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EFFECTS OF HEAVY APPLICATIONS OF LIME TO SOILS DERIVED FROM VOLCANIC ASH ON THE HUMID HILO AND HAMAKUA COASTS, ISLAND OF HAWAII.

University of Hawaii, Ph.D., 1962
Agriculture, soil science
University Microfilms, Inc., Ann Arbor, Michigan

EFFECTS OF HEAVY APPLICATIONS OF LIME TO SOILS DERIVED FROM VOLCANIC ASH ON THE HUMID HILO AND HAMAKUA COASTS, ISLAND OF HAWAII

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

JANUARY 1962

By

Alan James Rixon

THESIS COMMITTEE

Dr. G. Donald Sherman, Chairman

Dr. Otto R. Younge

Dr. Agatin T. Abbot

Dr. Neal M. Bowers

Dr. Bruce J. Cooil

Dr. Donald H. Smith

ACKNOWLEDGMENTS

This investigation was conducted in the Department of Agronomy and Soil Science, University of Hawaii. I wish to acknowledge the encouragement and advice of Dr. G. Donald Sherman and the rest of the soil scientists of this department. The cooperation of Dr. H. F. Clements and field workers of C. Brewer & Company's sugar plantations has been appreciated. Finally, I wish to thank my wife, Patricia, for her continuous encouragement and assistance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

The humid tropics provide an environment conducive to active alteration of geological material. Volcanic ash with its high porosity and extensive specific surface area weathers rapidly under these conditions. There is a heavy loss of silica and bases and an accumulation of iron and aluminum compounds. The resulting soils have a low content of crystalline clay minerals in the clay fraction, an acid reaction and a low base status particularly in regard to calcium. Soils derived from volcanic parent material are of considerable agricultural importance in the humid tropics. Abundant sources of lime in the form of coral stone often occur in the vicinity of these acidic soils. Thus an understanding of the effects of lime application to such soils is desirable.

In their natural conditions the soils of the humid tropics support a dense vegetation. Lumber is a natural product from such locations. Where there is favorable topography the natural vegetation is often replaced by agricultural crops and pastures. Modifications, which may include liming of these soils are often necessary to obtain the most efficient production of these introduced species.

Liming in the temperate regions has been intensively studied. At this stage there is a fairly comprehensive knowledge of the effects of liming on the soils of these latitudes. Frequently, these studies have been conducted with soils having a high percentage of crystalline clay minerals in their clay fraction. Only sparse and fragmentary knowledge regarding the effects of liming in the humid tropics is available. The existing information is often concerned with relatively light applications of lime.

The soils derived from volcanic ash, in this study, are located on the humid Hamakua and Hilo coasts on the Island of Hawaii. They are used for growing sugar cane. A series of lime phosphate experimental plots has been installed on the Hilo and Hamakua coasts, with the aim of increasing the yields of sugar cane. The high aluminum content and low pH values of these soils present the possibility that toxic amounts of aluminum may be a limiting factor in plant growth. These soils are highly amorphous, having a high capacity to fix phosphates, thus making them sparingly soluble for plant use. It is suggested that benefits to sugar cane, because of heavy liming of these soils, are due to either the reduction of the toxic effects of aluminum or improved phosphate availability. In the latter case, applied lime may produce a liberation of fixed phosphate, or reduced fixation when phosphatic fertilizers are added simultaneously, or a combination of both these effects could occur. Accordingly, in the present study, the effects of heavy lime application on the soil properties, leaching losses, and presence of various elements in sugar cane tissues were investigated. Inasmuch as little information in regard to soil modifications and sugar cane response to heavy lime applications is available, the investigation of this problem appeared worthwhile.

LITERATURE REVIEW

1. Climate, weathering processes and properties of soils derived from volcanic ash in the humid tropics

a. Climate

According to the Trewartha (124) system of climatic classification the Hamakua and Hilo coasts on the Island of Hawaii have a tropical wet climate. The two most distinguishing features of such a climate are uniformly high temperature and heavy precipitation distributed throughout the year so that there is no marked dry season.

b. Rock weathering and soil formation in tropical regions

Compared with the other regions, a more rapid rate of alteration of soil-forming materials is a feature of the humid tropics. This is due to a high moisture content and to prevailing high temperatures which accelerate the rate of chemical reaction. The literature provides some generalizations concerning weathering in the tropics. These situations usually present relationships between meteorological features and soil properties. Tanada (118) found that SiO_2/AL_2O_3 ratio decreases with increasing rainfall in Hawaiian soils. Similar relationships are reported by Prescott and Hoskins (93) for red basaltic soils from eastern Australia, by Martin and Doyne (64) from Sierra Leone and by Craig and Hailais (25) from Mauritius. Harrison (47) conducted a number of detailed analyses concerning the alteration of igneous rocks in British Guiana. He found a great loss of silica was accompanied by an increase in aluminum when dolerite was weathered in British Guiana. The English term "dolerite" is equivalent to the American term "diabase". Gordon and Tracey (39) considered that a warm more or less continuously moist sub-tropical to tropical climate in early Eocene time provided the ideal chemical environment for the formation of the Arkansas bauxite deposits. Sherman (108) stated under an evenly distributed high rainfall the kaolinite clays decompose into their "free oxides". The free oxides in this case are the hydrated oxides of aluminum especially gibbsite and the iron oxide limonite. Mohr and van Baren (75) considered that the alteration of basic or intermediate rocks under good drainage conditions is accompanied by almost complete removal of silica and bases. There is an accumulation of hydrated aluminum compounds, limonite, a few unaltered fragments of feldspar, and at times secondary quartz.

c. Volcanic ash and rate of weathering of volcanic ash

Wentworth and Williams (131) defined volcanic ash as a pyroclastic rock whose fragments are less than 4 millimeters in diameter. Pyroclastic rocks are the products of explosive volcanic eruptions. An understanding of the rapid rate of alteration of volcanic ashes may be gained by considering the rate of establishment of vegetation on areas where ash has been deposited. The catastrophic explosion of Krakatoa in 1883 completely destroyed all the flora of this island according to Docters van Leeuwen (28). It was reported that one year later only a few shoots of grass were present. Three years later 26 species, including cryptograms, monocotyls and dicotyls were reported. The 1951 eruption of Mount Lamington, Papua, described by Taylor (121) produced a volume of volcanic ash and in the process partially or completely devastated an area of 90 square miles. Three days after the eruption, and following some intervening light rain, a fungus appeared on the freshly deposited ash. Within two months garden plants, such as yams, taro, sweet potatoes and bananas were growing vigorously. These plants had previously been established in native gardens. Grass grew in the following months and trees became well established within the next two years. The establishment of vegetation on freshly erupted volcanic ash is extremely rapid in the humid tropics. However, this phenomenon is not confined to this region but may occur in the temperate zone where it may proceed at a slower rate. The recovery of vegetation at Kodiak, which received about one foot of ash from the 1912 eruption of The Valley of Ten Thousand Smokes, is described by Griggs (41). This place is located within ten degrees of the Arctic Circle. A vigorous vegetation, mainly of species which withstood an enforced dormancy was established three years after the eruption. Grasses and berry bushes were included in this vegetation.

Genesis and formation of soils from volcanic ash in humid climates of Grenada and St. Vincent, in the West Indies have been described by Hardy, et al (45,46).

d. Origin of parent material of soils of Hilo and Hamakua coasts

The parent material of the soils in this study is Pahala ash. Stearns and Macdonald (116) described Pahala ash as a late member of the Kahuku volcanic series of probably middle Pleistocene age. Macdonald (60) described this material as being composed of pumiceous glass fragments and is mainly mafic andesite in composition. Pahala ash is widespread on the Island of Hawaii and there is some controversy among geologists concerning its main source. Because of the high rainfall and extensive weathering, it is difficult to determine the composition and source of the ash on the Hilo coast. Fraser (37), working with field evidence, considered that Kilauea volcano was the main source of this material. His contention is based on the observation of a systematic change that occurs outward from Kilauea. This change is principally concerned with a decrease in particle size and a decrease in thickness of layers. Stearns and Macdonald (116) indicated the four volcanoes, Mauna Kea, Mauna Loa, Kilauea and Kohala as general sources of Pahala ash, with Mauna Kea as the main source of the bulk of the ash on Mauna Kea and also on the adjacent slopes of Mauna Loa.

e. Description of weathering condition of soils

The prevailing hot, humid climate of the Hilo and Hamakua coasts provides an environment for very rapid weathering of soil forming materials. Hough, et al (49) recorded a heavy loss of bases and silica and accumulations of aluminum and iron for profiles of soils formed in this area. Tamura, et al (119) found approximately 30 per cent allophane in the Akaka and Hilo series, two Hydrol Humic Latosols from this region. Weathering has advanced to such a stage that this material has been considered as a potential commercial source of aluminum by Sherman (110). In his study of Hydrol Humic Latosols from this region, Sherman (109) found that on complete dehydration a mixture of light and dark colored aggregates is formed. Chemical analysis, differential thermal analysis and X-ray diffraction techniques have shown the light colored aggregates to be gibbsite. The dark colored aggregates have more than 20 per cent silica and 30 to 40 per cent iron oxide. Bates (6) considered that the high concentration of allophane along the Hamakua coast indicates that this amorphous mineral is a stage in weathering of volcanic glass which is so widespread in the volcanic ash and also occurs in the matrix of the volcanic rocks. This worker also drew attention to the abundance of mineral material which occurs in quiet sections of streams in the high rainfall regions of Hawaii. The andosols in Java, described by Dudal (30) appear to have an origin and properties closely related to these Hawaiian soils.

2. Liming soils

a. Liming tropical soils

The main purpose of liming soils is to raise their pH. The general action follows the fundamental equation: Clay 2H + $CaCO_3 \rightleftharpoons$ Caclay + CO_2 + H_2O. The hydrogen of the cation exchange complex being replaced by calcium. Greene (40) reported that results from liming in the tropics have usually been unsatisfactory and concluded that the whole question of liming tropical soils should be reconsidered. Richardson (97) emphasized extreme caution in liming tropical soils and mentioned the high probability of causing trace element deficiencies. The possibility of selecting acid tolerant agronomic crops was suggested. An application of two tons of lime to a Humic Ferruginous Latosol on the Island of Maui produced a substantial increase in yield of forage and seed production for Kaimi clover, according to Younge (135). Cassidy (13) suggested that in Fiji the red earths on basalt andesitic tuff are more likely to respond to liming than are recent volcanic ash soils. Response to 3 tons coral sand per acre by rice, sugar cane and particularly pastures in Fiji was reported by Cassidy (14). It was indicated, by a separate experiment, that one ton of ground calcium carbonate would give approximately the same benefit as $2\frac{1}{2}$ tons of crushed coral stone.

b. Calcium status of Hawaiian soils

Hance (42) drew attention to the exceedingly low calcium content of Hilo coast soils and estimated that some of these soils had lost more than 99 per cent of the original calcium content.

c. Rates of lime application

Rates of application of lime are dependent upon the buffering capacity of the soil. After conducting pot experiments with wheat, barley, maize and clover, Chizhevskiĭ and Korovkin (18) reported that the lime requirements cannot be deduced from the pH of the salt extract of the soil. Also in need of consideration are exchange and hydrolytic acidity, base saturation and available aluminum. Titration curves using 0.1N NaOH established by Matsusaka and Sherman (67) have been used for calculating the lime requirements of Hawaiian soils.

d. Effects of heavy calcium additions

The heavy applications of lime which are at times recommended may raise the question as to whether large calcium increments may affect plant growth adversely. Loomis (59) reported that gypsum at the rate equivalent to 100,000 pounds per acre did not affect significantly the growth of corn and soy beans grown on an Iowa soil.

The adverse effects of overliming are usually minor element deficiencies. However, Evans (33) considers that sugar cane is probably less prone to minor element deficiencies than any other tropical crop.

Younge and Otagaki (137) considered that applications of $1\frac{1}{2}$ tons of lime to pasture areas on the Island of Hawaii would shift the calcium deficient forages above the critical level for most classes of beef cattle. Akaka series soils were indicated to be in particular need of calcium.

3. Aluminum concentrations and toxicity

a. Soil acidity and aluminum toxicity

Soils which have very acidic pH values (below pH 5.0) have long been known to be generally less productive than soils with reactions closer to the neutral point. A limiting factor in these very acidic soils may be a nutrient deficiency, which would probably be calcium. With many of these soils the high concentrations of hydrogen ions or forms of aluminum that can affect plant growth adversely are considered to be a the limiting factors for productivity. The aluminum ions and hydrogen ions may be present together in high concentrations and thus make it difficult to ascertain their separate effects. But it is generally believed that high concentrations of aluminum ions have a much more toxic effect on plant growth than high concentrations of hydrogen ions. Hardy (43) compiled an extensive account of soil acidity, with emphasis on tropical regions. He considered that where a deficiency of easily soluble nutrient bases exists, soil solutions may contain appreciable concentrations of ions of aluminum, iron and manganese, either together or separately. When these concentrations rise above a critical level, the soils will become appreciably infertile due to the toxicity of these ions in the soil solution. According to Scharrer and Schroph (101) the main reason for poor crop growth is the ease with which aluminum goes into solution from acid soils by base exchange reactions. Arnon and Johnson (3) found that provided there were adequate nutrients, pH fluctuations from 4.0 - 8.0 were tolerated. Only at pH 3.0 and 9.0 was plant growth affected in an extremely adverse manner. Martin (63) reported that sugar cane plants grown in a nutrient solution maintained at pH 4.0 continued to make good growth during the 8 weeks of the test and no leaf symptoms of acid injury appeared. Chizhevskiĭ and Korovkin (18) found that soil acidity due to available aluminum was more harmful to wheat, barley and clover than was acidity due principally to exchangeable hydrogen. On the other hand, DeTurk (27) found that red clover grew normally at pH 7.0 in sand cultures containing 160 P.P.M. calcium but failed to grow at pH 5.0 in sand cultures at the same calcium level. Schmehl, et al (103) found that the rate of calcium absorption in alfalfa was greatly reduced in the presence of AL^{+++} and to a less extent with Mn^{++} and H^{+} in nutrient solution. It was suggested that the often observed low calcium content in plants grown on acid soils may be due to the antagonistic effect of AL^{+++}, Mn^{++} and H^{+} on the absorption of Ca^{++}. Schofield (104) considered that for certain strongly acid soils high in sesquioxides the basic positive charges exceed the permanent negative charge combined with the acidic negative charge. It was suggested that such soils retain anions but not cations. The basic positive charges occur in positions on the surfaces of sesquioxides. The positions are uncharged when the hydrogen ion is dissociated and positively charged when it is combined.

The combination of high acidity and high contents of aluminum, mainly in an amorphous state, in these Hawaiian soils presents the probability that aluminum may have a limiting effect on crop production. According to McGeorge (69) the presence of toxic amounts of aluminum in many Hawaiian soils was strongly indicated by analytical evidence. Several workers have found that high concentration of aluminum can affect plant growth adversely. Nondiffusible colloidal aluminum hydroxide was shown by McLean and Gilbert (72) and Trenel and Alten (123) to be definitely harmful when in contact with plant roots.

b. <u>Mechanism of aluminum toxicity</u>

Information concerning the actual mechanism of aluminum toxicity is meager. From his studies with Elodea, Spirogyra and Lemna it was found by Fluri (35) that aluminum salts produced a plasmolysis of the protoplasm without any considerable contraction. Sergeev and Sergeeva (106) considered that the beneficial effects of heavy phosphate applications to a soil containing soluble aluminum were due to the physiological antagonism of these ions in the plant. Plasmolysis measurements showed that the viscosity of the protoplasm of the epidermis of fleshy scales of an anthocyanin-bearing onion was increased by aluminum and decreased by phosphate. Hoffer and Carr (48) found that plants containing the largest quantities of iron and aluminum appeared to develop the most severe cases of root rot under conditions favorable for maximum growth of the responsible organism. The effects of additions of aluminum salts to excised root hairs were studied by Addoms (1). A flocculation of the protoplasm was obtained. The internal precipitation of phosphorus by aluminum within the plant tissue was recorded by Wright (134). He considered that interference with the uptake and translocation of phosphorus by aluminum is the main cause of aluminum toxicity. Coleman, et al (23) state: "The mechanism of aluminum toxicity is not known."

c. <u>Nature of aluminum ions</u>

A comprehensive study of aluminum ions and their reactions has been made by Brossett (9,10). Starting from very acidic reaction values, soluble AL+++ ions change to complex hydrolysed and polymerized forms with increased pH values. Raupach (96) considered that aluminum ions of varying valence may be involved as the pH of the soil rises. The colloidal properties and amphoteric nature as related to aluminum toxicity have been studied by Mattson and Hester (66).

