.06	0.07	-0.19	-0.16							
	K		1.00	0.20	-0.34	0.12	-0.40	0.08							
	Ca			1.00	0.06	0.17	-0.15	-0.13							
	P				1.00	0.62	0.25	0.11							
	S					1.00	0.12	0.32							
	Si						1.00	-0.12							
	Mn							1.00							

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[1] r for significance at 0.05 probability with 22 d.f.=0.404.

[2] Modified Truog reagent extractable P.

[3] 0.5M $NaHCO_3$ extractable P.

Table 47. Correlation Coefficients[1] among Yield, Nutrient Uptake and Tissue Analysis of Sudax (*Sorghum bicolor* x *sorghum sudanensis*) and Cations Extracted by H-resin and Chemical Methods from Lualualei Soil.

	H-RESIN			
	Mg	K	Ca	Mn
Yield	-0.63	-0.57	-0.47	-0.26
Uptake				
Mg	-0.62	-0.63	-0.46	-0.27
K	-0.59	-0.59	-0.51	-0.27
Ca	-0.59	-0.60	-0.43	-0.25
P	-0.57	-0.64	-0.43	-0.29
S	-0.62	-0.64	-0.49	-0.27
Si	-0.60	-0.57	-0.48	-0.24
Mn	-0.62	-0.62	-0.47	-0.24
Tissue				
Mg	-0.56	-0.72	-0.46	-0.29
K	0.62	0.52	0.46	0.23
Ca	-0.50	-0.65	-0.36	-0.25
P	-0.32	-0.62	-0.28	-0.29
S	0.45	0.17	0.33	0.16
Si	0.51	0.37	0.36	0.22
Mn	-0.56	-0.63	-0.46	-0.25
Chemical				
Mg	0.34	0.20	0.20	0.13
K	0.55	0.89	0.50	0.58
Ca	0.61	0.29	0.66	0.25
Mn	-0.41	-0.20	-0.34	0.38
H-Resin				
Mg	1.00	0.35	0.90	0.36
K		1.00	0.26	0.39
Ca			1.00	0.46
Mn				1.00

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[1] r for significance at 0.05 probability with 22 d.f. = 0.404.

APPENDIX IV

Field Experiment: Soil, Yield and Plant Tissue Data and Multiple Regression Analysis.

Table 48. Field Lime Experiment: Cation Extraction from 1 gm Wahiawa Soil Using 1 NH_4-saturated Cation Exchange Resin Disc.

Block No.	Plot No.	pH 1:1 H_2O	Mg	Al	K	Ca	Mn	Fe	Cu	Zn
			m.e./100gm soil				ppm			
I	1	4.70	1.91	2.14	1.17	4.86	206.5	13.0	32.6	11.4
	2	4.85	1.89	2.08	1.12	4.14	209.9	13.0	33.7	11.2
	3	4.95	1.88	2.03	1.08	4.25	203.0	13.0	32.6	7.7
	4	5.00	2.02	1.98	1.08	5.87	170.4	13.0	32.6	6.2
	5	5.20	1.75	2.27	1.05	4.91	192.0	13.5	32.6	8.0
	6	5.40	1.75	1.86	1.03	6.23	154.2	13.0	33.2	6.2
	7	5.50	1.92	1.93	1.03	8.80	130.1	13.0	32.6	6.2
	8	6.00	1.79	1.78	0.95	9.49	121.5	13.0	32.6	6.2
	9	6.30	1.49	1.70	0.87	11.69	119.4	13.0	32.6	6.2
	10	6.80	1.00	1.64	0.85	18.87	119.4	12.4	32.6	5.0
II	1	4.90	2.32	2.00	1.00	6.25	143.9	13.0	32.8	6.2
	2	5.00	2.12	1.83	0.98	6.50	147.6	13.0	33.9	7.0
	3	5.20	2.32	1.85	1.06	6.58	133.2	13.0	32.6	6.2
	4	5.40	2.21	1.97	1.09	5.32	129.8	13.0	32.8	6.2
	5	5.60	1.87	1.75	1.02	4.77	123.9	13.0	32.8	6.2
	6	5.80	2.02	1.80	0.98	5.54	121.5	13.0	33.2	6.2
	7	6.00	1.47	1.64	0.98	5.03	119.8	12.7	32.6	6.2
	8	6.60	1.83	1.76	0.95	7.51	120.1	13.0	33.0	6.5
	9	6.95	1.56	1.68	0.90	9.76	119.4	13.0	32.6	6.2
	10	7.20	1.21	2.08	0.86	16.38	119.4	12.1	32.6	5.5
III	1	4.85	2.06	2.59	0.95	4.60	176.2	13.0	32.6	7.0
	2	4.95	1.91	2.11	0.95	4.59	225.3	13.0	34.1	11.2
	3	5.10	1.87	2.17	0.97	5.04	168.6	13.0	32.8	5.4
	4	5.30	1.69	1.97	0.91	6.15	149.4	13.0	32.6	6.2
	5	5.40	1.75	1.87	0.93	7.90	124.6	13.0	32.6	6.2
	6	5.70	1.12	1.60	0.94	5.79	125.3	13.0	32.6	6.2
	7	6.10	1.47	1.67	1.00	7.20	126.3	13.0	32.6	6.2
	8	6.50	1.24	1.80	0.95	8.76	120.1	13.0	33.0	6.2
	9	6.90	1.33	1.75	0.95	9.98	119.4	13.0	32.6	6.2
	10	7.30	0.78	1.70	0.95	16.98	119.4	12.7	32.6	6.0
IV	1	4.75	2.34	2.07	0.95	6.08	133.9	13.0	33.2	6.2
	2	4.90	2.39	2.15	1.01	5.91	150.4	13.0	33.5	6.5
	3	5.05	2.25	1.95	0.95	5.52	124.3	12.1	33.0	8.2
	4	5.20	2.39	2.00	0.86	5.77	121.5	13.0	32.8	6.2
	5	5.40	2.09	1.73	0.89	5.31	120.8	13.0	33.0	6.2
	6	5.70	2.04	1.81	0.93	5.82	120.1	13.0	33.4	6.2
	7	6.05	1.92	1.69	0.85	7.18	119.4	13.0	32.6	6.2
	8	6.35	1.53	1.70	0.81	7.59	119.4	13.0	32.6	6.2
	9	6.80	1.45	2.17	0.84	12.20	119.4	12.4	32.6	5.0
	10	7.10	1.00	1.69	0.85	17.56	119.4	13.0	32.6	6.2

Table 49. Field Lime Experiment: Cation Extraction from 2 gm Wahiawa Soil Using 2 NH_4-saturated Cation Exchange Resin Discs.

Block	Plot	pH 1:1	Mg	Al	K	Ca	Mn	Fe	Cu	Zn
No.	No.	H_2O	m.e./100gm soil				ppm			
I	1	4.70	2.25	1.34	1.03	5.75	141.9	6.5	16.8	4.6
	2	4.85	1.99	1.18	0.96	4.70	154.3	9.3	16.8	6.1
	3	4.95	1.93	1.23	0.96	4.89	148.3	7.5	16.9	4.7
	4	5.10	1.86	1.12	0.90	6.24	108.1	4.5	16.4	3.7
	5	5.20	1.91	1.32	0.91	5.81	133.0	7.0	16.8	4.7
	6	5.40	1.78	0.91	0.88	6.84	88.1	5.5	16.8	4.2
	7	5.50	1.68	0.87	0.82	8.16	62.6	5.6	16.4	0.1
	8	6.00	1.57	0.92	0.78	9.58	59.9	7.3	16.7	2.2
	9	6.30	1.45	0.93	0.76	12.66	59.6	5.1	15.8	0.0
	10	6.80	1.00	0.92	0.69	18.75	59.6	4.0	15.6	0.0
II	1	4.90	2.26	1.00	0.83	6.98	79.8	5.9	16.8	3.4
	2	5.20	2.15	0.98	0.80	7.27	82.7	5.6	16.7	3.9
	3	5.20	2.33	1.09	0.88	6.98	69.7	4.0	16.7	3.9
	4	5.40	2.27	1.02	0.92	6.94	64.4	6.8	16.8	1.6
	5	5.60	2.14	0.95	0.90	5.87	60.1	6.6	16.8	2.0
	6	5.80	2.04	0.92	0.84	6.18	59.9	4.5	16.3	0.1
	7	6.00	1.80	1.01	0.80	6.85	59.7	6.3	16.4	0.2
	8	6.60	1.90	0.92	0.82	8.72	59.9	4.0	16.8	0.0
	9	6.95	1.52	1.24	0.74	10.74	59.7	2.8	15.9	0.0
	10	7.20	0.94	1.05	0.69	17.41	59.6	4.9	16.0	0.0
III	1	4.85	2.02	1.10	0.81	5.29	117.2	8.6	16.8	4.7
	2	4.95	1.95	2.20	0.84	5.17	169.8	9.8	16.8	5.0
	3	5.10	1.94	1.15	0.83	5.91	106.2	4.1	16.6	4.1
	4	5.30	1.62	1.09	0.75	5.92	80.9	4.9	16.4	4.4
	5	5.40	1.86	1.00	0.77	8.25	59.9	6.2	16.7	3.0
	6	5.70	1.74	1.00	0.86	6.09	62.3	4.4	16.6	2.2
	7	6.10	1.60	0.96	0.88	7.83	61.1	4.5	16.7	2.7
	8	6.50	1.56	0.99	0.82	9.93	59.9	7.2	16.6	2.0
	9	6.90	1.41	1.02	0.81	10.83	59.9	5.9	16.8	1.9
	10	7.30	0.93	1.08	0.80	18.88	59.9	4.7	16.0	0.0
IV	1	4.75	2.20	1.12	0.78	6.12	69.7	8.0	16.9	4.7
	2	4.90	2.28	1.13	0.84	5.95	82.6	8.3	16.8	4.7
	3	5.05	2.30	1.06	0.78	5.97	59.9	5.4	16.6	2.9
	4	5.20	2.23	1.00	0.74	5.60	60.2	6.9	16.8	3.9
	5	5.40	1.94	0.90	0.74	5.38	59.9	7.7	16.8	4.0
	6	5.70	1.84	0.95	0.82	5.78	59.9	8.2	16.8	3.5
	7	6.05	1.89	0.93	0.71	7.38	50.9	8.4	16.8	3.9
	8	6.35	1.61	0.95	0.70	8.39	59.9	8.7	16.8	4.5
	9	6.80	1.25	1.36	0.70	11.31	59.9	6.9	16.8	2.2
	10	7.10	1.04	0.83	0.71	17.72	59.9	6.5	16.7	2.2