Jones (53) conducted experiments which showed aluminum is present in fly-ash at high pH values, and that it is available to plants grown in the ash. His studies were concerned with some of the problems of reclamation of pulverized coal-ash (fly-ash) deposits from industrial areas in England. The problem of how plants could absorb aluminum in the anionic form was discussed, and it was suggested that organic acids produced by the plants may act as chelating agents which prevent precipitation of aluminum at physiological pH values. This hypothesis was used as a basis for an explanation of the different responses exhibited by various ecological groups of plants to excesses of aluminum.

Pioneer work relating to soluble aluminum content to soil reaction was conducted by Magistad (61). Energy of adsorption by soil of hydrogen was reported by Chernov (15) to be much less than the energy of adsorption of aluminum. Paver and Marshall (85) considered that in an acid soil aluminum acts as an exchangeable base and may occupy the greater part of the exchange positions in such soils. Lin and Yu (58) concluded that aluminum is almost entirely responsible for the acidity of krasnozems.

d.-- Determination of aluminum values

A number of terms have been used for the component of soil aluminum that is directly concerned with soil acidity and any related limiting effect on plant growth. The terms "mobile" and less commonly "easily soluble" frequently used by Russian and European workers is probably the same as "soluble" or "water soluble." The term "active" aluminum has been used by workers from different localities. While the term is descriptive, lack of clarity concerning its exact meaning limits its value for comparison purposes. A number of "extractable" aluminum values have been reported in the literature. The method of extraction has usually been included with the reports. A number of workers have determined "exchangeable" aluminum. Such investigations are based on titrations using KOH or NaOH. The work of Chernov (15) who found that titratable acidity of KCI extracts of podsols and red soils to be equal to their aluminum content, provides a basis for such methods. The presence of aluminum in the solution was due to the exchange of potassium with aluminum cations adsorbed on the soil. Although there are numerous methods of determination and terms for aluminum, the trends of the values in a great majority of situations are similar. A critical level for aluminum values occurs at pH 5.0. Soils having a pH below this value often have considerably higher aluminum values than soils which have a pH value slightly in excess of 5.

e. Acid sulphate (cat clay) soils

Acid sulphate soils were first studied in the temperate zone by Van Bemmelen (127). They usually occur on marine flood plain. They are characterized by high sulphate content and extremely high potential acidity. Drainage produces the oxidized or cat clay form and promotes the production of sulphuric acid. This results in extremely low pH values and extremely high aluminum values.

These soils with their high aluminum content or potentially high aluminum content are widespread in the tropics where they often occupy a considerable area. Examples of acid sulphate soils have been described for Vietnam (77), Thailand (87), East Pakistan (125), Borneo (129), tropical Africa (17, 29), and Surinam (80).

Up to the present these acid sulphate soils with their special aluminum toxicity problems have been utilized to a limited extent. With rapidly increasing world population increasing utilization of such soils may well be anticipated. Thus, the work at Vietnam is of great importance. Under conditions prevailing in Vietnam, aluminum toxicity is the most prominent feature of acid sulphate soils, according to Auriol and Lam-Van-Vang (4.) Sugar cane and some rice varieties are highly susceptible to aluminum toxicity, according to Moormann (77). Specially selected rice varieties are grown on the acid sulphate soils. On medium acid sulphate soils sugar cane often shows a poorly developed root system in the compacted clays. This worker considers the best method of reclamation for such soils is the combination of liming with careful and progressive drainage aiming to gradually release and neutralize the potential acidity. It appears, pH values upon oxidation of these sulphate clay soils provide an indication of whether reclamation would be worthwhile. At present when such pH values are 3.5 or less, such soils are not cultivated.

It was pointed out by Moormann (77) that normally productive areas may have serious losses in yield due to aluminum toxicity of inundation waters which have been in contact with acid sulphate soils.

f. Aluminum content of plants

Bertrand and Levy (7) studied a great number of plants, including various vegetables, and concluded that aluminum exists in all flowering plants in widely varying amounts. Levy (57) found that all phanerogams in the 75 specimens that she studied contained aluminum, which was found to accumulate more rapidly at early stages of growth than later.

The relative tolerance to crop plants was studied by McLean and Gilbert (71). Dwarfing and root injury were found to be the first effects of aluminum toxicity. Olsen (84) published a list of lime-loving and lime-hating plants and discussed the relationships between lime, soil acidity and aluminum toxicity.

Robinson and Edgington (98) report a number of alumina accumulator plants mainly from the U. S. mainland. Accumulation of aluminum in the Australian-New Guinea flora is described by Webb (130). An exceptionally high accumulation of aluminum in Australian silky oak is reported by Smith (114).

The aluminum content of some Hawaiian plants has been reported by Moomaw, et al (76). The plants were obtained principally from acidic soils which were known to have a high aluminum content. Pteridophytes with aluminum values of 3,000 to 9,000 p.p.m. were prominent. However, values in excess of 1,000 p.p.m. for some grasses, such as rattail grass (Sporobolus capensis) and ricegrass (Paspalum orbiculare), were reported for the first time.

Sommer (115) conducted a series of experiments aiming to prove the essential nature of aluminum. An increase in amount of seed and small increase in total dry weight for pea cultures were obtained with aluminum additions. A big response in dry weight for millet to aluminum was obtained and it was suggested that this element may be essential for this plant. Tauböck (120) took great care to exclude aluminum from a series of solution culture experiments. The 124 kinds of flowering plants that were studied showed no lack of aluminum, even in the second generation. Culture of pteriodophytes was unsuccessful under the same conditions. With pteridophytes the lack of aluminum was manifested in cessation of growth within a few weeks followed by a progressive necrosis. Mazé (68) considered that the presence of aluminum is necessary for the normal development of maize.

Pellet and Fribourg (86) reported a very low aluminum content in sugar cane. Hoffer and Carr (48) established with a series of injections, a definite cumulative toxicity of aluminum within corn plants It was believed that the same phenomenon occurs naturally in the field. A series of excellent photographs illustrating the accumulation of aluminum and iron in basal tissues of unthrifty corn plants is included in Hoffer and Carr's publication. These plants had usually been produced on highly acidic soils.

4. Phosphate additions and modifications

a. General behavior of phosphate additions and soil phosphate

The condition of soil phosphate is greatly influenced by the presence and forms of calcium and aluminum compounds. Additions of phosphate to acidic soils usually reduce the content of mobile aluminum. In some instances the beneficial effect of phosphatic fertilizer could be attributed partially at least to reduction of available aluminum. Liming generally improves the availability of phosphates.

In his studies with red soils Nakaidze (83) found that the effect of phosphatic fertilizer on growth of buckwheat and corn was increased by liming. Phosphatic fertilizers added to limed soils one month before planting had a greatly reduced effect compared with that added immediately before planting. The increased phosphate mobility was attributed chiefly to the coagulation of the sols of $AL(OH)_3$ and $Fe(OH)_3$. Ratner (95) showed that by supplying sufficient phosphate for plants, the mobile aluminum did not interfere with the yield. It was noted that large quantities of phosphorus as well as aluminumwere absorbed when no phosphorus was added. It was considered that precipitation of phosphates by aluminum in plant tissues caused phosphate starvation.

The effects of calcium on the distribution of phosphorus in aqueous systems were studied by Naftel (81) who found calcium phosphates as follows: monobasic pH 3.0 to 5.0; dibasic pH 5.0 to 6.4 and tribasic above pH 6.4. It appeared that liming acid soils causes a decrease in available phosphorus by increasing the sorption by the soil colloids only on soils of high SiO_2/R_2O_3 ratio. The absorption of phosphates by colloids of low SiO_2/R_2O_3 ratio was practically unaffected by calcium.

Reduction of aluminum in soil solution, without any pH change, with heavy (2,000 pounds P_2O_5 per acre) applications of superphosphate was obtained by Pierre and Stuart (90). The heavy phosphate applications were considered to reduce injurious effects of aluminum by precipitation in the soil and in the plant tissue. The increased productivity due to added phosphate was considered to be due to increased mobility of phosphate in the soil and in the plant. In view of the very heavy calcium additions in these experiments it is of great interest to encounter a somewhat different viewpoint. Any appreciable chemical union of aluminum and phosphate according to Ratner (94) could only take place in a soil saturated with calcium. In an acid environment with high soluble aluminum content a precipitation of phosphate in the beet plants was observed by Wright (133) who considered that this reduced the availability of phosphorus for utilization by the plant.

The efficiency of phosphatic fertilizers, particularly superphosphate, on the growth of New Zealand pastures was greatly increased by liming according to Melville (73) and Woodcock (132). The "active" aluminum in a New Zealand soil derived from andesitic volcanic ash, is derived from amorphous allophane according to Saunders (100). It was concluded from pH-phosphate retention curves that fixation of added phosphorus was due to "active" aluminum and not exchangeable calcium.

Davis (26) reported that relatively small increases in cation exchange capacity due to additions of monocalcium phosphate were dependent on the amount of added phosphate.

b. Tropical conditions

The availability of phosphorus in most lateritic soils in the tropics is increased by liming, according to Koch (56).

A liming-phosphate experiment with an acidic soil was conducted by Schroo and Schmidt (105) at Trinidad. Sugar cane plants were grown to maturity in 40-gallon oil drums. It was noticed that the root tips were severely damaged in non-limed soils. Such damage, called "club-tip," was considered to be possibly due to toxic effect of aluminum. Liming increased by 10 per cent the total sugar produced by the cane. Although there were small responses to phosphate in the absence of lime, it was concluded that the only real need of this soil is lime. Younge and Moomaw (136) considered that the stripsoil culture on bauxite land on Kauai requires a phosphorus treatment of 600 pounds phosphorus per acre compared with 300 pounds phosphorus for the topsoil. Chu and Sherman (19) reported that Hawaiian soils fix as much as 90 per cent of added phosphate in the presence of hydrated iron and aluminum oxides. In these experiments the maximum rate of phosphorus used was 10,000 P.P.M. The maximum fixation occurs below pH 4.0 and the minimum fixation occurs at neutral or alkaline pH values.

5. Leaching studies

Studies in leaching losses have been concerned principally with retention of calcium with liming practices (107) particularly in regard to sandy soils (2). Joffe (51) studied the movement of cations in a grey brown podsoilic soil. These experiments which were usually carried out on a long term basis have produced a considerable understanding of the mechanism and products of leaching. However, it may be pointed out that virtually all the information concerning leaching losses from soils has been obtained with experiments in the temperate zone with soils from the same latitudes. The clay mineral fraction of such soils usually consists of crystalline clay minerals. Seasonally fluctuating temperatures would be of importance. Thus this information is of limited value when interpreting leaching losses from heavily limed and unlimed highly amorphous soils.

Magistad (61) found that the curve for solubility of aluminum in the soil solution at various pH values almost coincides with the curve for the solubility in water at the same reactions. At the neutral point there was practically no soluble aluminum. There was a substantial increase as pH value went below 5.0 and at pH 4.5 the amount of soluble aluminum increased very rapidly.

Pierre, et al (89) indicated that high concentrations of soluble salts were associated with high contents of soluble aluminum. On the other hand, at a given pH, soils with high organic matter were associated with low soluble aluminum values and soils with low organic matter contents were associated with high soluble aluminum values. Naftel (82) found that added lime more than doubled the soluble phosphate. Exchangeable manganese was replaced by lime directly with the amounts added.

In their studies of podzolic illuvial horizons, Martin and Reeve (65) studied the flocculation of humus from an Australian podzol, at carbon-aluminum ratios of 16, complete precipitation of carbon and aluminum occurred only at pH 4.0 to 4.5. As the pH was increased above

4.5, almost all the added carbon and aluminum remained unflocculated. No precipitation was found with any pH used with carbon-aluminum ratios of 20 or more. In the Amazon Valley clear water with pH 5.2 free of aluminum was reported by Sioli (113). Black water, with pH 4.1, which came from forested podzolic areas in the same vicinity contained aluminum. The color difference in the waters was due to the degree of oxidation of the organic matter.

In his comprehensive study of silica and silicates, Iler (50) states: "There is considerable evidence that silica can exist in solution in water in the monomeric form, presumably hydrated as monosilic acid, $Si(OH)_4$, or, if the pH is high enough, as silicate ions." However, this worker considered the mechanism by which silica is dissolved and deposited was still largely a matter of speculation.

Mink (74) considered that the composition of the fresh water lens of southern Oahu is rather uniform. The absence of variation in the water suggested an independence of location and time of residence in the basalt environment. Fresh ground water from the aquifer of southern Oahu had modal values of: Ca 8 p.p.m., SiO_2 36 p.p.m., and 0.20 p.p.m. for PO_4.

6. Sugar cane plant and plant analysis

There are some excellent sources of scientific information concerning the production of sugar cane in the tropics. The principal reason for this situation is the widespread economic importance of this crop.

A comprehensive description of physiology, growth, nutrition and chemical composition is included in "Botany of Sugar Cane" by Van Dillewijn (128). The mineral nutrition of all elements except NPK has recently been described by Evans (33). The distribution and range in concentration of mineral elements in stem tissues is an important inclusion in this publication. An account of mineral nutrition for sugar cane under Hawaiian conditions was presented by Burr, et al (12). It was found that the sensitivity of sugar cane varieties to environment is of such importance that cane-breeders have devoted much attention to producing varieties highly suited for each locality. Root temperatures below 70°F. become strongly limiting to growth. The "crop-logging" procedure for Hawaiian sugar cane as described by Clements (20) includes values for phosphorus and calcium in sugar cane tissue. The study of plant composition as a nutritional index by Goodall and Gregory (38) includes values for sugar cane.

Martin (62) grew sugar cane plants in culture solutions from which calcium had been omitted. A marked retardation of growth and a slight chlorosis of the leaves developed within 3 to 4 weeks. Minute spots, which first developed on older leaves, increased with the age of the leaves. The spots developed dead centers and the necrotic areas soon coalesced. The innermost leaves failed to make growth and death of the spindle occurred. Root development was greatly retarded three weeks after calcium had been omitted from the nutrient solution. The roots became soft and flaccid as a result of Phythium root rot. When the rapidly dying plants were placed in a plus-calcium solution, an immediate growth response resulted. As the terminal bud had died in each plant, lateral buds began to develop shoots of a normal color and growth.

In their investigations of chemical composition of Hawaiian pastures, Edwards and Goff (32) considered location, species and season. Low calcium and phosphorus values for pasture grass species were found in the wet windward section of Parker Ranch on the Island of Hawaii.

Younge and Otagaki (137) found definite evidence of forage phosphorus deficiencies in many areas on the Island of Hawaii. Acute phosphorus deficiencies were found in the Olaa and Akaka series soils. The absence of visual calcium symptoms in Hawaiian cattle was thought to be probably masked by the more acute protein deficiency, which in turn slows growth of the cattle to levels where available calcium is adequate, or there may be a scarcity of cattle in calcium deficient areas.

MATERIALS AND METHODS

A. CHEMICAL EFFECTS DUE TO LIME AND PHOSPHATE APPLICATIONS TO EXPERIMENTAL FIELD PLOTS

Description of Field Plot Experiments

A series of lime-phosphate replicated field plot trials planned by Dr. H. F. Clements of the University of Hawaii are being conducted on Brewer Sugar Plantations on the Hamakua and Hilo coasts on the Island of Hawaii. Sugar cane is grown in these experimental plots. It is intended that the experiment should continue for one plant crop and one ratoon crop. This means four to six years duration.

Lime applications: Three levels of lime, added in the form of crushed coral stone, were applied for each experiment as in table 1. These liming values were determined from buffer curves after the pH values of some collected field samples were obtained. The highest lime applications were anticipated to produce a pH of 7.0.

Phosphate Treatments: The phosphate additions were in the form of superphosphate. Gypsum in quantities that would compensate for the calcium content of the high applications was placed under the seed in the nil and medium phosphate plots. Thus, the zero phosphate plots were supplied with as much calcium as the 200 and 400 pounds P_2O_5 treatments. The possibility of studying calcium as a nutrient was eliminated.

Metecrological data: Meteorological data for the experimental plot areas are presented in tables 2 and 3. The rainfall data for Hilo plantation were taken at 150 feet elevation. The mean is of 64 complete years. The rainfall for Pepeekeo was taken at 900 feet elevation and is the mean of

Table 1. Rates of lime application to experimental field plots in soils of the Hilo, Akaka and Kaumoali Series, on the Island of Hawaii.

Soil Series	Plantation	Pounds of crushed coral stone per acre
Hilo	Hilo	0
		4,000
		11,000
		22,000
Akaka	Hakalau	0
		4,000
		11,000
		22,000
	Pepeekeo	0
		4,000
		19,000
		34,000
Kaumoali	Paauhau	0
		12,000
		30,000
		46,000

Table 2. Mean monthly rainfall data in inches for Hilo, Pepeekeo and Paauhau plantations, Island of Hawaii.

	Mean Monthly Rainfall in Inches		
Month	Hilo at 150 feet	Pepeekeo at 900 feet	Paauhau at 1200 feet
January	8.6	12.7	6.2
February	8.6	14.3	7.6
March	13.1	18.7	13.7
April	12.0	12.1	5.4
May	8.8	16.0	3.3
June	6.9	7.2	1.4
July	10.6	12.7	3.2
August	11.8	13.0	4.3
September	8.2	7.1	1.6
October	9.9	13.2	4.2
November	14.1	15.5	6.7
December	13.4	21.3	6.5
TOTAL	139.0	183.5	67.8

Table 3. Monthly mean maximum and mean minimum temperature figures for Hilo and Hakalau Plantations, Island of Hawaii.

Month	Hilo 40 feet		Hakalau Mauka			
	Max. °F	Min. °F	Max. °F		Min. °F	
			1959	1960	1959	1960
January	78.1	62.9	77.2	74.5	60.3	57.3
February	78.4	62.7	74.0	76.0	59.4	58.0
March	77.9	63.2	77.5	76.1	59.7	58.3
April	78.6	64.3	77.5	74.8	60.9	60.8
May	80.4	65.3	78.1	79.1	61.2	61.4
June	81.5	66.5	82.3	80.5	62.1	61.5
July	81.9	67.5	82.6	81.0	62.8	63.0
August	82.7	68.2	81.9	79.9	64.9	62.8
September	82.6	67.6	80.9	80.2	63.7	62.5
October	82.1	67.1	82.2	80.5	62.0	62.6
November	80.4	65.7	77.2	77.2	62.6	66.4
December	78.8	64.0	73.3	78.2	60.2	58.4

10 complete years. Both these recording stations are reasonably close to the respective field experimental plot area for each plantation. There is no recording station adjacent to the Hakalau experimental plot area but this location is considered to have slightly lower mean annual rainfall than the Pepeekeo experimental area. The rainfall figures for Paauhau were from 1200 feet elevation. This recording station is the closest to the experimental field plots on this plantation. The records are the means of 9 complete years. The rainfall information, also the rainfall isohyetal map of the Island of Hawaii in figure 1 was obtained from a Hawaii Water Authority publication (117). Included in this map are the locations of the experimental field plots.

The temperature figures for Hilo plantation were taken at 40 feet elevation and are the mean of 50 years' records. The Hakalau Mauka temperature figures have not been completely processed so the records for 1959 and 1960 were taken. This temperature was supplied from the records of Hawaiian Sugar Planters' Association Research Station.

Field Plots: Plot size was consistent within each experimental area, but varied slightly from plantation to plantation. Each plot was approximately 0.05 acres and consisted of eight rows of sugar cane.

A general view of the Hamakua coast, including sugar cane plantations, is illustrated in plate 1.

The soil series and locations described in this study are as follows:

Hilo Series: Hilo silty clay loam, on Hilo Plantation has an elevation of 150 feet. The experimental area was on a moderately uniform slope with an aspect towards the Pacific Ocean. These field plots were installed

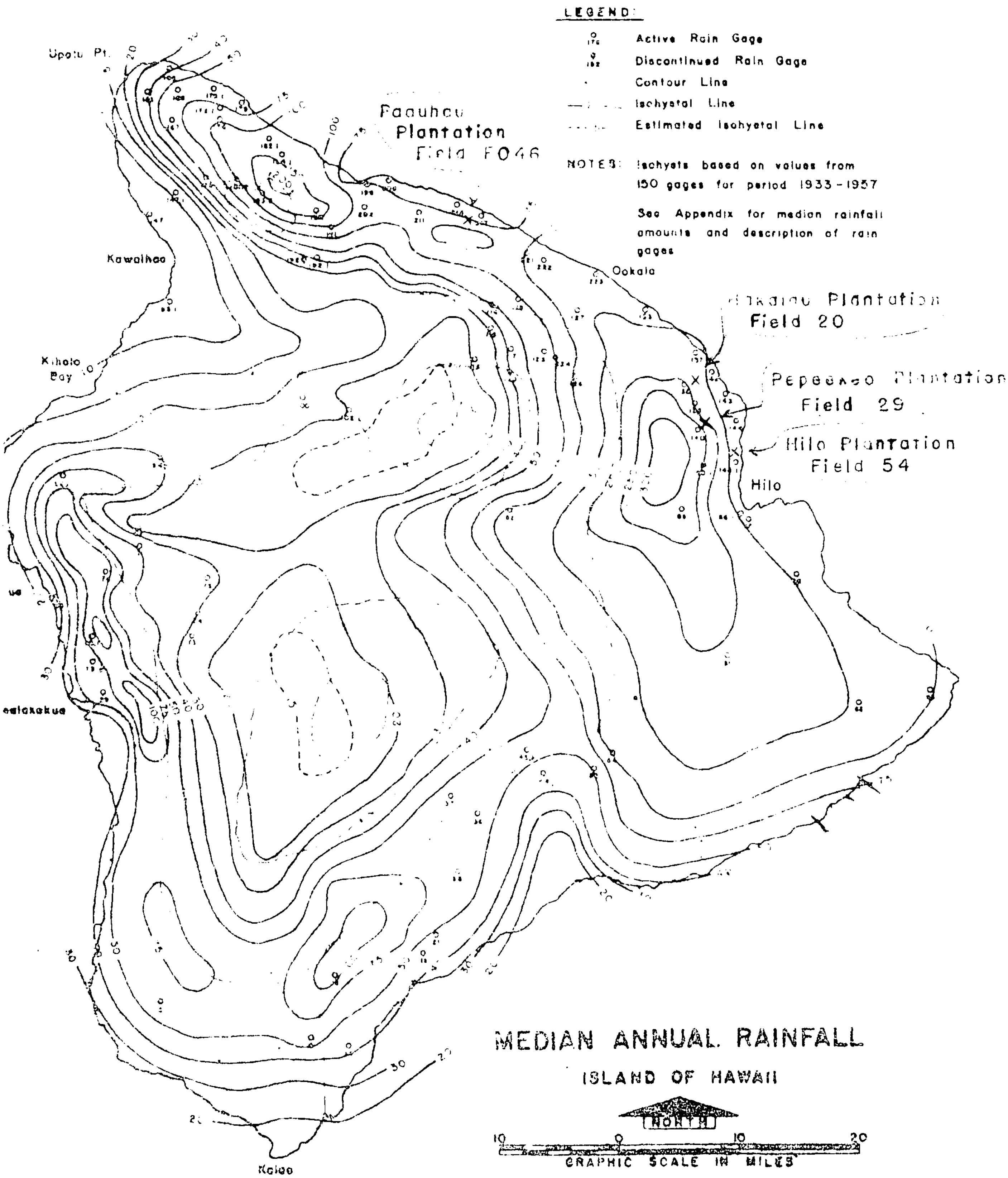


Figure 1. Map of Hawaii showing mean annual rainfall and location of experiment field plots.

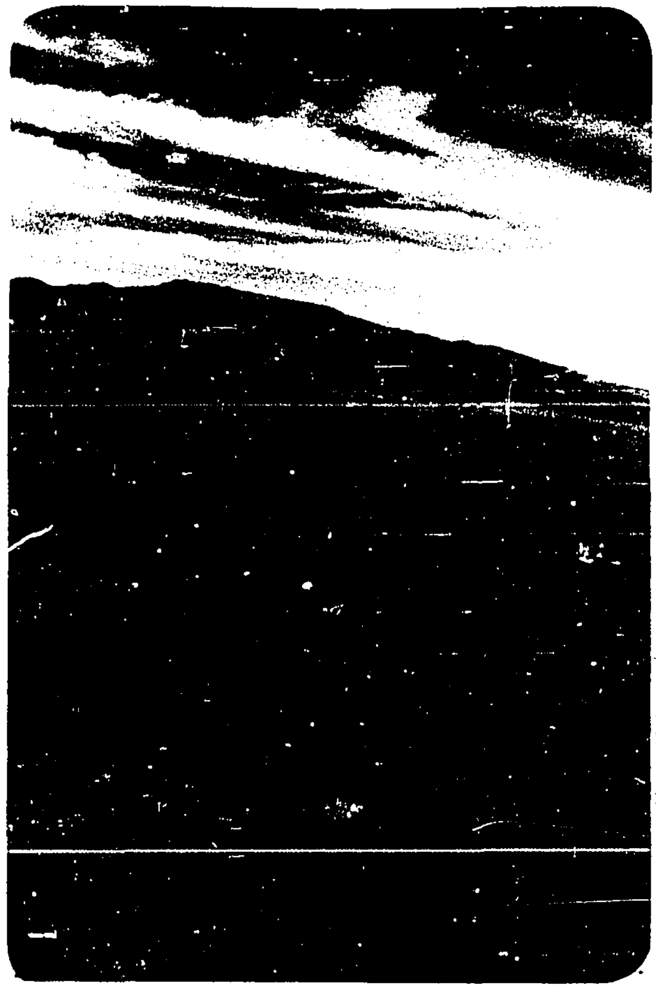


Plate 1. View of Hamakua Coast showing vertical extension from sea level to summit of Mauna Kea which is 13,784 feet high. Sugar cane is grown in the area that extends from just above sea level to approximately 2000 feet elevation.

on the 11th of February, 1959, in field No. 54. The previous fertilizer history for Hilo series soils from Hilo Plantation field 54 is presented in table 4. A view of sugar cane growing on Hilo series soils is presented in plate 2.

Akaka Series: Two experimental areas of Akaka silty clay were studied. On Hakalau plantation at an elevation of 800 feet the field plots had a moderate slope towards the Pacific Ocean and a rather steep slope towards the south. The sugar cane variety was 49-5. The field plots were installed in Field 20 on the 27th of January, 1959. The field plots on Pepeekeo were at 900 feet elevation and were on moderately uniform slopes towards the Pacific Ocean. The sugar cane variety was 44-3098. The field plots were established in Field 29 on the 9th of June, 1959. The previous fertilizer history of Akaka series soils for Hakalau plantation Field 20 and for Pepeekeo plantation Field 29, is presented in tables 5 and 6 respectively. A view, taken on Pepeekeo plantation of an Akaka series soil profile is presented in plate 3.

Both the Hilo and Akaka series are Hydrol Humic Latosols developed from volcanic ash. These soil series have been described by Cline, et al (21).

Kaumoali Series: The Kaumoali silty clay loam field plots are at an elevation of 1,500 feet on Paauhau plantation. Sugar cane variety 38-2915 was used. This field plot area has a moderately uniform slope towards the Pacific Ocean. The location is adjacent to a bitumen-topped road. Some glass and fragments of crockery were visible in these field plots. Thus this location may either have been the site of a former dwelling or a former rubbish dump. The field plots were installed in Field

Table 4. Previous fertilizer history for Hilo series soil from Field 54, Hilo Plantation, Island of Hawaii .

Year	Applications Pounds Per Acre		
	P_2O_5	CaO	K_2O
1952	44	0	242
1954	291	310(Super)	335
1956	111	155(Super)	311
1959	347	478(UA#1)	429

Table 5. Previous fertilizer history for Akaka series soil from Field 20, Hakalau Plantation, Island of Hawaii.

Year	Applications Pounds Per Acre		
	P	K	CaO
1952	179	321	226
1954	155	368	195
1956	126	254	158
1958	257	416	354

Plate 2. Sugar cane growing on Hilo series soil. A characteristic feature of this series is the prominent banding.

Table 6. Previous fertilizer history for Akaka series, Field 29, Pepeekeo Plantation, Island of Hawaii.

Year	Applications Pounds Per Acre			
	N	P	K	CaO
1952	191	50	280	0
1954	250	120	422	0
1956	338	446	474	0
1959	345	203	425	530
1961	284	396	415	0

Table 7. Previous fertilizer history for Kaumoali series soil from Field F046, Paauhau Plantation, Island of Hawaii.

		Applications Pounds Per Acre			
Year	Rotation	N	P	K	Ca
1952	Plant	192	390	272	579
1954	1st Rat.	208	-	347	-
1956	2nd Rat.	316	23	528	-
1959	Plant	308	413	410	679

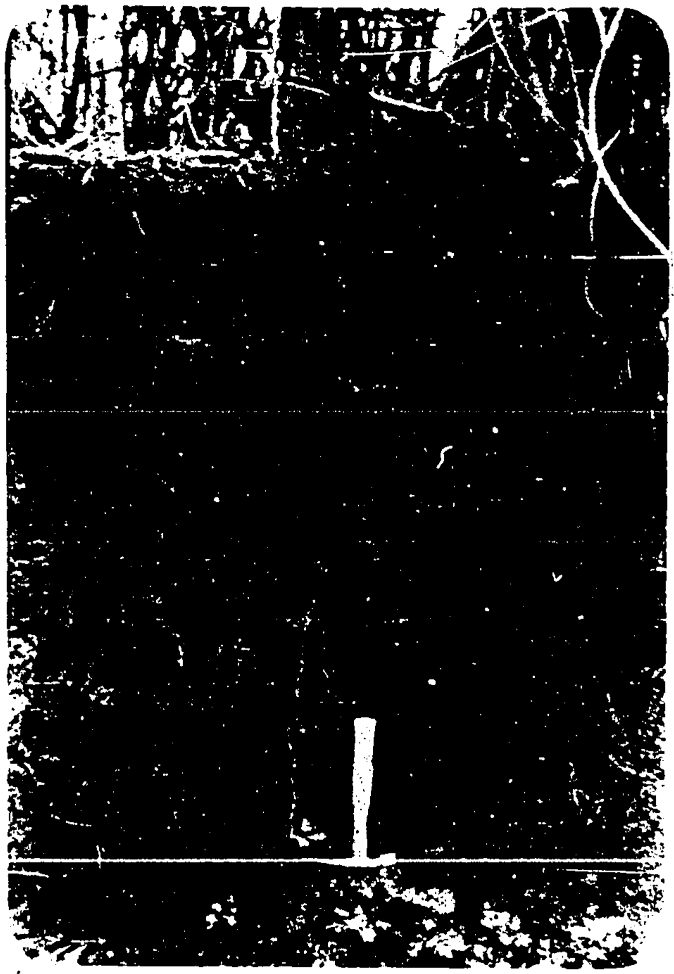


Plate 3. A profile of Akaka series soils taken in a roadcut near Akaka Falls on Pepeekeo plantation. The dehydrated and hardened soil material can be seen either side of freshly exposed profile.