Table 50. Field Lime Experiment: Cation Extraction from 3 gm Wahiawa Soil Using 3 NH_4-saturated Cation Exchange Resin Discs.

Block No.	Plot No.	pH 1:1 H_2O	Mg	Al	K	Ca	Mn	Fe	Cu	Zn
			m.e./100gm soil				ppm			
I	1	4.70	1.89	0.92	0.97	5.64	124.4	4.4	12.3	6.1
	2	4.85	2.05	0.89	0.95	5.36	144.9	6.5	13.6	9.6
	3	4.95	1.83	0.89	0.88	4.83	132.3	4.9	12.5	7.6
	4	5.00	1.94	0.73	0.87	7.03	97.9	5.0	13.1	7.3
	5	5.20	1.73	0.77	0.86	5.98	117.0	4.5	12.8	7.0
	6	5.40	1.79	0.64	0.85	7.13	74.4	4.8	12.7	3.9
	7	5.50	1.63	0.61	0.79	8.59	51.2	4.4	11.5	1.7
	8	6.00	1.74	0.63	0.76	10.67	44.7	4.8	11.9	2.1
	9	6.30	1.53	0.73	0.69	13.21	43.9	5.3	11.0	1.6
	10	6.80	0.96	0.55	0.64	19.12	41.1	5.8	9.8	1.3
II	1	4.90	1.93	0.75	0.81	6.95	65.6	5.3	12.6	3.3
	2	5.00	2.20	0.60	0.76	7.44	66.5	4.7	12.2	2.0
	3	5.20	2.10	0.74	0.83	7.29	58.9	5.1	13.3	4.6
	4	5.40	2.09	0.69	0.86	6.02	54.2	4.8	12.3	3.3
	5	5.60	2.13	0.61	0.85	6.19	46.3	4.5	12.1	2.7
	6	5.80	1.83	0.62	0.75	6.37	43.9	4.6	12.7	3.1
	7	6.00	1.79	0.64	0.76	7.25	42.3	4.9	12.6	3.7
	8	6.60	1.74	0.65	0.73	8.26	42.1	4.5	12.4	1.3
	9	6.95	1.56	9.73	0.70	11.18	41.8	5.7	12.3	1.7
	10	7.20	0.97	0.80	0.62	15.31	42.3	4.7	10.7	1.3
III	1	4.85	2.02	0.94	0.75	4.97	88.0	4.3	8.9	1.2
	2	4.95	2.11	1.01	0.77	5.21	138.9	3.8	9.1	3.2
	3	5.10	1.77	0.75	0.75	5.28	78.8	4.0	9.1	1.6
	4	5.30	1.70	0.80	0.68	6.21	64.7	4.2	9.1	1.4
	5	5.40	1.73	0.66	0.71	8.36	44.0	4.2	8.4	1.3
	6	5.70	1.79	0.72	0.76	6.47	50.7	4.2	8.4	1.0
	7	6.10	1.69	0.63	0.80	8.08	48.1	4.3	8.8	1.3
	8	6.50	1.41	0.60	0.77	9.43	38.0	3.9	8.5	0.4
	9	6.90	1.45	0.60	0.77	10.42	37.3	4.3	8.4	0.7
	10	7.30	1.01	0.93	0.77	19.12	37.3	3.3	8.3	0.0
IV	1	4.75	2.26	0.83	0.73	6.48	48.9	4.3	9.3	1.4
	2	4.90	2.21	0.85	0.79	6.25	65.0	4.0	9.3	1.4
	3	5.05	2.05	0.72	0.73	5.85	40.2	3.9	8.9	1.3
	4	5.20	1.94	0.67	0.66	5.82	39.1	4.2	9.0	1.1
	5	5.40	1.72	0.61	0.66	5.04	37.3	3.9	8.4	0.7
	6	5.70	2.09	0.51	0.73	6.48	37.3	3.8	8.8	1.3
	7	6.05	1.82	0.50	0.68	7.60	37.3	3.3	8.6	0.6
	8	6.35	1.72	0.50	0.66	8.77	37.3	3.3	8.3	0.8
	9	6.80	1.31	0.78	0.65	12.08	37.3	2.8	8.3	0.0
	10	7.10	0.97	0.49	0.64	18.50	37.3	3.6	8.3	0.0

Table 51. Field Lime Experiment: Cation Extraction from 3 gm Wahiawa Soil Using 3 H-saturated Cation Exchange Resin Discs.

Block[1]	Plot	pH 1:1	Mg	Al	K	Ca	Mn	Fe	Cu	Zn
No.	No.	H_2O	m.e./100gm soil				ppm			
II	1	4.90	2.27	5.56	0.97	8.39	404.4	5.3	14.7	30.5
	2	5.00	2.35	6.13	0.94	9.01	418.2	6.4	14.9	35.8
	3	5.20	2.41	6.54	1.00	8.88	405.0	5.6	15.3	38.5
	4	5.40	2.64	4.34	1.07	8.81	381.7	5.3	14.7	33.0
	5	5.60	2.75	4.76	1.02	8.83	342.8	5.4	15.7	34.0
	6	5.80	2.58	4.08	0.93	9.57	308.8	4.0	14.2	29.6
	7	6.00	2.45	3.89	0.93	10.88	239.2	4.0	14.7	29.0
	8	6.60	2.05	4.31	0.91	12.15	299.1	4.0	14.1	30.2
	9	6.95	2.26	4.70	0.89	16.61	253.8	4.0	13.3	32.5
	10	7.20	1.87	4.00	0.84	23.85	383.1	4.0	12.5	26.9
IV	1	4.75	2.48	5.46	0.88	7.86	335.5	5.2	16.5	37.8
	2	4.90	2.53	4.65	0.97	7.96	428.5	5.8	15.0	38.7
	3	5.05	2.57	4.54	0.89	8.17	293.9	5.1	17.3	37.7
	4	5.20	2.85	3.86	0.86	9.22	313.7	6.4	16.7	36.7
	5	5.40	2.83	3.19	0.84	9.59	275.3	6.9	16.8	34.2
	6	5.70	2.88	4.27	0.91	10.38	197.8	6.7	18.1	41.2
	7	6.05	2.93	3.77	0.83	14.11	223.5	5.9	17.0	36.7
	8	6.35	2.53	2.65	0.82	15.14	134.4	4.2	15.7	28.1
	9	6.80	2.44	3.02	0.86	21.35	231.7	6.3	15.3	31.1
	10	7.10	2.50	3.13	0.86	35.88	382.5	4.2	23.5	31.4

[1] Extraction with H-resin were only for these blocks.

Table 52. Analysis of Variance for Cations Extracted by NH_4- and H-saturated Cation Exchange Resin from Wahiawa Soil.

Source of Variation	d.f.	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
		(Mean Squares)							
Block	1	2.57	0.165	0.05625	8.3	12467.9	0.225	8.28	5.77
<u>Whole Plot</u>									
pH	9	0.76*	0.273**	0.00747	93.0**	6321.3**	0.754	2.02**	13.28
Error <u>a</u>	9	0.15	0.027	0.00614	3.9	857.4	0.328	0.17	4.93
<u>Sub - Plot</u>									
Resin form	1	135.27**	4.658**	0.32761**	187.1**	710755.6**	8.836*	228.48**	10176.10**
Resin x pH	9	0.58	0.100	0.00039	8.0**	4346.2*	0.408	0.55	6.08
Error <u>b</u>	10	0.38	0.038	0.00005	1.2	1363.3	1.595	7.69	11.88
Total	39								

* Significant at 5% level

** Significant at 1% level

Table 53. Analysis of Variance for Cation Extraction by Single and Multiple Resin Discs from Wahiawa Soil.

Source of Variation	d.f.	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
		(Mean Squares)							
Block	3	0.073	0.478	0.0813	0.78	10073.9	1.52	12.41	17.22
<u>Whole Plot</u>									
pH	9	0.170**	1.506**	0.0294*	180.86**	5717.9**	1.98**	1.22**	16.14**
Error <u>a</u>	27	0.049	0.032	0.0097	2.75	1050.3	0.58	0.13	2.54
<u>Sub - Plot</u>									
Extraction	2	14.936**	0.016	0.4350**	5.22**	69915.1**	804.43**	5343.71**	225.19**
pH x Extraction	18	0.016	0.013	0.0003	0.07	5.9	1.36	0.29	0.96
Error <u>b</u>	60	0.017	0.017	0.0003	0.19	11.3	1.19	1.59	2.12
Total	119								

* Significant at 5% level

** Significant at 1% level

Table 54. Field Lime Experiment: Relationship Between the Number of Cation Exchange Resin Discs Used for Extraction and the Quantity of Cations Extracted.[1]

	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
	(m.e./100gm soil)				(ppm)			
Extraction with:				Means				
1 resin disc	1.899	1.774 a	0.962	7.717	140.2	12.9	32.8	6.7
2 resin discs	1.068	1.799 a	0.816	8.250 a	78.5	6.2	16.6	2.8 a
3 resin discs	0.707	1.760 a	0.760	8.406 a	60.5	4.4	10.5	2.4 a

[1] The same resin-soil ratio (1:1) was maintained in all extractions. Means followed by a letter are not significantly different at 5% level.

Table 55. Field Lime Experiment: Yields of Tropical and Temperate Legumes.[1]

Block No.	Plot No.	L.L.*	P.V.**	C.V.	A.H.	G.M.	G.W.	Stylo. (HA3038)	T.R.	D.I.
			(gm/plot)							
I	1	2.8	317	9.0	194	189	53	156	51	22
	2	1.0	277	21.0	132	183	34	250	10	30
	3	2.0	284	6.0	106	127	32	264	9	15
	4	2.1	211	11.0	114	98	43	290	69	9
	5	1.7	155	24.0	104	136	40	210	74	26
	6	1.5	112	12.0	141	127	68	245	37	39
	7	3.2	142	15.0	140	170	98	301	120	57
	8	4.7	837	92.0	175	160	68	240	121	86
	9	9.0	920	69.0	167	196	85	244	111	63
	10	7.0	626	151.0	117	204	102	208	108	76
II	1	1.3	466	26.0	114	129	41	191	10	18
	2	1.4	241	10.0	110	134	55	150	11	26
	3	1.7	222	2.5	118	145	86	202	81	47
	4	2.8	139	7.0	90	176	70	238	85	64
	5	10.5	135	1.5	140	181	102	220	73	27
	6	2.0	202	3.0	153	163	111	214	76	26
	7	3.6	250	8.0	113	180	54	170	96	22
	8	6.0	434	10.0	200	178	78	125	132	10
	9	6.4	635	19.0	159	190	129	46	168	15
	10	11.2	1255	25.0	109	215	222	140	128	7
III	1	0.5	65	1.0	60	97	25	214	55	4
	2	0.8	130	1.5	62	140	24	165	18	7
	3	1.7	146	0.5	115	131	30	248	55	16
	4	6.7	175	1.0	107	143	82	196	124	38
	5	5.0	285	0.5	74	135	95	247	145	41
	6	3.5	448	3.0	160	140	98	303	115	30
	7	4.6	333	4.0	116	115	136	135	144	25
	8	8.5	498	4.0	132	108	97	101	115	38
	9	10.0	493	10.0	174	234	109	86	112	40
	10	12.3	675	12.3	93	216	62	178	150	23
IV	1	1.2	120	12.0	93	140	22	58	18	11
	2	2.8	164	10.0	63	138	19	84	18	19
	3	2.0	187	2.0	80	138	35	98	29	22
	4	4.5	103	0.0	92	157	64	100	47	13
	5	4.3	255	1.0	72	159	36	137	16	16
	6	3.8	266	3.0	87	160	93	187	59	28
	7	2.0	462	4.0	67	144	96	154	113	36
	8	15.6	1078	15.0	137	182	120	202	127	20
	9	13.3	744	23.0	78	248	149	207	146	26
	10	16.5	812	114.0	88	200	120	129	133	7

[1] Legumes reported here have been selected according to their response to liming i.e. low, medium and high response.

* Yield in gm/plant

** Fresh Weight

P.V. - *Phaseolus vulgaris*
L.L. K63 - *Leucaena leucocephala*, K63 variety
C.V. - *Coronilla varia*
A.H. - *Arachis hypogea*
G.M. - *Glycine max*, Kanrich variety
G.W. - *Glycine wightii*, Tinaroo variety
D.I. - *Desmodium intortum*
T.R. - *Trifolium repens* (white clover)
Stylo - *Stylosanthes fruticosa*, HA3038

Table 56. Field Lime Experiment: Plant Tissue Analysis of Temperate and Tropical Legumes.[1]

Legume	Plot No.	Mg	K	Ca	P	S	Al	Mn	Fe	Cu	Zn
		Percent					ppm				
Leucaena	1	0.34	1.04	0.97	0.21	0.26	66	156	95	6	21
leucocephala	2	0.31	0.95	0.98	0.21	0.25	138	103	105	10	17
(glauca)	3	0.33	0.92	0.89	0.20	0.24	42	144	70	6	21
K63	4	0.32	1.08	0.90	0.21	0.24	66	135	83	6	15
	5	0.31	1.13	0.95	0.21	0.25	53	130	79	6	17
(tropical)	6	0.32	0.96	1.07	0.19	0.23	44	148	64	7	16
	7	0.32	1.32	1.14	0.24	0.23	53	132	130	8	22
	8	0.28	1.36	1.10	0.23	0.21	51	98	97	7	14
	9	0.27	1.48	1.13	0.23	0.21	51	106	87	8	13
	10	0.27	1.73	1.34	0.25	0.21	66	124	129	10	19
Stylosanthes	1	0.22	2.98	1.78	0.31	0.35	485	264	639	24	99
fruticosa	2	0.21	3.11	1.71	0.30	0.34	545	282	823	26	102
(HA3038)	3	0.21	3.02	1.75	0.28	0.32	463	260	644	24	99
	4	0.21	3.11	1.70	0.28	0.35	461	269	602	25	113
	5	0.21	3.07	1.84	0.27	0.35	496	258	722	24	87
(tropical)	6	0.21	2.83	2.10	0.28	0.35	404	250	568	26	83
	7	0.22	3.06	1.96	0.29	0.37	495	283	672	28	112
	8	0.21	2.88	1.81	0.27	0.30	348	264	498	21	99
	9	0.21	2.76	1.94	0.29	0.30	347	232	509	21	90
	10	0.21	2.66	2.16	0.30	0.32	430	253	641	25	85
Arachis	1	0.39	1.79	1.37	0.26	0.18	77	322	78	8	83
hypogea	2	0.38	1.61	1.34	0.26	0.18	96	281	85	7	82
(peanut)	3	0.38	1.87	1.41	0.28	0.16	51	303	66	7	69
	4	0.38	1.66	1.46	0.26	0.18	95	378	117	9	88
	5	0.34	1.39	1.40	0.24	0.17	85	320	83	8	74
(tropical)	6	0.34	1.75	1.61	0.26	0.17	77	329	68	10	61
	7	0.31	1.55	1.57	0.26	0.16	59	307	96	8	56
	8	0.29	1.70	1.77	0.26	0.17	61	296	91	12	54
	9	0.30	1.66	1.77	0.27	0.19	82	229	136	12	55
	10	0.25	1.54	1.80	0.25	0.16	48	188	93	9	51
Coronilla	1	0.50	2.56	1.68	0.29	0.29	103	411	162	12	130
varia	2	0.51	2.17	1.78	0.29	0.27	135	429	192	15	155
	3	0.58	2.65	2.08	0.31	0.27	221	436	285	16	195
	4	0.46	2.38	1.35	0.26	0.27	136	345	160	12	141
	5	0.47	3.26	2.12	0.30	0.27	96	323	156	14	116
(temperate)	6	0.48	2.00	2.14	0.24	0.25	136	421	219	13	134
	7	0.33	2.03	1.70	0.29	0.18	172	211	235	11	94
	8	0.36	3.01	2.03	0.24	0.14	90	211	153	10	91
	9	0.22	2.61	1.51	0.26	0.16	86	151	140	9	66
	10	0.23	2.59	1.57	0.27	0.18	65	132	87	10	67