F046 on the 10th of April, 1961. The previous fertilizer history for Kaumoali series soils for Paauhau plantation Field F046 is presented in table 7.

In a private communication from local soil conservation officers the Kaumoali silty clay loam was listed as a tentative series, subject to review and approval. It is a Humic Latosol developed on volcanic ash. This area had formerly been mapped as the Kukaiau Series.

<u>Collection of Soil Samples</u>: Soil samples representative of field plots were collected. These samples were kept in firmly tied polyethylene bags in order to retain their field-moist condition. In dealing with highly amorphous soils, this has been a regular practice of the Department of Agronomy and Soil Science, University of Hawaii. The substantial reduction in cation exchange capacity with dehydration reported by Kanehiro and Sherman (54) is the principal reason for this practice.

Analytical Methods

A Beckman pH meter was used to obtain pH readings, using a 1:1 soil water mixture, which was allowed to stand for 24 hours with occasional stirring. Cation exchange capacity was measured, using normal ammonium acetate, adjusted to pH 7.0, as described by Piper (91). Calcium was determined by precipitating as oxalate and subsequent titration with standard permanganate.

Ammonium acetate - barium chloride adjusted to pH 4.8 was used as an extracting medium for aluminum. Sufficient barium chloride was used to make this solution 0.2N in barium ions. Fifty ml. of this solution was left in contact with 10 gms. of soils for approximately 16 hours. This material was filtered through a Buchner filter using additional amounts of extracting solution until a total volume of 100 ml. was obtained.

The colorimetric analysis of aluminum using thioglycollic acid as inhibitor for iron, according to Chenery (16) was followed with a few modifications. A suitable aliquot, usually 1 ml., was taken from the extracted solution and had 20 ml. of water added to it. To reduce the ferric iron to the ferrous state 2 ml. of 1:100 thioglycollic acid was added. In this ferrous state iron does not interfere with the development of aluminum color. Next 10 ml. of the aluminum mixed reagent was added. Using dilute hydrocloric and dilute ammonium hydroxide, the pH of this mixture was adjusted to pH 4.8. The material was transferred to a 50 ml. standard flask and heated in a boiling water bath for 16 minutes. The flasks were removed from the water bath, cooled for one and one-half hours made up to volume and read in a Klett-Summerson colorimeter, using a green filter.

As these soil samples were in a moist condition, it was necessary to obtain a moisture factor in order to calculate results on an oven dry basis.

B. LEACHING COLUMN STUDIES

Introduction

One of the main effects of heavy liming was a substantial reduction in extractable aluminum. X-ray diffraction technique did not detect differences in the order of crystallinity for these heavily limed soils. In attempting to understand the fate of the decreased aluminum, attention was turned to the downward moving soil solutions. In addition to this aspect the differences in amount and rate of movement of various constituents in response to heavy coral treatments is of great interest. It was intended that this study should assist in the understanding of the effects of liming and the persistence of these effects.

Leaching Columns

Plastic tubing with an internal diameter of 2 inches and a length of 15 inches was used as the container for the soil column. The exterior walls of the plastic columns were painted black in order to reduce the light effects and consequently virtually remove the possibility of algal growth. A glass wool plug approximately 2 inches thick was placed in one end of the tubing and approximately 12 inches of soil was packed above the glass wool plug.

Three soil series were studied, namely the Hilo, Akaka and Kaumoali series. The soil for the Hilo series was obtained from Field 3, Hilo Plantation. The previous fertilizer history of this field is presented in table 8.

The bulk sample for Akaka series was taken from Field 41 at an elevation of 950-1000 feet on Hakalau plantation. The bulk sample used for leaching column studies with the Kaumoali series was taken from Field F046 Paauhau plantation. This field was also used for the field plot experiment. The fertilizer history of this field is presented in table 7.

Analytical reagent calcium carbonate was used as the source of lime. The amount of lime used was equivalent to the weight of the heaviest application for each soil series in the field plot trials. Thus, in this leaching experiment the Hilo and Akaka series soils received the equivalent of 22,000 pounds lime per acre, and the Kaumoali series received the equivalent of 46,000 pounds lime per acre. The lime was thoroughly

Table 8. Previous fertilizer history for Hilo series soil from Field 3, Hilo Plantation, Island of Hawaii.

Year	Applications Pounds Per Acre		
	P_2O_5	CaO	K_2O
1951	30	0	165
1953	175	0	286
1955	219	155(Super)	480
1957	116	0	463
1959	200	279(UA#1)	511

mixed with the soil before the soil was finally placed in the column. These operations were carried out as quickly as possible in order to avoid any appreciable loss of moisture from the soils. An equal volume of soil was placed in each tube. At the conclusion of the experiment the soil from each tube was weighed and a moisture factor determined. The soil was tamped into position in the leaching columns by tapping the plugged end against the bench. The tamping was done in order to pack the soil firmly and thus avoid empty spaces which could cause localized dehydration. There were three replicates for each limed soil and three replicates of untreated soils. This made a total of six tubes per soil series and a grand total of 18 tubes.

Clamps and racks supported the plastic tubes immediately above funnels which led directly into narrow-mouthed 2 liter reagent bottles.

Fifty ml. of distilled water was added everyday and the percolating solutions collected in the reagent bottles. At appropriate times, for example, when there was a liter or 2 liters of solution, this solution was taken for chemical analysis and a new collecting bottle installed. Collections from all the columns were made simultaneously. Thus there were five sets of samples taken.

The study commenced on the 3rd of April 1960, and the final collection was made on the 12th of September 1960.

Methods of Analysis

From the fresh sample 100 ml. was taken and used for the determination of pH, carbonate and bicarbonate. Titration with 0.1NHCl using phenolphthalein for carbonate and methyl orange for bicarbonate measurement was conducted according to Piper (91). These measurements were made as soon as possible after collection. The other considered constituents were usually measured at a much later date.

The aluminum and calcium values were determined by the methods previously described for soil analysis. Phosphorus was determined by the molybdo-vanadate method as described by Kitson and Mellon (55). Soluble iron was determined on one set of samples using the bipyridal method as described by Moss and Mellon (79).

Silica was determined by the following procedure. A suitable aliquot usually 25 ml. was taken. Two drops of phenolphthalein were added to the sample. Dilute sodium hydroxide was added until the pink color appeared. Fifty ml. of distilled water were added and this was followed by 4.0 ml. of $3NH_2SO_4$. Four ml. of 10% ammonium molybdate were added. The solution was made up to 100 ml. by adding distilled water and color transmission at 410 mμ was measured in a Beckman DU spectrophotometer.

After the leaching experiment was dismantled the soils were analyzed. Exchangeable calcium, extractable aluminum and pH were determined by previously described methods. The available phosphorus was extracted using 0.02N H_2SO_4 as described by Ayres and Hagihara (5). The molybdate method of Truog (125) was used and the developed blue was read on the Klett-Summerson colorimeter.

C. CHEMICAL ANALYSIS OF SUGAR CANE TISSUES

Introduction

Chemical analysis of plant tissue has often afforded useful information concerning their nutritional status. Goodall and Gregory (38) discussed the many factors that are considered in this approach to plant nutrition. Age of plant, stage of development, seasonal conditions, species, and even variety are some of the more important variables which influence the concentration of constituents within the plant.

The study of the effects of various field plot applications to sugar cane composition necessitates the analysis of a number of plant samples. With a plant as large as sugar cane, it is impractical to use the entire plant for chemical analysis. The selection of a suitable sugar cane tissue for chemical analysis is considered. Most of the work of this nature in Hawaii(20) is concerned with leaf sheaths, leaf blades and the upper portion of the plant generally. Restricted root growth and sometimes actual root damage are the usual manifestations in highly acid soils especially when high concentrations of aluminum are present. Hoffer and Carr (48) found that iron and aluminum accumulate in the vascular plate tissue of corn nodes and also in the scutellum of the corn grains. Plugging of vascular tissue was studied by tracing the movement of methylene blue within a cut corn stem. Aluminum compounds were found to be especially active in the plugging of vascular bundles. Thus any elements such as aluminum that may be present in sparingly soluble form are likely to be in high concentration in the lower portions of the plant. As the vascular tissue crosses over within the node, there is a reduction in rate of movement, which can result in the precipitation of the less soluble constituents.

Collection and Preparation of Sugar Cane Tissues

Nodal tissue: The two lowest nodes from a stalk of healthy growing cane were selected. Ten stalks were selected per plot which made a total of 20 nodes per plot.

The bark was removed from above and either side of the nodal material. A hacksaw was used to separate the node from the internode material. The nodes were diced into small squares and oven-dried. In the case of Hakalau plantation samples the moisture content was recorded. This material was ground in a Wiley Mill. As it was highly hygroscopic the material was heated at 65°F. in an oven for about 4 hours and stored in tightly stoppered bottles. Two gm. of this oven-dry material was used for analysis.

On the 20th of December 1960, 24 node samples were collected from Hilo series plots, Hilo Plantation. From the Akaka series plots, Field 20, Hakalau plantation, 16 node samples were collected on the 22nd of December 1960. The node samples from Kaumoali series field plots, Paauhau plantation were collected the first week in January 1961.

Root Samples: Root samples were collected simultaneously with the node samples. Each sample was taken immediately adjacent to a healthy plant. A surface area of six inches by six inches with a depth of 6-8 inches was collected. The coarser soil particles were shaken free and the root sample was placed in a firmly tied polyethylene bag. Four root samples were taken from the Akaka series and Hilo series plots and six samples from the Kaumoali series plots.

The high proportion of colloidal gels in these soils was mainly responsible for making root preparation an exacting undertaking. The loose soil was shaken free from the roots. "Dreft," a commercial detergent, was added to washing water which was changed six times. There was a second addition of "Dreft" followed by six changes of washing water. The material was rinsed then six times in distilled water. They were dried in an oven with exhaust at 75°C. for 16 hours. The samples were ground in a Wiley Mill and stored in firmly sealed screw top jars.

The washing operations were conducted as quickly as possible in order that the roots not be left in contact for a long period with any solution. This was done to minimize the possibility of these washing solutions extracting constituents from the tissues.

When the prepared root material was examined with a binocular microscope, a complete absence of soil particles was noted.

Analytical Methods

Dry ashing and sample solution: Two gms. of oven-dry material was pre-ignited with alcohol and then dry ashed overnight at 475°C. in an electric muffle furnace. After ashing this material was cooled. Ten ml. of 3NHCI was added and gently brought to boil on a hotplate. This material was filtered into 100 ml. standard volumetric flask using S&S White Ribbon filter paper. All residues were removed from the crucible with a rubber policeman. The crucible and filter papers were washed several times with distilled water. The contents of the standard flask were made up to volume and used in the determination of calcium, aluminum, phosphorus and iron.

Calcium: 50 ml. aliquot was used for calcium analysis. This element was determined by precipitation as oxalate and subsequent titration with standard permanganate solution.

Aluminum: For the nodal material a 10 ml. aliquot was used. For the root material a 1 ml. aliquot was used for the determination of aluminum. The colorimetric method as outlined previously under soil analysis methods was employed for the determination of the concentration of this element.

Phosphorus: A 10 ml. aliquot was used for phosphorus which was determined by the molybdovanadate method as described by Kitson and Mellon (55).

Iron: A 50 ml. aliquot was used for nodal material, and a 20 ml. aliquot for root material was used for iron analysis. Iron was determined by the $\alpha\alpha$ Dipirydyl method aa described by Moss and Mellon (79).

Silica: A 2 gm. sample was ashed and allowed to cool as previously described. The cooled ashed sample was moistened with a small amount of distilled water. Ten ml. of concentrated hydrochloric acid were added. The acid was evaporated slowly on a hot plate under a hood with exhaust functioning. After evaporation of the acid the crucibles were heated an additional 3 hours at 130°-150°C. The crucibles were cooled, 10 ml. 3NHCI were added and brought gently to the boil. This material was filtered using S&S White Ribbon filter paper. All residues were carefully removed from the crucibles using a rubber policeman. Crucibles and filter papers were washed several times with hot water. The filter paper containing the residue was transferred into the same crucible. The residue and filter paper were ignited overnight at 600°C. in an electric muffle furnace. Next day it was cooled partially placed in a dessicator, and weighed as soon as it was cold. The difference between crucible weight and crucible plus ash residue weights being taken as silica content.

EXPERIMENTAL RESULTS AND DISCUSSION

A1. SHORT TERM EFFECT OF TREATMENT ON EXPERIMENTAL FIELD PLOTS

Results

The experimental plots were installed on Hilo Plantation on the 11th of February 1959 and sampled 21 weeks later. The results of the chemical analysis of these soils are given in table 9. Considering the control plots and then those having the highest lime applications, the range in values for exchangeable calcium was from 1.94 to 16.86 me. per 100 gms. This was accompanied by a range of 10.74 to 7.13 me. per 100 gms. for extractable aluminum. Applied lime did not directly affect the cation exchange values. A significant (table 10) increase in cation exchange capacity was obtained with each level of applied phosphate in the 22,000 pounds lime per acre plots. The pH range was from 5.4 to 6.3.

The experimental plots on Hakalau plantation were installed on the 27th of January 1959 and sampled 23 weeks later. The results of the chemical analysis of these soils are presented in table 11. Comparing the values from control plots with those of the plots receiving the highest lime applications, the exchangeable calcium had a range from 0.54 to 15.22 me. per 100 gms. and extractable aluminum had a range from 15.44 to 8.89. Liming applications did not directly produce any modifications to the cation exchange capacity, which varied from 60.2-69.4 me./100 gms. The pH range was from 4.6 to 6.0.

The Pepeekeo experimental plots were installed on the 9th of June 1959 and sampled 12 weeks later. The results of the chemical analysis of these soils are presented in table 12. Considering the results from the control to the plots receiving the heaviest lime application, the

Table 9. Cation exchange capacity, pH exchangeable calcium, extractable aluminum mean values (of 2 samples) for various lime and phosphate treatments with Hilo series soils Hilo Plantation, Island of Hawaii.

Pounds coral per acre	Pounds P_2O_5 per acre	pH	Cation exchange capacity me./100 gms.	Exchange-able Ca me./100 gms.	Extract-able AL me./100 gms.
0	0	5.4	53.4	1.94	10.40
0	200	5.4	44.7	2.58	9.58
0	400	5.4	47.2	2.20	10.74
4,000	0	5.5	45.8	3.52	7.92
4,000	200	5.6	50.3	4.68	8.49
4,000	400	5.5	46.6	4.61	7.82
11,000	0	6.0	47.3	9.00	7.15
11,000	200	5.8	50.2	7.02	9.02
11,000	400	5.9	44.2	9.34	7.21
22,000	0	6.2	45.8	15.46	7.35
22,000	200	6.3	50.6	16.86	8.02
22,000	400	6.2	54.6	15.58	7.13

Table 10. Effects of phosphate application on cation exchange capacity in the 22,000 pounds lime per acre Hilo plantation, Hilo series plots, and on the exchangeable calcium values for the 34,000 pounds per acre Pepeekeo plantation, Akaka series plots, Island of Hawaii.