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[1] Values are for composite samples of all blocks

Table 57. Field Lime Experiment: Plant Tissue Analysis
of Temperate and Tropical Legumes.
Soybean (Glycine max), Kanrich Variety

Block	Plot	Mg	K	Ca	P	Si	S	Mn	Fe	Cu	Zn
No.	No.	Percent						ppm			
I	1	0.44	2.84	0.96	0.36	0.13	0.18	1021	134	12	148
	2	0.46	2.56	0.96	0.33	0.14	0.14	1118	124	9	140
	3	0.52	2.56	1.08	0.33	0.15	0.13	1276	113	9	166
	4	0.52	2.58	1.12	0.32	0.15	0.14	1074	108	8	147
	5	0.49	2.60	1.15	0.32	0.14	0.14	1186	122	8	137
	6	0.52	2.55	1.16	0.31	0.17	0.15	991	114	9	155
	7	0.53	2.49	1.36	0.31	0.16	0.15	950	131	8	124
	8	0.48	2.54	1.40	0.33	0.12	0.17	757	116	10	80
	9	0.47	2.46	1.46	0.31	0.12	0.17	752	112	8	93
	10	0.47	2.21	1.57	0.31	0.08	0.16	491	104	8	73
II	1	0.39	2.70	1.12	0.34	0.13	0.14	417	98	8	54
	2	0.46	2.67	1.31	0.33	0.15	0.14	685	101	8	96
	3	0.41	2.60	1.29	0.31	0.15	0.15	971	100	6	93
	4	0.43	2.64	1.27	0.37	0.15	0.14	793	105	7	82
	5	0.42	2.55	1.29	0.32	0.16	0.15	853	112	7	98
	6	0.44	2.38	1.41	0.32	0.15	0.14	775	104	7	86
	7	0.40	2.56	1.36	0.34	0.11	0.16	672	109	7	62
	8	0.44	2.60	1.42	0.34	0.10	0.16	752	100	9	65
	9	0.46	2.32	1.68	0.31	0.12	0.17	789	119	8	86
	10	0.38	2.34	1.43	0.30	0.08	0.16	476	102	9	39
III	1	0.41	1.94	1.04	0.26	0.18	0.16	1241	152	6	160
	2	0.41	2.04	0.95	0.27	0.14	0.16	1390	144	7	140
	3	0.37	1.80	0.92	0.25	0.13	0.16	1018	124	6	106
	4	0.33	2.27	0.99	0.30	0.13	0.20	1148	136	8	119
	5	0.36	2.29	1.15	0.33	0.11	0.21	1090	129	8	98
	6	0.39	2.33	1.14	0.31	0.13	0.20	1109	123	6	107
	7	0.41	2.39	1.20	0.31	0.15	0.20	1139	136	7	126
	8	0.38	2.25	1.26	0.32	0.12	0.17	882	119	8	84
	9	0.34	2.28	1.25	0.35	0.10	0.21	847	137	8	79
	10	0.33	2.11	1.34	0.33	0.11	0.21	790	131	7	100
IV	1	0.39	1.94	1.07	0.26	0.22	0.17	1015	130	7	157
	2	0.34	2.16	0.88	0.28	0.16	0.19	1259	161	7	125
	3	0.39	2.02	1.13	0.29	0.20	0.18	1017	135	7	139
	4	0.39	1.97	1.10	0.30	0.16	0.17	1116	129	7	124
	5	0.41	2.04	1.17	0.29	0.17	0.18	1153	143	7	123
	6	0.38	2.14	1.04	0.30	0.14	0.19	1349	144	7	117
	7	0.39	2.34	1.22	0.30	0.16	0.20	1198	137	7	118
	8	0.40	2.10	1.33	0.33	0.12	0.22	1219	123	7	112
	9	0.37	2.11	1.37	0.34	0.11	0.23	1148	131	7	114
	10	0.37	2.11	1.26	0.32	0.08	0.21	909	125	8	96

Table 58. Field Lime Experiment: Plant Tissue Analysis
of Temperate and Tropical Legumes.
(*Desmodium Intortum*).

Block	Plot	Mg	K	Ca	P	Si	S	Al	Mn	Fe	Cu	Zn
No.	No.	Percent						ppm				
I	1	0.32	3.00	1.04	0.25	0.33	0.27	828	949	1018	21	93
	2	0.32	2.82	1.01	0.24	0.33	0.25	792	795	1037	19	73
	3	0.36	2.52	1.07	0.21	0.27	0.28	533	908	635	17	98
	4	0.37	2.65	1.05	0.25	0.22	0.23	406	744	519	14	81
	5	0.29	2.96	0.83	0.23	0.34	0.25	1180	802	1680	26	73
	6	0.24	3.24	0.90	0.22	0.30	0.24	1136	714	1613	27	58
	7	0.23	3.06	1.09	0.23	0.15	0.20	424	498	597	14	44
	8	0.21	3.60	1.00	0.21	0.34	0.25	1595	672	2455	32	49
	9	0.20	4.08	1.05	0.22	0.57	0.38	2878	839	5047	52	62
	10	0.20	3.21	1.21	0.24	0.18	0.22	813	511	1189	19	43
II	1	0.27	2.95	1.26	0.28	0.29	0.30	841	588	1428	20	55
	2	0.28	3.13	1.44	0.28	0.29	0.32	848	727	1379	20	68
	3	0.25	3.13	1.37	0.29	0.26	0.28	524	470	852	17	48
	4	0.24	3.08	1.15	0.25	0.22	0.27	556	506	814	15	52
	5	0.27	3.09	1.27	0.29	0.25	0.33	1059	618	1101	22	63
	6	0.30	3.53	1.19	0.27	0.30	0.30	1252	746	2015	26	59
	7	0.26	3.73	1.20	0.29	0.41	0.33	1903	954	3083	38	66
	8	0.27	3.55	1.29	0.28	0.46	0.38	2255	1125	3736	43	81
	9	0.28	3.56	1.48	0.28	0.40	0.41	1868	1165	2990	36	93
	10	0.25	3.08	1.45	0.29	0.14	0.29	562	674	913	17	56
III	1	0.36	2.65	1.03	0.27	0.28	0.33	812	1297	1031	20	100
	2	0.31	2.76	0.92	0.25	0.38	0.32	1437	1036	2118	30	79
	3	0.28	3.32	1.00	0.23	0.29	0.25	1070	867	1551	24	65
	4	0.23	2.90	0.94	0.24	0.18	0.22	520	658	744	15	53
	5	0.25	3.11	0.98	0.22	0.27	0.25	1059	782	1532	23	58
	6	0.25	2.95	1.06	0.22	0.24	0.25	888	692	1275	20	58
	7	0.26	3.43	1.19	0.26	0.29	0.29	1311	789	2018	30	61
	8	0.26	3.16	1.23	0.28	0.17	0.25	607	599	885	18	51
	9	0.26	3.26	1.14	0.25	0.24	0.25	981	570	1492	22	48
	10	0.29	3.38	1.42	0.27	0.24	0.28	1205	661	1896	28	60
IV	1	0.30	2.48	1.22	0.25	0.24	0.30	482	682	717	13	56
	2	0.26	2.87	1.10	0.24	0.17	0.22	353	545	544	14	51
	3	0.24	2.76	1.08	0.21	0.17	0.21	374	386	569	12	43
	4	0.25	2.66	1.15	0.23	0.18	0.23	392	437	618	13	45
	5	0.23	2.93	1.12	0.19	0.16	0.18	351	384	612	11	37
	6	0.25	2.94	1.20	0.21	0.14	0.18	298	477	507	12	40
	7	0.23	2.97	1.27	0.22	0.10	0.17	204	433	330	10	39
	8	0.29	3.16	1.37	0.29	0.12	0.23	469	569	766	15	45
	9	0.25	3.40	1.30	0.27	0.20	0.25	997	572	1650	24	52
	10	0.26	3.15	1.44	0.31	0.14	0.26	642	560	1146	19	49

Table 59. Summary of Multiple Regression Analysis of Nutrient Uptake by *Leucaena leucocephala* (glauca) in Relation to Cations Extracted by Resin from Wahiawa Soil.