Pounds per acre applied P_2O_5	34,000 pounds lime per acre, Pepeekeo plantation, Akaka series plots	22,000 pounds lime per acre, Hilo plantation, Hilo series plots
	Exchangeable Ca/me/100 gms.	Cation exchange capacity me/100 gms.
0	28.44 a	45.8 a
200	19.72 b	50.6 b
400	13.42 b	54.6 c

Where different letters are used, the values differ significantly according to Duncan (31) multiple range test.

Table 11. Cation exchange capacity, exchangeable calcium, pH and extractable aluminum mean values (of 2 samples) for various levels of applied lime and phosphate with Akaka series soils, Hakalau plantation, Island of Hawaii.

Pounds coral per acre	Pounds P_2O_5 per acre	pH	Cation exchange capacity me./100 gms.	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	0	4.8	63.6	1.08	15.44
0	200	4.6	67.8	0.79	15.00
0	400	4.6	63.5	0.54	14.83
4,000	0	5.2	60.2	3.42	13.66
4,000	200	5.0	64.2	3.66	13.92
4,000	400	5.3	68.5	3.70	14.84
11,000	0	5.5	64.4	10.48	10.97
11,000	200	5.4	64.3	7.17	11.90
11,000	400	5.6	69.5	9.04	11.69
22,000	0	6.0	64.5	13.00	10.47
22,000	200	6.0	69.4	15.22	8.89
22,000	400	5.8	68.2	13.62	10.48

Table 12. Cation exchange capacity, pH, exchangeable calcium and extractable aluminum mean values (of 2 samples) for various lime and phosphate levels added to Akaka series soils, Pepeekeo plantation, Island of Hawaii.

Pounds coral per acre	Pounds P_2O_5 per acre	pH	Cation exchange capacity me./100 gms.	Exchange-able Ca me./100 gms.	Extract-able AL me./100 gms.
0	0	5.0	53.9	0.99	16.09
0	200	5.4	64.6	1.64	15.66
0	400	5.0	68.7	0.72	17.85
4,000	0	5.6	66.8	3.61	14.66
4,000	200	5.7	77.3	3.63	14.57
4,000	400	5.5	63.3	2.90	13.87
19,000	0	6.0	61.6	11.19	12.96
19,000	200	6.1	58.2	11.72	11.93
19,000	400	6.2	71.2	10.72	13.72
34,000	0	6.4	68.4	28.44	10.06
34,000	200	6.2	67.6	19.72	11.21
34,000	400	6.2	66.4	13.42	12.43

range of exchangeable calcium values was from 0.72 to 28.44 me./100 gms. and extractable aluminum from 17.85 to 10.06 me./100 gms. A significant decrease, shown in table 10, for exchangeable calcium with each level of applied phosphate, was obtained in the plots that received 34,000 pounds lime per acre. Neither lime nor phosphate caused any significant change in cation exchange capacity, which varied from 53.9-77.3 me./100 gms. The pH range was from 5.0 to 6.4.

The Kaumoali series plots were installed on Paauhau plantation on the 10th of April 1959 and sampled 22 weeks later. The results of the chemical analysis of these soils are presented in table 13. Considering the results from the control to the 46,000 pounds lime per acre plots, the range in exchangeable calcium was 1.15-32.07 me. per 100 gms. and for extractable aluminum was 22.78-13.20 me. per 100 gms. There was a significant increase in exchangeable calcium for the 400 pounds phosphorus per acre plots compared with the other levels of applied phosphate in the 30,000 pounds lime acre plots. This relationship is shown in table 14. Neither applied lime nor phosphate caused any significant change in the cation exchange capacity which varied from 55.4-63.7 me. per 100 gms. The pH range was from 5.0 to 6.0.

The relationship between extractable aluminum and exchangeable calcium for soil of each experimental plot area is illustrated in figure 2. The correlation coefficients for these relationships are presented in table 15. The correlation coefficients and regression factors for the relationships between soil pH and logarithm of exchangeable calcium are given in table 16. The correlation coefficient and regression factors for soil pH and extractable aluminum are set out in table 17. In calculating the regression values x = pH value.

Table 13. Cation exchange capacity, pH, exchangeable Ca, extractable AL mean values (of 2 samples) for various lime and phosphate additions with Kaumoali series soils, Paauhau plantation, Island of Hawaii.

Pounds coral per acre	Pounds P_2O_5 per acre	pH	Cation exchange capacity me./100 gms.	Exchange-able Ca me./100 gms.	Extract-able AL me./100 gms.
0	0	4.7	61.4	1.16	22.78
0	200	4.9	58.0	1.50	21.45
0	400	4.9	59.9	1.82	22.40
12,000	0	5.4	59.1	7.58	17.84
12,000	200	5.2	63.7	5.30	19.39
12,000	400	5.3	58.6	6.44	19.45
30,000	0	5.5	55.4	12.00	17.49
30,000	200	5.4	62.8	12.81	17.86
30,000	400	6.0	58.0	23.86	14.74
46,000	0	5.8	58.6	24.56	14.71
46,000	200	5.9	60.6	21.08	16.34
46,000	400	5.8	57.8	32.07	13.20

Table 14. Effects of phosphate application on exchangeable calcium in 30,000 pounds lime per acre, Kaumoali Series plots, Island of Hawaii.

Pounds per acre applied P_2O_5	30,000 pounds lime per acre Kaumoali Series plots Exchangeable Ca me./100 gms.
0	12.00 b
200	12.81 b
400	23.86 a

Where different letters are used the values differ significantly according to Duncan (31) multiple range test.

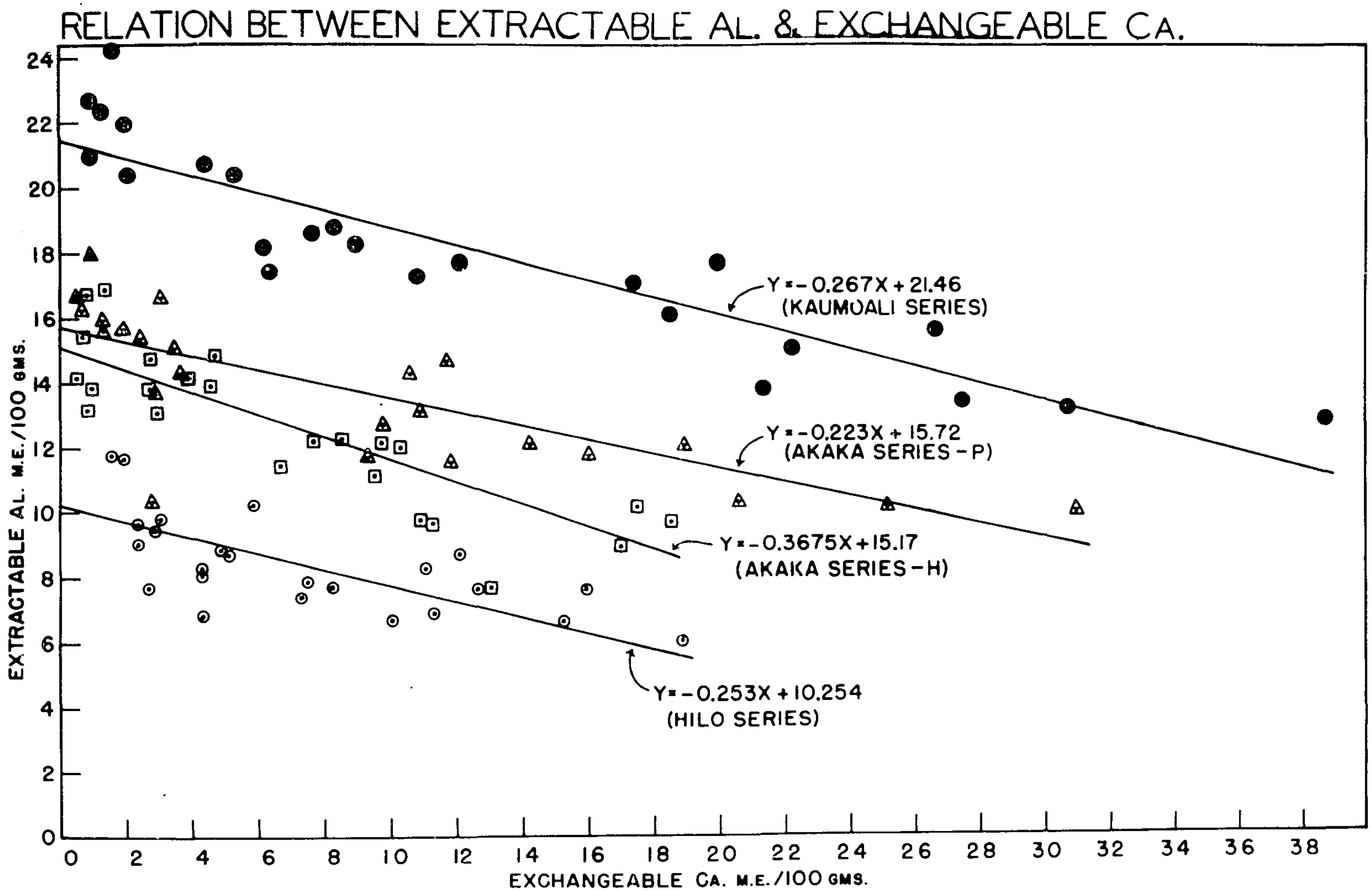

RELATION BETWEEN EXTRACTABLE AL. & EXCHANGEABLE CA.
Y = -0.267X + 21.46
(KAUMOALI SERIES)
Y = -0.223X + 15.72
(AKAKA SERIES - P)
Y = -0.3675X + 15.17
(AKAKA SERIES - H)
Y = -0.253X + 10.254
(HILO SERIES)
EXTRACTABLE AL. M.E./100 GMS.
EXCHANGEABLE CA. M.E./100 GMS.

Figure 2. Relationship between extractable aluminum and exchangeable calcium five months after installation of experimental field plots in Hilo series soils, Hilo plantation; Akaka series soils, Hakalau plantation and Pepeekeo plantation; and Kaumoali series soils on Paauhau plantation, Island of Hawaii.

Table 15. Correlation coefficients of exchangeable calcium-extractable aluminum relationships for field plot soils of Hilo Series, Akaka Series, and Kaumoali Series, Island of Hawaii.

Soil Series	Plantation	Correlation coefficient r value
Hilo	Hilo	- 0.76**
Akaka	Hakalau	- 0.86**
	Pepeekeo	- 0.82**
Kaumoali	Paauhau	- 0.91**

P (0.01) = 0.515 n = 24, for all plantations

Table 16. Correlation coefficients and regression factors of pH and logarithm of exchangeable calcium relationships for field plot soils of Hilo Series, Akaka Series, and Kaumoali Series, Island of Hawaii

Soil series	Plantation	Correlation coefficients r value	Regression factors α	β
Hilo	Hilo	0.90**	-3.61	0.76
Akaka	Hakalau	0.95**	-3.13	0.90
	Pepeekeo	0.95**	-4.46	1.07
Kaumoali	Paauhau	0.87**	-3.98	1.08

P (0.01) = 0.515 n = 24, for all plantations

Table 17. Correlation coefficients and regression factors of pH and extractable aluminum relationships for field plot soils of Hilo Series, Akaka Series, and Kaumoali Series, Island of Hawaii.

Soil series	Plantation	Correlation coefficients r value	Regression factors α	β
Hilo	Hilo	-0.54**	20.5	-2.10
Akaka	Hakalau	-0.80**	33.2	-3.85
	Pepeekeo	-0.76**	35.0	-3.66
Kaumoali	Paauhau	-0.87**	52.5	-6.34

P (0.01) = 0.515 n = 24, for all plantations

There were no situations where the heavy lime applications had a detrimental effect on the growth of sugar cane.

Discussion

Substantial reductions in extractable aluminum, accompanied by increased exchangeable calcium, resulted from heavy applications of crushed coral. When there is an appreciable amount of aluminum in a form that is liable to affect plant growth adversely, heavy applications of lime are probably necessary before a substantial modification of this element is obtained.

Highly significant negative correlations for all experimental plot areas were found between extractable aluminum and soil pH and between extractable aluminum and exchangeable calcium. Highly significant positive correlations for all experiment plot soils were found for soil pH and exchangeable calcium values expressed as logarithms. In his studies of soils from various localities within a humid tropical region Popenoe (92) reported similar relationships between exchangeable calcium-soil pH, exchangeable calcium and exchangeable aluminum, and between exchangeable aluminum and soil pH. However, curvilinear relationships for both pH-exchangeable aluminum and exchangeable calcium-exchangeable aluminum as well as for exchangeable calcium-pH were obtained by Popoenoe. These three soil properties are very closely associated with each other, and any attempts to separate their effects under field conditions would meet with difficulties.

Fieldes et al (34) concluded from studies of highly amorphous soils of the Cook Islands, that the principal exchange material is amorphous hydrous aluminum oxide. Similarly, the high content of amorphous hydrous aluminum compounds of these Hawaiian soils would make a considerable contribution to their high cation exchange capacities. It is of interest that the applied coral did not significantly alter the magnitude of the cation exchange capacity in any situation for these Hawaiian soils. This indicates that the reduction in extractable aluminum was not associated with any modification of the cation exchange capacity. It appeared that the addition of 22,000 pounds crushed coral per acre to the Hilo series soils produced an environment that resulted in increased cation exchange capacity, with increased phosphate additions.

The substantial reductions in extractable aluminum resulting from liming, introduces the question of the fate of this element. The downward movement of soluble aluminum within the soil profile could have occurred. However, because of the high total aluminum content, the equilibrium between colloidal aluminum and soluble aluminum would be of importance in these soils. This equilibrium would be governed principally by degree of soil acidity. Trenel (122) states that the formation of soluble aluminum, by the effect of NH_4 or K salts, is explained by the equation $AL(OH)_3 + 3\ KCL = ALCL_3 + KOH$. He also states that in the presence of silicic acid gel or humus gels lacking bases, the formation of $ALCL_3$ is favored. Silicic acid gels and humic gels lacking bases are presumed to be plentiful in these Hawaiian soils. Thus, a downward movement of soluble aluminum would probably not be of lasting benefit if the equilibrium is as such that additional aluminum is contributed to the soil solution. A shift in equilibrium away from the ionic forms of aluminum to the complexed and polymerised forms as described by Brosset (9, 10) is envisaged. Extreme modification of this material could lead to an increase in crystallinity. X-ray diffraction patterns showed gibbsite peaks in all the series studied. The Akaka soils had the largest peak and the Kaumoali soils had the smallest peak. No increase in crystallinity due to liming was recorded for these soils. If such a phenomenon was taking place, the time period of approximately five months could have been too brief for this effect to develop and be measured by such methods. The material could be in a crypto-crystalline condition.

For each soil series studied, there is a high degree of correlation between pH and extractable aluminum. In his studies of the nature of pH, it was considered by Raupach (96), that aluminum ions of varying valence may be involved as the pH rises. Magistad (61) and Schmehl, et al (102) found a decrease in aluminum that is harmful to plants with increased pH from just below 5.0 to above 5.0. On the other hand, Moskal (78) found a correlation between mobile aluminum concentration and exchange acidity, but not between mobile aluminum and the pH levels, whether measured in H_2O or KCL.

Throughout this study it appeared that there was a relationship between extractable aluminum and buffer capacity. The highest extractable aluminum contents were found in the Kaumoali series which required the highest coral dressings to bring the soil to the anticipated pH of 7.0. The dependence of an acid soil buffer curve on aluminum, shown by Schofield, was described by Russell (99).

In view of the much lower rainfall for the Kaumoali series, the very high extractable aluminum value for this soil was surprising. In his studies on widely separated acid soils, Burgess (11) recorded his highest "active" aluminum figure for a soil from Honokaa Sugar Company.

This plantation is immediately adjacent to Paauhau Plantation.

The significant decrease in exchangeable calcium with applied phosphate for the 34,000 pounds lime per acre Pepeekeo plots is difficult to explain. Phosphate sorption by calcium carbonate, as described by Cole, et al (22) is suggested as a possible explanation. The resulting reduced rate of the reaction between lime and soil may have reduced the content of calcium entering the exchange complex. On the other hand, the 400 pounds phosphate application significantly increased the exchangeable calcium in the 30,000 pounds lime per acre Kaumoali series plots.

It is of interest that any modification in soil properties due to applied phosphate was confined within a particular level of lime treatment.

In order to learn how long these chemical modifications of these test soils would endure or what subsequent changes would occur, further samples were taken at approximately 1 year and 2 years after installation of the experimental plots. In these further studies the phosphate treated plots were omitted and attention was given to lime treated plots. The chemical analysis and procedures were the same as for the previous samples.

A2. LONG TERM EFFECTS OF LIME APPLICATIONS

Results

Soil samples collected approximately one year and approximately two years after installation of the experimental field plots are referred to as the one year and two year samples. The previously described liming response general pattern of increased exchangeable calcium and pH values and decreased extractable aluminum was maintained for the one and two year samples. The relationship between exchangeable calcium and extractable aluminum values for the one and two year samples are presented in figures 3 and 4, respectively. Cation exchange capacity was not determined for the one year samples. Table 18 contains the correlation coefficient and regression factors for the soil pH and extractable aluminum relationships for the one and two year samples. Correlation coefficients and regression factors for the logarithmic values of exchangeable calcium and soil pH relationships for the one and two year samples are presented in table 19. In calculating the regression values x = pH value.

Hilo series. The results of the chemical analysis of Hilo series soils for the one and two year samples are presented in tables 20 and 21. The pH values showed a slight change when the one and two year samples were compared. The cation exchange capacity values showed no modifications due to liming. Compared with the one year samples, there was a decrease in exchangeable calcium accompanied by increased extractable aluminum values for the two year samples. Exchangeable calcium mean values for each liming rate for 5 months, one and two year samples, are presented in figure 5.

Akaka series. The results of the chemical analysis of the Akaka series one and two year samples for Hakalau plantation are presented in tables 22 and 23. After two years there has been a general reduction in pH values for all levels of applied lime. The steady reduction in exchangeable calcium over the two year period is illustrated in figure 6. The trend towards reduced cation exchange capacity values with each liming increment was not significant.

The results of the chemical analysis of the Akaka series soils from Pepeekeo plantation are presented in table 24. The Pepeekeo plantation pH values were greater than the Hakalau plantation values. There

RELATIONSHIP BETWEEN EXCHANGEABLE Ca. & EXTRACTABLE Al.
(ONE YEAR LATER)

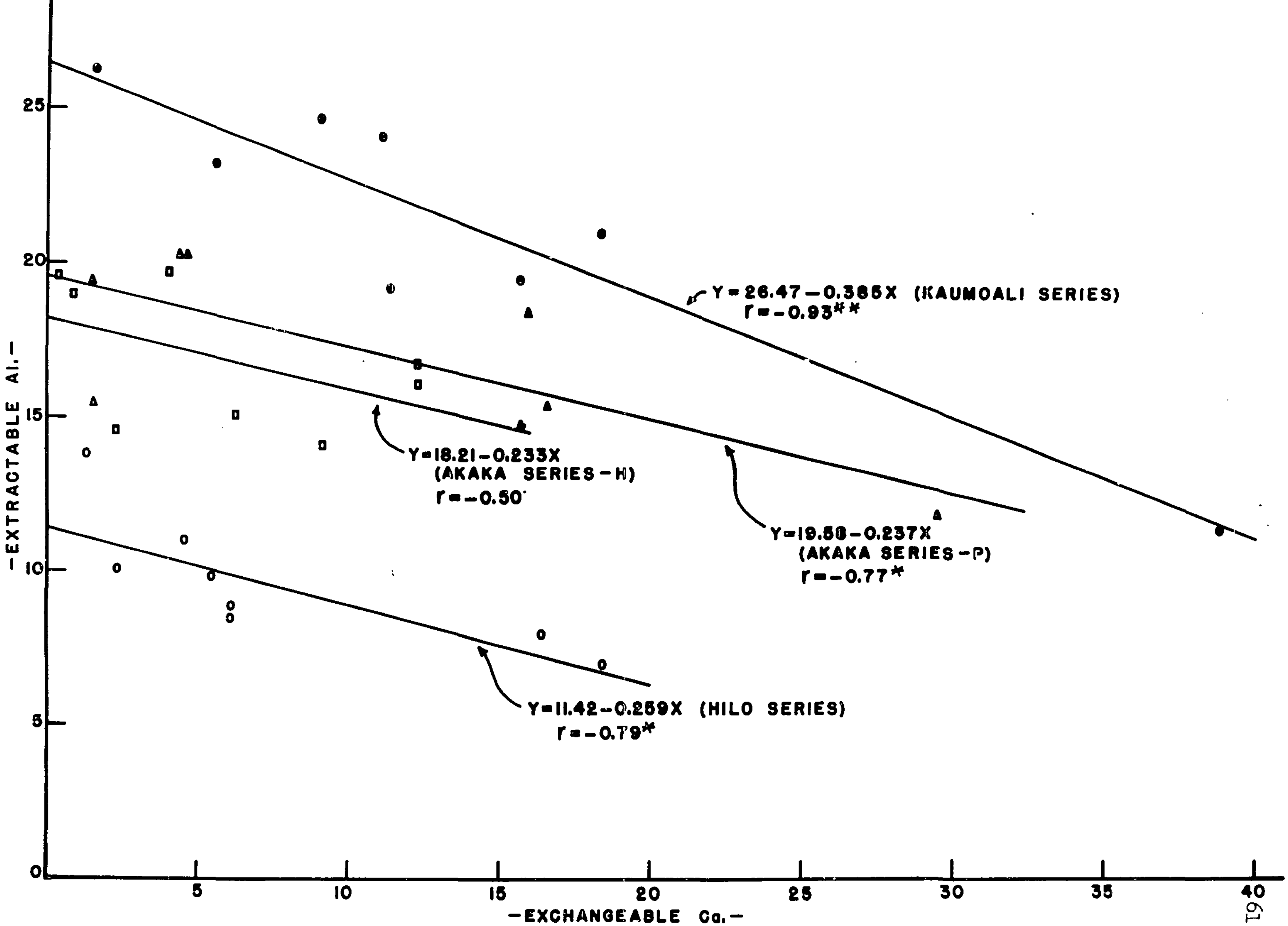
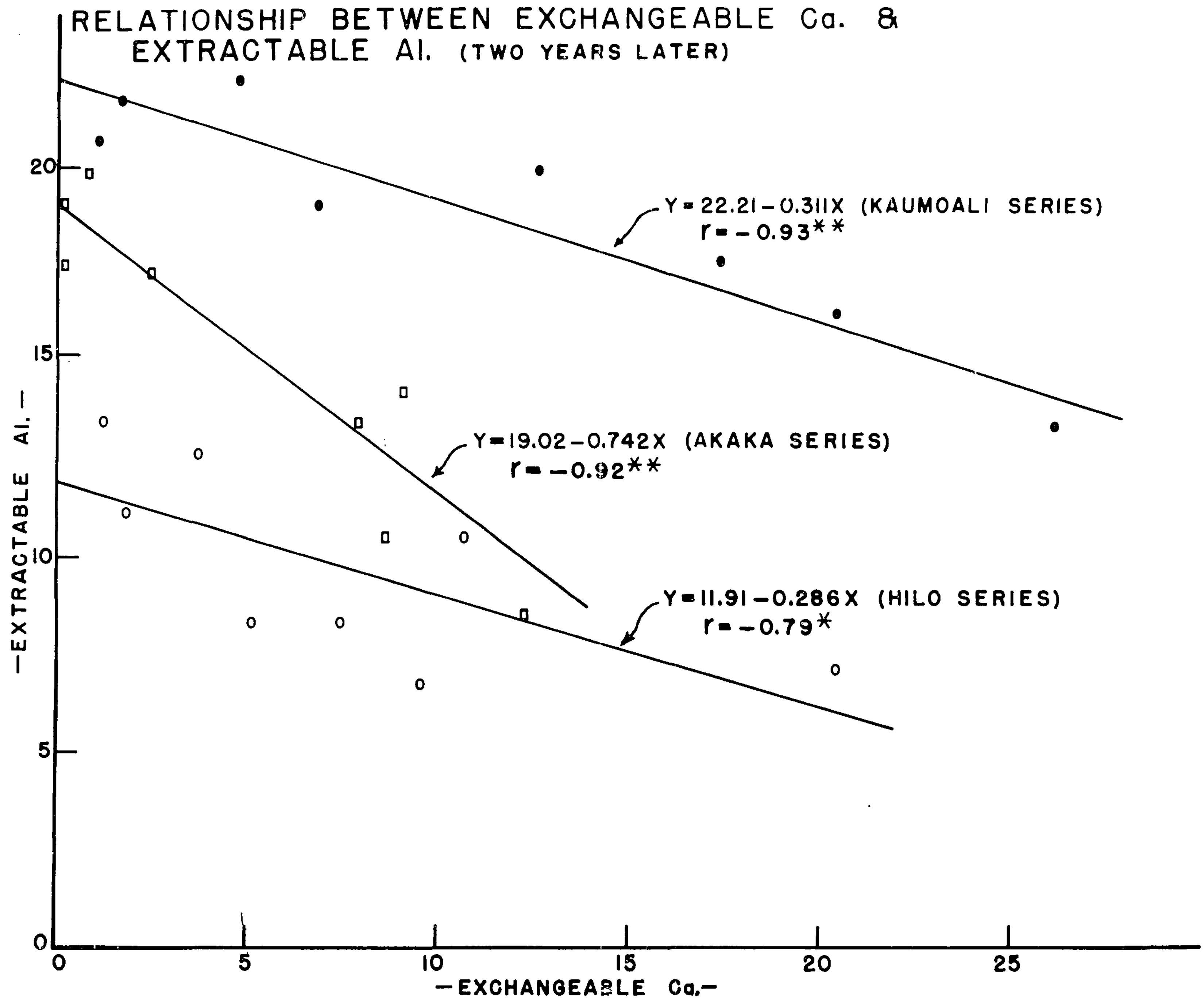


Figure 3. Relationship between extractable aluminum and exchangeable calcium one year after installation of experimental field plots on Hilo series soils, Hilo plantation; Akaka series soils, Hakalau plantation and Pepeekeo plantation; and Kaumoali series soils on Paauhau plantation, Island of Hawaii.



RELATIONSHIP BETWEEN EXCHANGEABLE Ca. &
EXTRACTABLE Al. (TWO YEARS LATER)
Y = 22.21 – 0.311X (KAUMOALI SERIES)
r = – 0.93**
Y = 19.02 – 0.742X (AKAKA SERIES)
r = – 0.92**
Y = 11.91 – 0.286X (HILO SERIES)
r = – 0.79*
– EXTRACTABLE Al. –
– EXCHANGEABLE Ca. –
0
5
10
15
20
25

Figure 4. Relationship between extractable aluminum and exchangeable calcium two years after installation of experimental field plots on Hilo series soils, Hilo plantation; Akaka series soils, Hakalau plantation; and Kaumoali series soils on Paauhau plantation, Island of Hawaii.

Table 18. Correlation coefficient and regression factors of pH and extractable aluminum relationships for field plot soils of Hilo Series, Akaka Series, and Kaumoali Series, Island of Hawaii. One year and two years after installation.

Soil series	Plantation	Time elapsed since Installation	Correlation coefficient r value	Regression factor α	β
Hilo	Hilo	1 year	-0.63	24.9	-2.72
		2 years	-0.70	33.7	-4.16
Akaka	Hakalau	1 year	-0.56	31.5	-2.70
		2 years	-0.78*	43.8	-5.37
	Pepeekeo	1 year	-0.81*	38.6	-3.67
Kaumoali	Paauhau	1 year	-0.90**	63.2	-7.38
		2 years	-0.78*	44.8	-4.75

P (0.05) = 0.71 n = 8, for all plantations

P (0.01) = 0.83

Table 19. Correlation coefficients and regression factors of pH and logarithmic exchangeable calcium relationships for the field plot soils of Hilo Series, Akaka Series, and Kaumoali Series, Island of Hawaii. One year and two years after installation.

Soil series	Plantation	Time elapsed since installation	Correlation coefficient r value	Regression factor α	β
Hilo	Hilo	1 year	0.84**	-3.42	0.73
		2 years	0.86**	-4.01	0.95
Akaka	Hakalau	1 year	0.98**	-5.75	1.16
		2 years	0.96**	-6.36	1.46
	Pepeekeo	1 year	0.94**	-3.28	0.69
Kaumoali	Paauhau	1 year	0.95**	-2.90	0.68
		2 years	0.91**	-4.17	0.92

P (0.01) = 0.83   n = 8, for all plantations

Table 20. Exchangeable calcium, pH and extractable aluminum values for lime treated Hilo Series plots, Hilo Plantation, Island of Hawaii. Fourteen months after installation.

Pounds coral per acre	Plot No.	pH	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	34	5.5	1.32	13.51
0	42	5.1	2.23	9.91
4,000	12	5.5	6.05	8.32
4,000	20	5.5	4.52	10.90
11,000	3	5.6	5.43	9.65
11,000	9	5.5	6.09	8.71
22,000	17	6.3	16.39	7.80
22,000	27	6.4	18.40	6.83

Table 21. Exchangeable calcium, pH, cation exchange capacity, and aluminum values for lime treated Hilo Series plots, Hilo plantation, Island of Hawaii. Twenty-six months after installation.