Dependent Varibles	Independent Variables in Multiple Regression Equation								
	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Al	7.1	-11.5 $K/\sqrt{Ca + Mg}$	0.89	0.1 Zn	0.94	-1.2 $\sqrt{Fe}$	0.95	-0.3 pH	0.97
Mg	-25.2	-144.5 $\log_e K$	0.92						
K	417.0	-140.7 $K/\sqrt{Ca + Mg}$	0.95						
Ca	317.6	-1055.9 $K/\sqrt{Ca + Mg}$	0.96						
Mn	11.6	-4.7 $\sqrt{K \times Cu}$	0.95	7.7 $\sqrt[3]{Al}/\sqrt{Ca+Mg}$	0.98				
Fe	-0.6	0.7 $\log_e(Ca/Mg)$	0.95						
Cu	-0.1	0.06 $\sqrt{Ca}$	0.97						
Zn	1.9	-0.34 $\sqrt{K \times Cu}$	0.95	-2.67 $K/\sqrt{Mn}$	0.98	-0.33 $\sqrt{K \times Fe}$	0.99		

Table 60. Correlation Coefficients[1] among Soil pH, Yield, Nutrient Uptake and Tissue Analysis of <u>Leucaena leucocephala</u> (glauca), and Cations Extracted by Resin from Wahiawa Soil.

	NH_4-RESIN							
	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
<u>Soil pH</u>								
	-0.58	-0.94	-0.98	0.90	-0.85	-0.51	-0.90	-0.92
<u>Yield</u>								
	-0.43	-0.92	-0.96	0.89	-0.75	-0.44	-0.89	-0.81
<u>Uptake</u>								
Al	-0.29	-0.91	-0.92	0.94	-0.60	-0.27	-0.89	-0.71
Mg	-0.47	-0.91	-0.96	0.87	-0.77	-0.47	-0.89	-0.81
K	-0.36	-0.96	-0.96	0.95	-0.72	-0.37	-0.93	-0.81
Ca	-0.39	-0.96	-0.96	0.95	-0.73	-0.40	-0.93	-0.82
P	-0.41	-0.94	-0.96	0.92	-0.74	-0.42	-0.91	-0.82
S	-0.44	-0.91	-0.95	0.87	-0.75	-0.45	-0.89	-0.79
Mn	-0.43	-0.95	-0.96	0.92	-0.76	-0.40	-0.94	-0.79
Fe	-0.38	-0.96	-0.94	0.96	-0.70	-0.40	-0.95	-0.80
Cu	-0.32	-0.96	-0.95	0.98	-0.66	-0.30	-0.93	-0.80
Zn	-0.39	-0.97	-0.94	0.95	-0.70	-0.40	-0.96	-0.78
<u>Tissue</u>								
Al	0.54	0.30	0.31	-0.10	0.68	0.63	0.28	0.44
Mg	0.38	0.81	0.90	-0.82	0.62	0.33	0.76	0.73
K	-0.41	-0.95	-0.93	0.93	-0.75	-0.43	-0.94	-0.89
Ca	-0.44	-0.88	-0.83	0.90	-0.69	-0.39	-0.89	-0.87
P	-0.32	-0.79	-0.74	0.79	-0.58	-0.40	-0.80	-0.77
S	0.62	0.81	0.90	-0.76	0.83	0.54	0.71	0.85
Mn	0.21	0.30	0.46	-0.35	0.18	0.18	0.27	0.33
Fe	-0.10	-0.49	-0.38	0.56	-0.21	-0.16	-0.55	-0.48
Cu	0.02	-0.47	-0.44	0.61	-0.04	0.18	-0.45	-0.33
Zn	0.27	0.13	0.38	-0.12	0.29	0.07	0.07	0.20
<u>NH_4-Resin</u>								
Al	1.00							
Mg	0.42	1.00						
K	0.54	0.95	1.00					
Ca	-0.25	-0.97	-0.91	1.00				
Mn	0.82	0.77	0.83	-0.62	1.00			
Fe	0.84	0.39	0.44	-0.23	0.75	1.00		
Cu	0.46	0.97	0.90	-0.93	0.75	0.47	1.00	
Zn	0.65	0.84	0.86	-0.77	0.91	0.66	0.85	1.00

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[1] r for significance at 0.05 probability with 8 d.f. = 0.632

Table 61. Summary of Multiple Regression Analysis of Nutrient Uptake by *Stylosanthes Fruticosa* in Relation to pH and Cations Extracted by Resin from Wahiawa Soil.

Dependent Variable	Independent Variables in Multiple Regression Equation										
	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Al	-43.8	619.3 $K/\sqrt[3]{Al}$	0.46	14.9 Zn	0.59	-611.1 Mg/Fe	0.95	-5.6 Ca + Mg	0.97	-13.3 Cu	0.98
Mg	3209.9	-2438.1 $\sqrt{Mg/Fe}$	0.64	-997.3 $\sqrt{Ca+Mg} + \sqrt[3]{Al}$	0.90	83.3 $\sqrt{Ca}/\sqrt[3]{Al}$	0.93	597.8 $\sqrt{K \times Cu}$	0.95	45.1 pH	0.97
K	-7774.8	15442.1 $K/\sqrt[3]{Al}$	0.56								
Ca	13180.6	-35483.7 $\sqrt[3]{Al}/\sqrt{Cu}$	0.33								
Mn	217.5	216.1 $K/\sqrt[3]{Al}$	0.57	-347.0 $\sqrt{Mg/Fe}$	0.70	-33.8 $\sqrt{Ca+Mg} + \sqrt[3]{Al}$	0.89				
Fe	1872.3	-476.1 Al x K	0.65	-798.0 $\sqrt{Cu}$	0.74	91.2 K x Cu	0.85	69.2 Fe	0.94	21.2 Zn	0.96
Cu	27.2	27.1 $K/\sqrt[3]{Al}$	0.40	-67.0 $\sqrt{Mg/Fe}$	0.64	-3.3 $\sqrt{Ca+Mg} + \sqrt[3]{Al}$	0.91	4.9 $\sqrt{Mg}/\sqrt[3]{Al}$	0.97		
Zn	-23.7	48.4 $K/\sqrt[3]{Al}$	0.48								

Table 62. Correlation Coefficients[1] among Soil pH, Yield, Nutrient Uptake and Tissue Analysis of Stylosanthes Fruticosa, and with Cations Extracted by Resin from Wahiawa Soil.

	NH_4-RESIN							
	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
Soil pH								
	-0.58	-0.94	-0.98	0.90	-0.86	-0.51	-0.90	-0.92
Yield								
	-0.40	0.32	0.28	-0.44	-0.04	-0.14	0.31	0.31
Uptake								
Al	0.00	0.55	0.59	-0.59	0.42	0.19	0.48	0.63
Mg	-0.40	0.34	0.32	-0.47	-0.03	-0.15	0.33	0.29
K	-0.29	0.50	0.45	-0.62	0.14	-0.05	0.49	0.47
Ca	-0.57	-0.03	-0.04	-0.09	-0.31	-0.27	-0.05	-0.06
P	-0.27	0.34	0.34	-0.43	0.07	0.01	0.33	0.35
S	-0.34	0.39	0.38	-0.51	0.05	-0.06	0.35	0.34
Mn	-0.34	0.44	0.42	-0.54	0.11	-0.12	0.42	0.40
Fe	-0.01	0.49	0.53	-0.51	0.44	0.20	0.41	0.61
Cu	-0.34	0.31	0.31	-0.40	0.04	-0.03	0.30	0.30
Zn	-0.24	0.49	0.44	-0.59	0.13	-0.05	0.52	0.42
Tissue								
Al	0.48	0.53	0.66	-0.45	0.74	0.50	0.44	0.68
Mg	0.13	0.19	0.33	-0.20	0.07	-0.07	0.09	-0.09
K	0.25	0.85	0.82	-0.86	0.66	0.27	0.80	0.77
Ca	-0.53	-0.73	-0.67	0.69	-0.68	-0.35	-0.75	-0.72
P	0.65	-0.07	0.10	0.24	0.35	0.58	-0.07	0.03
S	0.01	0.47	0.54	-0.50	0.30	0.18	0.35	0.37
Mn	0.12	0.49	0.54	-0.43	0.49	0.07	0.42	0.41
Fe	0.45	0.40	0.50	-0.28	0.72	0.49	0.30	0.60
Cu	-0.03	0.23	0.33	-0.21	0.26	0.22	0.18	0.26
Zn	0.15	0.42	0.40	-0.42	0.29	0.11	0.48	0.30

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[1] r for significance at 0.05 probability with 8 d.f. = 0.632

Table 63. Summary of Multiple Regression Analysis of Tropical and Temperate Legume Yields in Relation to pH and Cations Extracted by Resin from Wahiawa Soil.