Pounds coral per acre	Plot No.	pH	Cation Exchange capacity me./100 gms.	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	34	5.5	58.6	0.56	13.55
0	42	5.1	56.5	1.00	11.13
4,000	12	5.6	58.6	2.88	8.28
4,000	20	5.7	58.5	1.72	12.65
11,000	3	6.0	60.0	5.32	6.75
22,000	17	5.9	56.7	5.84	10.42
22,000	27	6.4	55.0	10.36	7.06

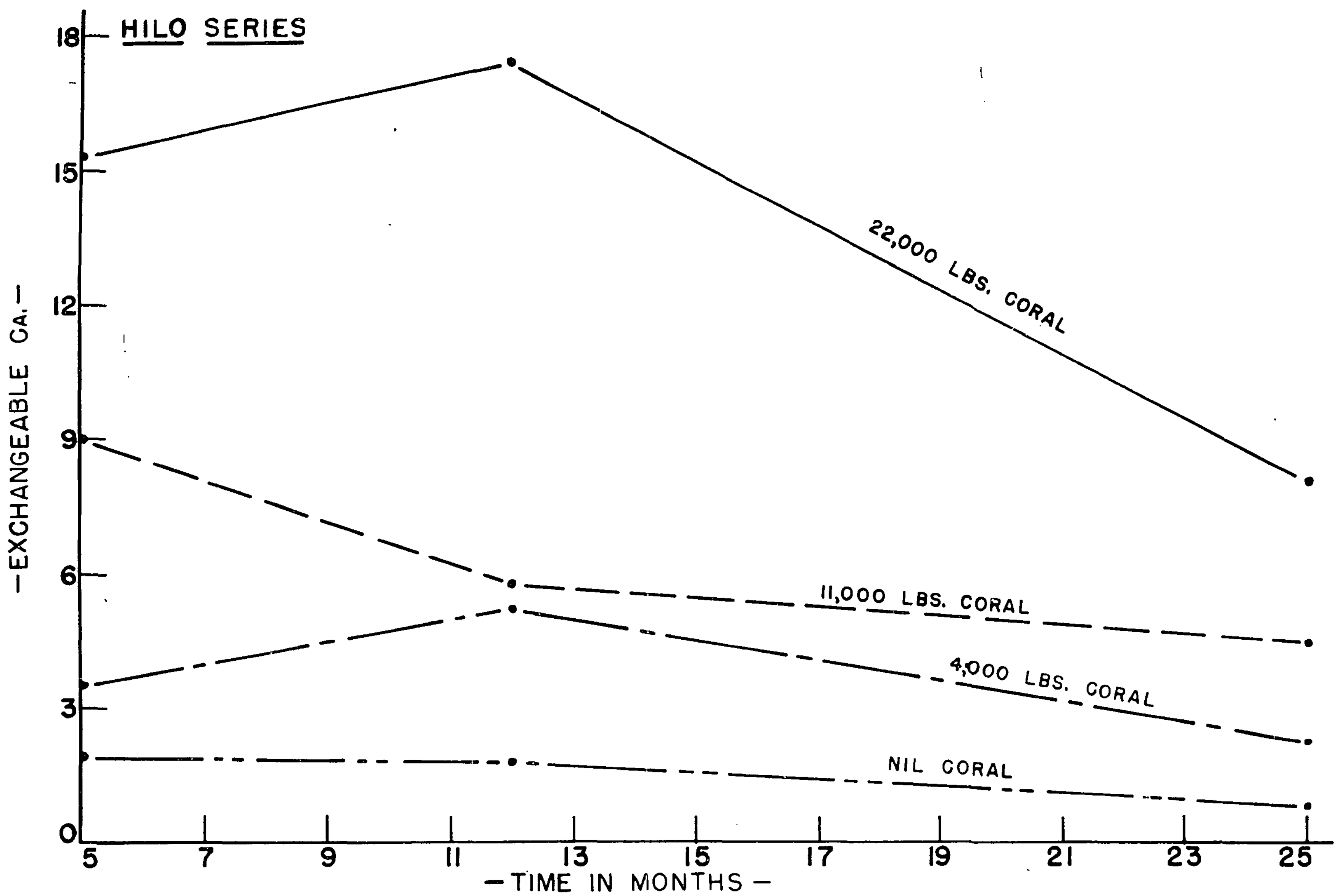

HILO SERIES
22,000 LBS. CORAL
11,000 LBS. CORAL
4,000 LBS. CORAL
NIL CORAL
18
15
12
9
6
3
0
—EXCHANGEABLE CA.—
5
7
9
11
13
15
17
19
21
23
25
—TIME IN MONTHS—

Figure 5. Progressive changes in mean exchangeable calcium values over a two-year period for the four liming levels used in Hilo series experimental field plots, Hilo plantation, Island of Hawaii

Table 22. Exchangeable calcium, pH and extractable aluminum values for lime treated Akaka Series plots, Hakalau plantation, Island of Hawaii. Fourteen months after installation.

Pounds coral per acre	Plot No.	pH	Exchangeable Ca. me./100 gms.	Extractable AL me./100 gms.
0	20	4.9	0.82	18.99
0	23	4.7	0.38	19.64
4,000	14	5.1	2.26	14.56
4,000	17	5.4	3.97	19.69
11,000	2	5.6	6.22	15.05
11,000	5	5.9	12.33	16.68
22,000	8	5.8	9.16	14.03
22,000	11	6.0	12.35	16.00

Table 23. Exchangeable calcium, pH, cation exchange capacity and extractable aluminum for lime treated Akaka Series plots, Hakalau plantation, Island of Hawaii. Twenty-six months after installation.

Pounds coral per acre	Plot No.	pH	Cation Exchange Capacity me./100 gms.	Exchangeable Ca. me./100 gms.	Extractable AL me./100 gms.
0	20	4.6	67.2	0.20	17.51
0	23	4.7	67.5	0.20	19.08
4,000	14	4.9	60.5	0.83	19.87
4,000	17	5.3	65.5	2.51	17.12
11,000	2	5.5	49.9	8.63	10.49
11,000	5	5.7	64.2	7.99	13.41
22,000	8	5.6	61.9	8.53	12.33
22,000	11	5.9	52.5	9.19	14.22

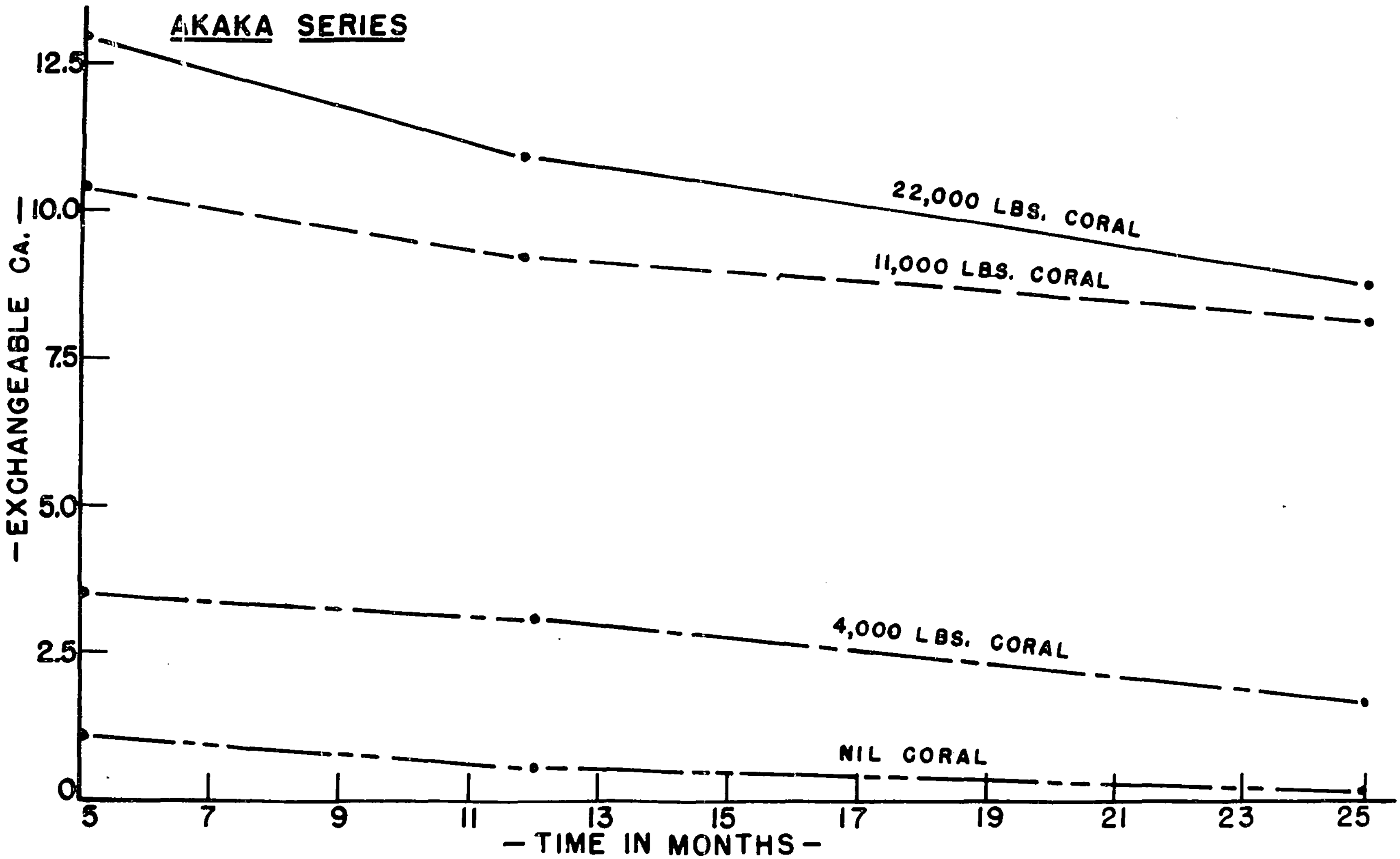


Figure 6. Progressive changes in mean exchangeable calcium values over a two-year period for the four liming levels used in Akaka series experimental field plots, Hakalau plantation, Island of Hawaii.

Table 24. Exchangeable calcium, pH and extractable aluminum values for lime treated Akaka Series plots, Pepeekeo plantation, Island of Hawaii, 10 months after installation.

Pounds coral per acre	Plot No.	pH	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	8	5.4	1.56	15.47
0	30	5.1	1.50	19.44
4,000	3	5.5	4.56	20.25
4,000	27	5.3	4.38	20.21
19,000	12	6.2	15.90	18.29
19,000	31	6.4	16.58	15.25
34,000	10	6.4	15.71	14.74
34,000	26	7.0	29.49	11.75

was one Pepeekeo plot which had a pH of 7 as a result of the heaviest lime application. Although the calcium values for Pepeekeo plantation were higher than those for Hakalau plantation, the general response pattern for the two plantations was similar.

Kaumoali series. The results of the chemical analysis of the Kaumoali series soils for one year and two year samples are presented in tables 25 and 26. The pH values and exchangeable calcium values showed little change for the one and two year samples. The exchangeable calcium mean values for the 5 months, one year and two year samples are presented in figure 7.

Discussion

The response of these soils to liming for the two-year period was indicated by the exchangeable calcium mean values in figures 5, 6, and 7. The highest values are obtained in the one year samples of the Kaumoali series. The Kaumoali series samples collected at 5 months and two years had similar values for exchangeable calcium. The highest exchangeable calcium values were found in the 5 month Akaka series samples and this was followed by a continuous reduction in values, with time, for all levels of applied lime. The response of Hilo series soils was intermediate between the other two soil series.

Throughout the two-year period the calcium-aluminum relationships remained relatively constant for the Hilo series and Kaumoali series. For the first year the Akaka series was similar to the other soils in this relationship,but the linear regression gradient increased markedly for the two year samples of this soil series.

The observations illustrated in the five figures have demonstrated that the Akaka series soil has less exchangeable calcium retaining capa-

Table 25. Exchangeable calcium, pH and extractable aluminum values for lime treated Kaumoali Series plots, Paauhau plantation, Island of Hawaii, 12 months after installation.

Pounds coral per acre	Plot No.	pH	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	11	4.9	1.61	26.24
0	23	5.1	5.57	23.22
12,000	1	5.5	9.07	24.64
12,000	16	5.7	11.36	19.08
30,000	6	5.7	11.17	24.00
30,000	17	6.0	15.64	19.38
46,000	8	6.0	18.29	20.90
46,000	20	6.7	38.82	11.39

Table 26. Exchangeable calcium, pH, cation exchange capacity and extractable aluminum values for the lime treated Kaumoali Series plots, Paauhau plantation, Island of Hawaii. Twenty-four months after installation.

Pounds coral per acre	Plot No.	pH	Cation exchange capacity me./100 gms.	Exchangeable Ca me./100 gms.	Extractable AL me./100 gms.
0	11	5.2	68.6	1.70	21.71
0	23	4.7	65.5	1.08	20.64
12,000	1	5.0	76.8	4.80	22.20
12,000	16	5.7	69.6	12.74	19.90
30,000	6	5.7	67.2	13.82	17.45
30,000	17	5.4	63.1	6.83	19.01
46,000	8	6.2	65.3	20.48	16.18
46,000	20	5.9	66.6	26.21	13.27

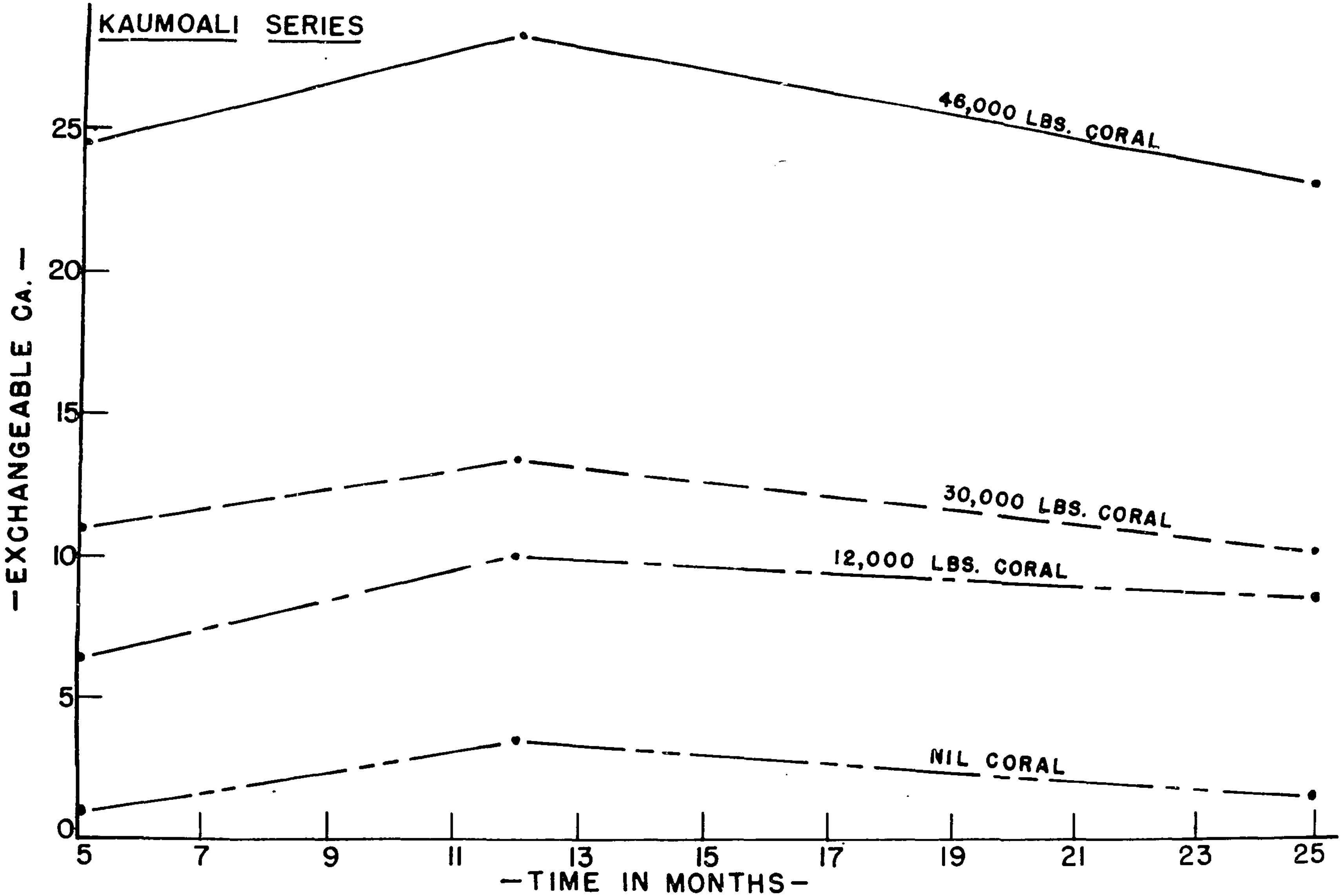


Figure 7. Progressive changes in mean exchangeable [illegible] year period for the four liming levels used in Kaumoali series experimental field plots, Paauhau plantation, Island of Hawaii.

Figure 7. Progressive changes in mean exchangeable calcium values over a two-year period for the four liming levels used in Kaumoali series experimental field plots, Paauhau plantation, Island of Hawaii.

city than the other two soil series. The decline in exchangeable calcium over the two-year period was accompanied by reduced pH values in the Akaka series soils. In view of these established trends, it would appear unlikely that there will be any appreciable increase in pH in the experimental plots for this soil series.