Dependent Variable	Independent Variables in Multiple Regression Equation												
	Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
P. vulgaris	-16544.8	-3340.8 $\frac{\sqrt{Mg}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.60	-39.2 Ca/Mg	0.64	-14166.9 $\log_e K$	0.66	17794.0 K	0.71	30.4 Mg x Ca	0.74	10.2 pH^2	0.76
L. leucocephala	-1.6	0.3 pH^2	0.64	-1.5 Fe	0.69	1.7 $\sqrt{Ca}$	0.71						
C. varia	-601.7	9.7 Ca/Mg	0.70	7.0 Fe	0.77	-20.8 Al x Ca	0.79	114.0 $\sqrt{Al \times Ca}$	0.81	-14.4 pH^2	0.84	151.7 pH	0.86
A. hypogea	216.6	49.2 $\sqrt{Ca}/\sqrt[3]{Al}$	0.24	9.1 pH	0.38	-9.5 Ca/Mg	0.42	-766.3 $\frac{\sqrt{Mg}}{\sqrt{Ca+Mg} + \sqrt[3]{Al}}$	0.51				
G. max	924.0	10.7 pH^2	0.46	-469.7 $\sqrt{pH}$	0.49								
G. wightii	-583.0	228.4 $\sqrt{pH}$	0.57	-19.9 Al x Ca	0.59	97.7 $\sqrt{Al \times Ca}$	0.61						
S. fruticosa	-7652.7	6.1 Zn	0.16	-84.2 pH^2	0.27	4522.4 $\sqrt{pH}$	0.34	16.6 Al x Ca	0.51	-231.8 $\sqrt{Mg}$	0.58	0.7 Mn	0.60
D. intortum	44.8	31.4 Mg x Ca	0.17	73.1 $K/\sqrt[3]{Al}$	0.27	-212.7 $\sqrt{Mg \times Ca}$	0.31	-130.6 Al^2	0.35	384.5 $\sqrt[3]{Al}$	0.39		
T. repens	-2413.5	1258.9 $\sqrt{pH}$	0.65	-18.9 pH^2	0.69	-3434.8 $\sqrt[3]{Al}/\sqrt{Ca}$	0.74	4180.3 $\sqrt[3]{Al}/\sqrt{Ca+Mg}$	0.77	-3.2 Cu	0.78	50.1 Al x Mg	0.80

Table 64. Correlation Coefficients[1] among Tropical and Temperate Legume Yields, Soil pH and Cations Extracted by Resin from Wahiawa Soil.

Legumes	pH	Al	Mg	K	Ca	Mn	Fe	Cu	Zn
Phaseolus vulgaris	0.76	-0.21	-0.71	-0.49	0.73	-0.39	-0.11	-0.17	-0.34
Leucaena leucocephala	0.80	-0.31	-0.71	-0.50	0.71	-0.51	-0.37	-0.39	-0.50
Coronilla varia	0.55	-0.17	-0.70	-0.36	0.83	-0.20	0.20	0.002	-0.16
Arachis hypogea	0.24	-0.17	-0.14	0.26	0.09	-0.03	0.37	0.46	0.17
Glycine max	0.67	-0.11	-0.57	-0.30	0.62	-0.33	-0.05	-0.06	-0.24
Glycine wightii	0.75	-0.43	-0.61	-0.46	0.55	-0.54	-0.11	-0.16	-0.40
Stylosanthes fruticosa	-0.23	0.04	0.05	0.32	-0.12	0.32	0.19	0.32	0.40
Desmodium intortum	0.15	-0.33	-0.13	0.03	0.25	-0.23	0.23	0.16	-0.05
Trifolium repens	0.80	-0.33	-0.66	-0.42	0.62	-0.55	-0.22	-0.25	-0.47

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[1] Correlation coefficients were obtained from a multiple regression analysis using individual yield values; r for significance at 0.05 probability with 38 d.f.=312.

Table 65. Summary of Multiple Regression Analysis of Nutrient Uptake by *Leucaena leucocephala* in Relation to Cations Extracted by Single and Multiple Resin Discs from Wahiawa Soil.

Dependent Variable	Number of resin discs	Independent Variables in Multiple Regression Equation								
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Al	1	2.6	-3.7 $K/\sqrt{Ca + Mg}$	0.89	-13.0 $K/\sqrt{Mn}$	0.93				
	2	-0.1	0.5 $K/\sqrt{Ca + Mg}$	0.89	-0.1 Zn	0.93	-3.5 $\log_e K$	0.95	-0.5 Mg	0.97
	3	7.1	-11.5 $K/\sqrt{Ca + Mg}$	0.89	0.1 Zn	0.94	-1.2 $\sqrt{Fe}$	0.95	-0.3 pH	0.97
Mg	1	-57.1	-192.0 $\log_e K$	0.93	52.3 $\sqrt[3]{Al}$	0.94				
	2	173.0	-790.4 $K/\sqrt{Cu}$	0.91						
	3	-25.2	-144.5 $\log_e K$	0.92						
K	1	364.5	-2088.6 $K/\sqrt{Ca + Mg}$	0.97	924.2 $Al/\sqrt{Ca + Mg}$	0.98				
	2	416.9	-1302.4 $K/\sqrt{Ca + Mg}$	0.96						
	3	417.0	-140.7 $K/\sqrt{Ca + Mg}$	0.95						
Ca	1	325.6	-826.9 $K/\sqrt{Ca + Mg}$	0.96						
	2	316.7	-973.8 $K/\sqrt{Ca + Mg}$	0.96						
	3	317.6	-1055.9 $K/\sqrt{Ca + Mg}$	0.96						

Table 65. (Continued) Summary of Multiple Regression Analysis of Nutrient Uptake by *Leucaena leucocephala* in Relation to Cations Extracted by Single and Multiple Resin Discs from Wahiawa Soil.

Dependent Variable	Number of resin discs	Independent Variables in Multiple Regression Equation								
		Constant	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2	Coefficient & Variable	R^2
Mn	1	38.7	-7.5 $\sqrt{K \times Fe}$	0.91	-0.8 pH	0.95	-1.3 $\sqrt{K \times Cu}$	0.96		
	2	-0.4	-4.5 $\log_e K$	0.89	0.02 Ca/Mg	0.91				
	3	11.6	-4.7 $\sqrt{K \times Cu}$	0.95	7.7 $\sqrt[3]{Al}/\sqrt{Ca+Mg}$	0.98				
Fe	1	2.2	-5.6 $K/\sqrt{Ca+Mg}$	0.94	0.03 Ca/Mg	0.96				
	2	2.9	-9.0 $K/\sqrt{Ca+Mg}$	0.95						
	3	-0.6	0.7 $\log_e(Ca/Mg)$	0.95						
Cu	1	0.4	-0.6 $K/\sqrt{Ca+Mg}$	0.97	-1.4 $K/\sqrt{Mn}$	0.99				
	2	-0.04	0.1 $\log_e(Ca/Mg)$	0.97						
	3	-0.1	0.06 $\sqrt{Ca}$	0.97						
Zn	1	2.3	-3.5 $K/\sqrt{Ca+Mg}$	0.92	0.05 Ca/Mg	0.94	-0.3 $\sqrt{Ca}$	0.96	-0.2 $\sqrt{Ca/Mg}$	0.97
	2	0.4	-1.2 $K/\sqrt{Ca+Mg}$	0.93						
	3	1.9	-0.3 $\sqrt{K \times Cu}$	0.95	-2.7 $K/\sqrt{Mn}$	0.98	-0.3 $\sqrt{K \times Fe}$	0.99		

APPENDIX V

Programs for Computing Cation and Anion Concentrations

PROGRAM FOR COMPUTING CATION CONCENTRATION

```
      DIMENSION A(11,12),SMPNO(6),NA(6),MG(6),AL(6),SI(6),CL(6),K(6),
     1CA(6),MN(6),FE(6),CU(6),ZN(6),CHNO(6,4),CNA(6),CMG(6),CAL(6),
     2CSI(6),CCL(6),CK(6),CCA(6),CMN(6),CFE(6),CCU(6),CZN(6),TITLE(20)
      INTEGER SMPNO,BATCH
      REAL NA,MG,K,MN
      DATA SKIP/'0000'/,HALT/'9999'/
      DO 5 I=1,11
C     READING COEFFICIENT CARDS
    5 READ (5,100) (A(I,J), J=1,12)
  100 FORMAT (10F8.0/2F8.0)
C     READING THE NUMBER OF DISCS PER TREATMENT
      READ (5,110) NUMBER
C     NUMBER IS THE NUMBER OF DISCS
  110 FORMAT (I2)
      NUM = NUMBER * 2
      DO 20 I = 1,NUM
C     READING THE CHECK INTENSITIES
      READ (5,125) (CHNO(I,L),L=1,4),CNA(I),CMG(I),CAL(I),CSI(I),CCL(I),
     1CK(I),CCA(I),CMN(I),CFE(I),CCU(I),CZN(I)
  125 FORMAT (4A1,11F6.3)
   20 CONTINUE
      CHNA=0.0
      CHMG=0.0
      CHAL=0.0
      CHSI=0.0
      CHCL=0.0
      CHK =0.0
      CHCA=0.0
      CHMN=0.0
      CHFE=0.0
      CHCU=0.0
      CHZN=0.0
      DO 25 I = 1,NUM
C     SUMMING THE CHECK INTENSITIES
      CHNA =CHNA + CNA(I)
      CHMG =CHMG + CMG(I)
      CHAL =CHAL + CAL(I)
      CHSI =CHSI + CSI(I)
      CHCL =CHCL + CCL(I)
      CHK  =CHK  + CK(I)
      CHCA =CHCA + CCA(I)
      CHMN =CHMN + CMN(I)
      CHFE =CHFE + CFE(I)
      CHCU =CHCU + CCU(I)
      CHZN =CHZN + CZN(I)
   25 CONTINUE
C     AVERAGING THE CHECK INTENSITIES
      CHNA =CHNA / NUM
      CHMG =CHMG / NUM
      CHAL =CHAL / NUM
      CHSI =CHSI / NUM
      CHCL =CHCL / NUM
      CHK  =CHK  / NUM
      CHCA =CHCA / NUM
      CHMN =CHMN / NUM
      CHFE =CHFE / NUM
      CHCU =CHCU / NUM
      CHZN =CHZN / NUM
      READ (5,400) BATCH
```

PROGRAM FOR COMPUTING CATION CONCENTRATION

(continued)

```
 400 FORMAT (I2)
 425 DO 450 N=1,BATCH
     WRITE (6,650)
 650 FORMAT('1',30X,'ELEMENTAL ANALYSIS OF ION EXCHANGE RESIN MEMBRANE
    1BY X-RAY QUANTOMETER'//45X,'DEPARTMENT OF AGRONOMY AND SOIL SCIENC
    2E'//49X,'COLLEGE OF TROPICAL AGRICULTURE'//49X,'PLANT TISSUE TESTI
    3NG LABORATORY'///)
     WRITE (6,800)
 800 FORMAT (53X,'ELEMENTAL CONCENTRATIONS'//27X,'* * * * * * * * * MIL
    1LIGRAMS * * * * * * * * *      '* * * * * * * * MICROGRAMS * * * * *
    2 * *'/13X,'SAMPLE NOS',6X,'NA',9X,'MG',8X,'AL',9X,'K',8X,'CA',12X,
    3'MN',8X,'FE',3X,'CU',8X,'ZN'//)
  85 READ (5,600) (TITLE(L),L=1,20)
 600 FORMAT (20A4)
     IF(TITLE(1).EQ.SKIP) GO TO 450
     IF(TITLE(1).EQ.HALT)STOP
     WRITE (6,605) (TITLE (L),L=1,20)
 605 FORMAT (10X,20 A4,/)
 610 DO 10  I= 1,NUM
C      READING THE TREATMENT INTENSITIES
     READ (5,120) SMPNO(I),NA(I),MG(I),AL(I),SI(I),CL(I),K(I),CA(I),
    1MN(I),FE(I),CU(I),ZN(I)
 120 FORMAT(A4,11F6.3)
  10 CONTINUE
     SNA= 0.0
     SMG= 0.0
     SAL= 0.0
     SSI= 0.0
     SCL= 0.0
     SK = 0.0
     SCA= 0.0
     SMN= 0.0
     SFE= 0.0
     SCU= 0.0
     SZN= 0.0
C      SUMMING THE TREATMENT INTENSITIES
     DO 30 I=1,NUM
     SNA= SNA +  NA(I)
     SMG= SMG +  MG(I)
     SAL= SAL +  AL(I)
     SSI= SSI +  SI(I)
     SCL= SCL +  CL(I)
     SK = SK  +  K (I)
     SCA= SCA +  CA(I)
     SMN= SMN +  MN(I)
     SFE= SFE +  FE(I)
     SCU= SCU +  CU(I)
     SZN= SZN +  ZN(I)
  30 CONTINUE
C      AVERAGING THE TREATMENT INTENSITIES
     SANA= SNA / NUM
     SAMG= SMG / NUM
     SAAL= SAL / NUM
     SASI= SSI / NUM
     SACL= SCL / NUM
     SAK = SK  / NUM
     SACA= SCA / NUM
     SAMN= SMN / NUM
     SAFE= SFE / NUM
```

PROGRAM FOR COMPUTING CATION CONCENTRATION
(continued)

```
      SACU= SCU / NUM
      SAZN= SZN / NUM
C     AVE. CHECK INTENSITY SUBTRACTED FROM AVE. TREAT. INTENSITY
      TNA=SANA- CHNA
      TMG=SAMG- CHMG
      TAL=SAAL- CHAL
      TSI=SASI- CHSI
      TCL=SACL- CHCL
      TK =SAK - CHK
      TCA=SACA- CHCA
      TMN=SAMN- CHMN
      TFE=SAFE- CHFE
      TCU=SACU- CHCU
      TZN=SAZN- CHZN
      QNA=A(1,1)+A(1,2)*TNA+A(1,3)*TNA*TMG+A(1,4)*TNA*TAL+A(1,5)*TNA*TSI
     1+A(1,6)*TNA*TCL+A(1,7)*TNA*TK+A(1,8)*TNA*TCA+A(1,9)*TNA*TMN+A(1,10
     2)*TNA*TFE+A(1,11)*TNA*TCU+A(1,12)*TNA*TZN
      QMG=A(2,1)+A(2,2)*TMG*TNA+A(2,3)*TMG+A(2,4)*TMG*TAL+A(2,5)*TMG*TSI
     1+A(2,6)*TMG*TCL+A(2,7)*TMG*TK+A(2,8)*TMG*TCA+A(2,9)*TMG*TMN+A(2,10
     2)*TMG*TFE+A(2,11)*TMG*TCU+A(2,12)*TMG*TZN
      QAL=A(3,1)+A(3,2)*TAL*TNA+A(3,3)*TAL*TMG+A(3,4)*TAL+A(3,5)*TAL*TSI
     1+A(3,6)*TAL*TCL+A(3,7)*TAL*TK+A(3,8)*TAL*TCA+A(3,9)*TAL*TMN+A(3,10
     2)*TAL*TFE+A(3,11)*TAL*TCU+A(3,12)*TAL*TZN
      QK=A(6,1)+A(6,2)*TK*TNA+A(6,3)*TK*TMG+A(6,4)*TK*TAL+A(6,5)*TK*TSI+
     1A(6,6)*TK*TCL+A(6,7)*TK+A(6,8)*TK*TCA+A(6,9)*TK*TMN+A(6,10)*TK*TFE
     2+A(6,11)*TK*TCU+A(6,12)*TK*TZN
      QCA=A(7,1)+A(7,2)*TCA*TNA+A(7,3)*TCA*TMG+A(7,4)*TCA*TAL+A(7,5)*TCA
     1*TSI+A(7,6)*TCA*TCL+A(7,7)*TCA*TK+A(7,8)*TCA+A(7,9)*TCA*TMN+A(7,10
     2)*TCA*TFE+A(7,11)*TCA*TCU+A(7,12)*TCA*TZN
      QMN=A(8,1)+A(8,2)*TMN*TNA+A(8,3)*TMN*TMG+A(8,4)*TMN*TAL+A(8,5)*TMN
     1*TSI+A(8,6)*TMN*TCL+A(8,7)*TMN*TK+A(8,8)*TMN*TCA+A(8,9)*TMN+A(8,10
     2)*TMN*TFE+A(8,11)*TMN*TCU+A(8,12)*TMN*TZN
      QFE=A(9,1)+A(9,2)*TFE*TNA+A(9,3)*TFE*TMG+A(9,4)*TFE*TAL+A(9,5)*TFE
     1*TSI+A(9,6)*TFE*TCL+A(9,7)*TFE*TK+A(9,8)*TFE*TCA+A(9,9)*TFE*TMN+A(
     29,10)*TFE+A(9,11)*TFE*TCU+A(9,12)*TFE*TZN
      QCU=A(10,1)+A(10,2)*TCU*TNA+A(10,3)*TCU*TMG+A(10,4)*TCU*TAL+A(10,5
     1)*TCU*TSI+A(10,6)*TCU*TCL+A(10,7)*TCU*TK+A(10,8)*TCU*TCA+A(10,9)*T
     2CU*TMN+A(10,10)*TCU*TFE+A(10,11)*TCU+A(10,12)*TCU*TZN
      QZN=A(11,1)+A(11,2)*TZN*TNA+A(11,3)*TZN*TMG+A(11,4)*TZN*TAL+A(11,5
     1)*TZN*TSI+A(11,6)*TZN*TCL+A(11,7)*TZN*TK+A(11,8)*TZN*TCA+A(11,9)*T
     2ZN*TMN+A(11,10)*TZN*TFE+A(11,11)*TZN*TCU+A(11,12)*TZN
C     PRINTING VALUES CALCULATED WITH CHECK SUBTRACTED
      QNA= QNA * NUMBER
      QMG= QMG * NUMBER
      QAL= QAL * NUMBER
      QK = QK  * NUMBER
      QCA= QCA * NUMBER
      QMN= QMN * NUMBER * 1000.
      QFE= QFE * NUMBER * 1000.
      QCU= QCU * NUMBER * 1000.
      QZN= QZN * NUMBER * 1000.
C     PRINTING VALUES CALCULATED FOR AVE. TREAT. MINUS AVE. CHECK FOR 3 DISCS
C     STATEMENTS TO PRINT 0.0 IF CONC.COMPUTED IS NEGATIVE
      IF (QNA) 300,305,305
  300 QNA=0.0
  305 IF (QMG) 310,315,315
  310 QMG=0.0
  315 IF (QAL) 320,325,325
  320 QAL=0.0
```

PROGRAM FOR COMPUTING CATION CONCENTRATION
(continued)

```
325 IF (QK) 330,335,335
330 QK=0.0
335 IF (QCA) 340,345,345
340 QCA=0.0
345 IF (QMN) 350,355,355
350 QMN=0.0
355 IF (QFE) 360,365,365
360 QFE=0.0
365 IF (QCU) 370,375,375
370 QCU=0.0
375 IF (QZN) 380,385,385
380 QZN=0.0
385 WRITE (6,850) SMPNO(1),QNA,QMG,QAL,QK,QCA,QMN,QFE,QCU,QZN
850 FORMAT (16X,A4,7X,4(F6.2,4X),F6.2,7X,F7.2,4X,3(F6.2,4X)/)
    GO TO 85
450 CONTINUE
    END
```

PROGRAM FOR COMPUTING ANION CONCENTRATION

```
      DIMENSION A(4,5),SMPNO(6),SI(6),P(6),S(6),MO(6),MOB(6),CHNO(6,4),
     1CSI(6),CP(6),CS(6),CMO(6),CMOB(6),TITLE(20)
      INTEGER SMPNO,BATCH
      REAL MO,MOB
      DATA SKIP/'0000'/,HALT/'9999'/
      DATA SLOP,CEPT/2.832,3.307/
      DO 5 I=1,4
C     READING COEFFICIENT CARDS
    5 READ (5,100) (A(I,J),J=1,5)
  100 FORMAT (5F3.0)
C     READING THE NUMBER OF DISCS PER TREATMENT
      READ (5,110)NUMBER
C     NUMBER IS THE NUMBER OF DISCS
  110 FORMAT (I2)
      NUM = NUMBER * 2
      DO 20 I=1,NUM
C     READING THE CHECK INTENSITIES
      READ (5,125) (CHNO(I,L),L=1,4),CSI(I),CP(I),CS(I),CMO(I),CMOB(I)
  125 FORMAT (4A1,5F6.3)
   20 CONTINUE
      CHSI=0.0
      CHP =0.0
      CHS =0.0
      CHMO=0.0
      CHMOB=0.0
      DO 25 I=1,NUM
C     SUMMING THE CHECK INTENSITIES
      CHSI=CHSI+CSI(I)
      CHP =CHP +CP(I)
      CHS =CHS +CS(I)
      CHMO=CHMO+CMO(I)
      CHMOB=CHMOB+CMOB(I)
   25 CONTINUE
C     AVERAGING THE CHECK INTENSITIES
C     A= AVERAGE
      ACHSI=CHSI/NUM
      ACHP =CHP/NUM
      ACHS =CHS/NUM
      ACHMO=CHMO/NUM
      ACHMOB=CHMOB/NUM
C     SUBTRACTING AVE. CHECK MOB FROM AVE. CHECK MO INTENSITY
C     C=CORRECTED MO INTENSITY
      CCHMO =ACHMO-ACHMOB
      READ (5,400) BATCH
  400 FORMAT (I2)
  425 DO 450 N=1,BATCH
      WRITE (6,650)
  650 FORMAT('1',30X,'ELEMENTAL ANALYSIS OF ION EXCHANGE RESIN MEMBRANE
     1BY X-RAY QUANTOMETER'//45X,'DEPARTMENT OF AGRONOMY AND SOIL SCIENC
     2E'//49X,'COLLEGE OF TROPICAL AGRICULTURE'//49X,'PLANT TISSUE TESTI
     3NG LABORATORY'///)
      WRITE (6,800)
  800 FORMAT (53X,'ELEMENTAL CONCENTRATIONS'//29X,' * * * * * * * * * *
     1* * * *  PARTS PER MILLION * * * * * * * * * * * * * * * * * * '//
     280X
     3,'MOLYBDENUM           MOLYBDENUM'/10X,'SAMPLE NUMBER       SILICON
     4          PHOSPHORUS          SULFUR                 BY
     5 BY'/75X,'MULTIPLE LINEAR REG.     LINEAR REG.'/)
   85 READ (5,600) (TITLE(L),L=1,20)
```

PROGRAM FOR COMPUTING ANION CONCENTRATION

(continued)

```
  600 FORMAT (20A4)
      IF(TITLE(1).EQ.SKIP) GO TO 450
      IF(TITLE(1).EQ.HALT)STOP
      WRITE (6,605) (TITLE (L),L=1,20)
  605 FORMAT (10X,20A4,/)
  610 DO 10 I=1,NUM
C     READING THE TREATMENT INTENSITIES
      READ (5,120) SMPNO(I),SI(I),P(I),S(I),MO(I),MOB(I)
  120 FORMAT (A4,5F6.3)
   10 CONTINUE
      SSI  = 0.0
      SP   = 0.0
      SS   = 0.0
      SMO  = 0.0
      SMOB= 0.0
C     SUMMING THE TREATMENT INTENSITIES
      DO 30 I=1,NUM
      SSI  =SSI+SI(I)
      SP   =SP+P(I)
      SS   =SS+S(I)
      SMO  =SMO+MO(I)
      SMOB=SMOB+MOB(I)
   30 CONTINUE
C     AVERAGING THE TREATMENT INTENSITIES
      ASSI =SSI/NUM
      ASP  =SP/NUM
      ASS  =SS/NUM
      ASMO =SMO/NUM
      ASMOB=SMOB/NUM
C     SUBTRACTING AVE. SAMPLE MOB FROM AVE. SAMPLE MO INTENSITY
C     C = CORRECTED  MO INTENSITY
      CSMO=ASMO-ACHMO
C     SUBTRACTING AVE. CHECK INTENSITY FROM AVE. TREATMENT INTENSITY
      TSI=ASSI-ACHSI
      TP =ASP-ACHP
      TS =ASS-ACHS
      TMO=CSMO-CCHMO
      QSI=A(1,1)+A(1,2)*TSI+A(1,3)*TSI*TP+A(1,4)*TSI*TS+A(1,5)*TSI*TMO
      QP=A(2,1)+A(2,2)*TP*TSI+A(2,3)*TP+A(2,4)*TP*TS+A(2,5)*TP*TMO
      QS=A(3,1)+A(3,2)*TS*TSI+A(3,3)*TS*TP+A(3,4)*TS+A(3,5)*TS*TMO
      QMO=A(4,1)+A(4,2)*TMO*TSI+A(4,3)*TMO*TP+A(4,4)*TMO*TS+A(4,5)*TMO
C     COMPUTATION BY STRAIGHT LINE EQUATION
C     SLOP=LINE SLOPE
C     CEPT=INTERCEPT ON Y AT X=0
      ALMO=SLOP*TMO+CEPT
C     FINAL COMPUTATION
      QSI = QSI * NUMBER*1000
      QP  = QP * NUMBER*1000
      QS  = QS * NUMBER*1000
      QMO = QMO * NUMBER *1000
      ALMO=ALMO*NUMBER*1000
C     PRINTING  FINAL RESULTS
C     STATEMENTS TO PRINT 0.0 IF CONCENTRATION COMPUTED IS NEGATIVE
      IF (QSI) 300,305,305
  300 QSI =0.0
  305 IF (QP) 310,315,315
  310 QP=0.0
  315 IF (QS) 320,325,325
  320 QS=0.0
```

PROGRAM FOR COMPUTING ANION CONCENTRATION

(continued)

```
325 IF (QMO) 330,335,335
330 QMO=0.0
335 IF (ALMO) 340,345,345
340 ALMO=0.0
345 WRITE(6,850) SMPNO(1),QSI,QP,QS,QMO,ALMO
850 FORMAT (14X,A4,13X,F6.2,11X,F6.2,11X,F6.2,12X,F5.2,14X,F6.2)
    GO TO 85
450 CONTINUE
    END
```

APPENDIX VI

Suggestions for Further Research

SUGGESTIONS FOR FURTHER RESEARCH

There is a need for:

1) Improvement of technique for P extraction. For this, OH-saturated anion exchange resin is recommended.
2) More testing of single and multiple resin disc extraction to determine the resin-cell combination that involves less time in sample preparation and yet gives good results.
3) More testing of method with field samples. Soil sampling and analysis at the following times in field experiments are strongly recommended for better correlation of resin extraction with plant uptake. They are:
    a) Before planting.
    b) During growing period of crop.
    c) After harvest.