It appears that the progress of calcium release in these limed soils governs the rate at which their prelimed condition is resumed. Thus, the persistence of effects of heavy lime applications to these soils is dependent principally on their calcium retaining powers. Apparently the Akaka series soils have an acidic property which is of greater intensity than is the case for the other two soil series. Chizhevskii and Korovkin (18) considered that soils with a high exchange acidity due mainly to available aluminum are in particular need of lime. Hardy (44) concluded that the "potent acid-forming agent" in the upland soils derived from volcanic ash, on the Island of Dominica, was possibly due to hydrolizable compounds of aluminum and iron. A comparison of extractable aluminum values for these three Hawaiian soils series indicates that this property is not directly related to intensity of soil acidity. Schofield (104) found that for certain strongly acidic soils high in sesquioxides the basic positive changes exceed the permanent negative change combined with the acidic negative changes. It was suggested by Schofield that such soils retain anions but not cations.

It appears that there are two factors to consider in the effects of heavy lime applications. Firstly in changing the pH of a soil from a given value to another pH value the amount of lime is determined from titration curves. These titration curves represent the buffering capacity of the soil. The data from this time study demonstrate that there is some inherent factor that influences the persistence of the effects of liming. This factor, which could be called "inherent" acidity, controls or influences exchangeable calcium and probably extractable aluminum and pH with time-heavy lime relationships. These curves are to be considered when considering the lasting effects of liming. It would be advantageous if an indication of these patterns of behavior could be obtained in advance with laboratory methods. But the fact that time is a consideration in what is being measured would make it a difficult undertaking. Moormann (77) considered that the value of the Vietnam soils is mainly dependent on the real or the potential acidity of the soil material, in this case on the sulphur content. It is understood that these Hawaiian soils are different from the acid sulphate soils of Vietnam. However, the concept of potential acidity is of interest because the Hawaiian soils also have high aluminum values which are certainly increased with increased acidity.

B. LEACHING COLUMN STUDIES

Results

The chemical analysis of the leaching solutions is presented in tables 27-31. Chemical analysis of solution collected up to 24th April 1960 is in table 27. Chemical analyses for solutions collected up to the following dates are as follows: 2nd June 1960--table 28; 7th July 1960--table 29; 20th August 1960--table 30; 12th September 1960--table 31. These values have been calculated on a basis of unit per liter from 100 gms. of oven dry soil. The chemical analysis of the soils is presented in table 32.

The progressive changes over the 5-month period in carbonate, bicarbonate, phosphorus, aluminum, and calcium mean concentration values and mean pH values in the leaching solutions from limed and unlimed soils are presented in figures 8-25. The values for the Hilo series soils are

Table 27. Mean* concentration values for bicarbonate, carbonate, calcium, aluminum, silica and phosphorus and mean pH values of leached solution from limed and unlimed Hilo series, Akaka series and Kaumoali series soils. Solutions collected April 1960.

Soil Series	Ca CO_3 pounds per acre	pH	CO_3 10^{-3}me./liter	HCO_3 10^{-3}me./liter	Ca 10^{-3}me./liter	AL 10^{-5}me./liter	P 10^{-1}mg./liter
Hilo	0	7.3	0	2247	755	22	5.7
	22,000	7.7	0	3416	7503	341	15.0
Akaka	0	7.3	0	1432	631	358	20.3
	22,000	7.1	0	3842	20183	46	17.0
Kaumoali	0	7.0	0	1432	1117	83	N.D.**
	46,000	7.4	0	4037	17327	0	N.D.**

*mean of 3 replicates
**N.D.--not determined

Table 28. Mean* concentration values for bicarbonate, carbonate, calcium, aluminum, silica and phosphorus and mean pH values of leached solution from limed and unlimed Hilo series, Akaka series, and Kaumoali series soils. Solutions collected June 1960.

Soil Series	Ca CO_3 pounds per acre	pH	CO_3 10^{-3}me./liter	HCO_3 10^{-3}me./liter	Ca 10^{-3}me./liter	AL 10^{-5}me./liter	P 10^{-1}mg./liter
Hilo	0	7.1	0	1090	229	70	2.7
!	22,000	8.3	315	3948	4020	72	6.7
Akaka	0	5.1	0	342	206	577	5.5
	22,000	7.8	320	3588	7579	0	7.5
Kaumoali	0	7.1	0	960	349	19	6.0
	46,000	8.2	481	4149	9925	17	3.7

*mean of 3 replicates

Table 29. Mean* concentration values for bicarbonate, carbonate, calcium, aluminum, silica, and phosphorus and limed pH values of leached solution from limed and unlimed Hilo series, Akaka series and Kaumoali series soils. Solutions collected July 1960.

Soil Series	Ca CO_3 pounds per acre	pH	CO_3 10^{-3}me./liter	HCO_3 10^{-3}me./liter	Ca 10^{-3}me./liter	AL 10^{-5}me./liter	P 10^{-1}mg./liter
Hilo	0	N.D.**	0	N.D.**	468	26	4.3
	22,000	8.4	555	3700	3077	76	9.7
Akaka	0	7.1	0	835	188	145	12.3
	22,000	8.0	291	3127	4712	37	13.3
Kaumoali	0	7.6	0	1012	437	18	11.7
	46,000	8.2	423	4543	5818	21	12.3

*mean of 3 replicates
**N.D.--not determined

Table 30. Mean* concentration values for bicarbonate, carbonate, calcium, aluminum, silica and phosphorus and mean pH values of leached solution from limed and unlimed Hilo series, Akaka series and Kaumoali series soils. Solutions collected August 1960.

Soil Series	Ca CO_3 pounds per acre	pH	CO_3 10^{-3} me./liter	HCO_3 10^{-3} me./liter	Ca 10^{-3} me./liter	AL 10^{-5} me./liter	Si mg./liter	P 10^{-1} mg./liter
Hilo	0	6.9	112	1347	479	0	65	7.3
	22,000	8.5	691	4307	2500	7	189	12.7
Akaka	0	7.6	0	460	142	19	21	5.0
	22,000	8.3	436	3430	3428	6	145	6.7
Kaumoali	0	7.1	58	1079	505	0	60	5.3
	22,000	8.3	729	4666	4603	13	177	6.7

*Each value is the mean value obtained from 3 replicates.

Table 31. Mean* concentration values for bicarbonates, carbonates, calcium, aluminum and phosphorus and mean pH values of leached solution from limed and unlimed Hilo series, Akaka series and Kaumoali series soils. Solutions collected September 1960.

Soil Series	$CaCO_3$ pounds per acre	pH	CO_3 10^{-3} me./liter	HCO_3 10^{-3} me./liter	Ca 10^{-3} me./liter	AL 10^{-5} me./liter	P 10^{-1} mg./liter
Hilo	0	6.5	61	1347	366	27	6.3
	22,000	8.1	313	3996	1809	32	18.3
Akaka	0	6.2	0	609	194	1	4.7
	22,000	8.8	361	2962	2475	28	12.0
Kaumoali	0	7.6	58	1026	485	5	3.3
	46,000	8.3	788	4309	3809	3	10.0

*Each value is the mean value obtained from 3 replicates.

Table 32. Concentration of calcium, aluminum and phosphorus and pH values for Hilo Series, Akaka Series, and Kaumoali Series and at the commencement and completion of the leaching studies.

Soil Series	Pounds $CaCO_3$ per acre	pH	Ca me./100 gms.	AL me./100 gms.	P P.P.M.
Hilo	Initial soil*	5.2	2.59	8.58	37.0
	leached 0	5.4	1.60	8.96	35.8
	leached 22,000	7.0	18.43	5.73	42.8
Akaka	Initial soil*	4.3	0.34	18.59	28.0
	leached 0	4.4	0.28	17.82	48.2
	leached 22,000	6.6	15.60	10.29	36.1
Kaumoali	Initial soil*	4.3	1.22	19.62	38.0
	Leached 0	4.6	1.03	19.96	41.0
	leached 46,000	7.2	38.23	11.40	39.2

*Soils from the original bulk soil samples were analyzed.

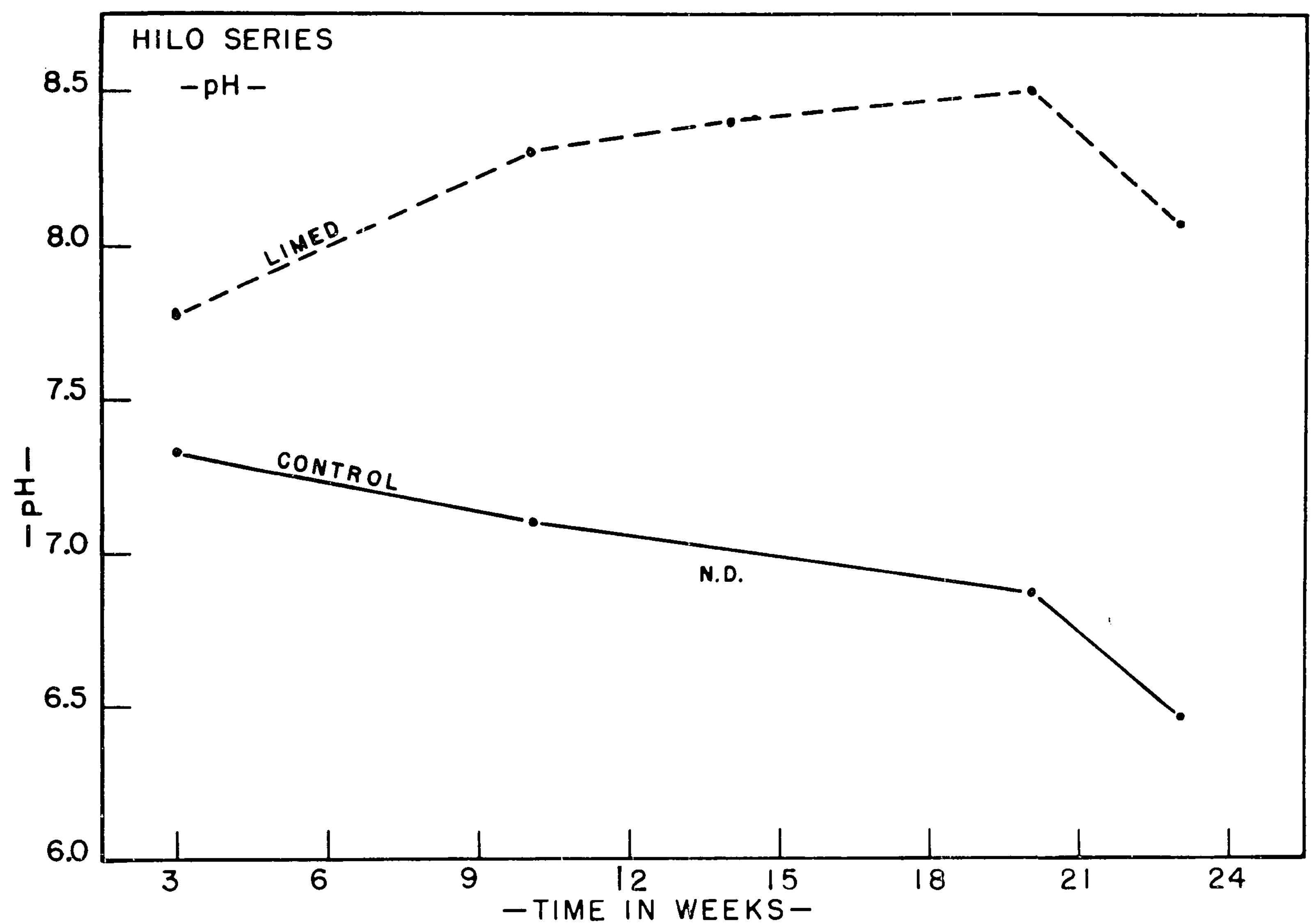

HILO SERIES
-pH-
LIMED
CONTROL
N.D.
8.5
8.0
7.5
7.0
6.5
6.0
-pH-
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 8. Progressive changes, over a six-month period, in mean pH values for solutions from limed and unlimed Hilo series soils.

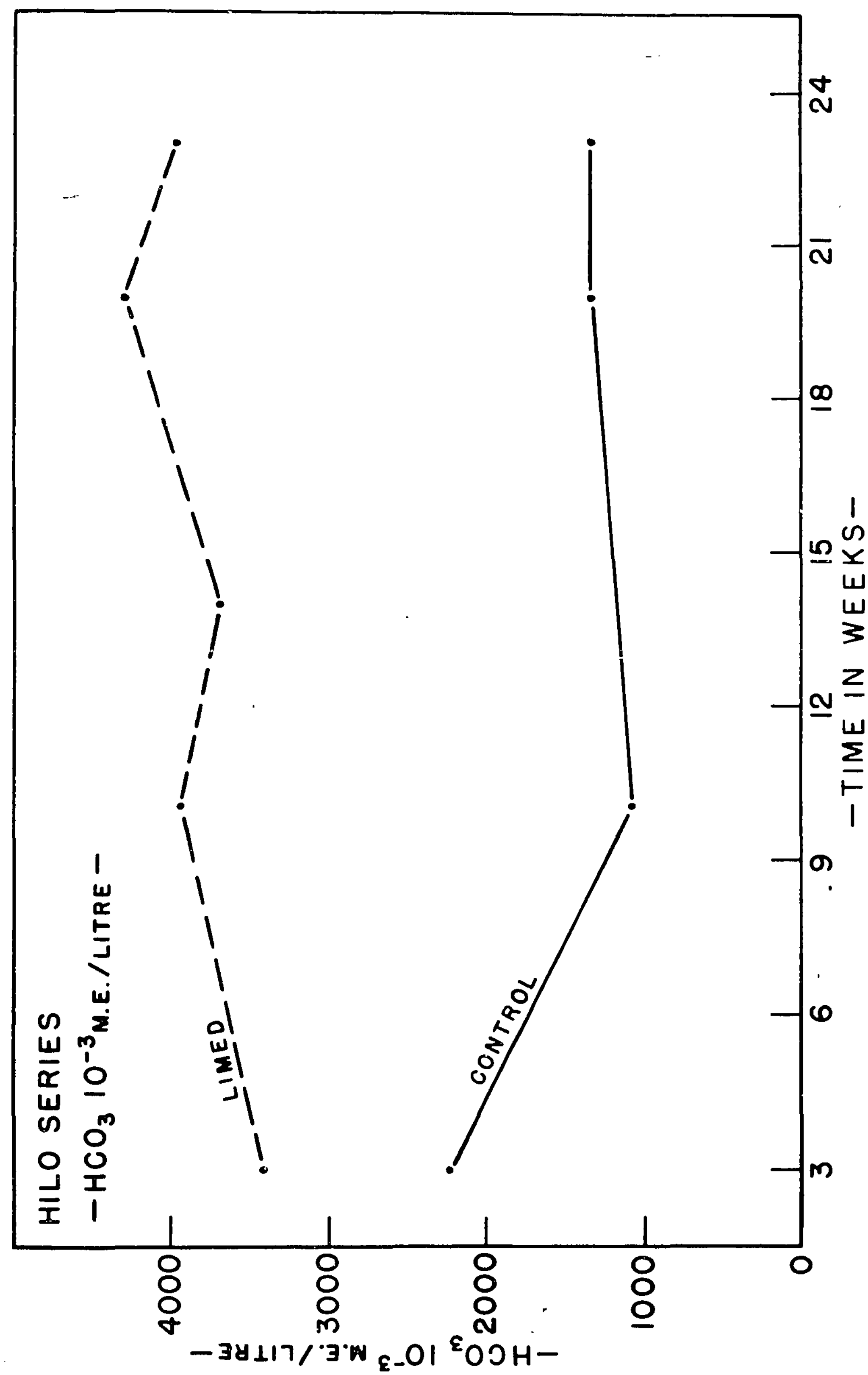

HILO SERIES
—HCO_3 10^{-3} M.E./LITRE—
LIMED
CONTROL
—HCO_3 10^{-3} M.E./LITRE—
0
1000
2000
3000
4000
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 9. Progressive changes over a six-month period in mean carbonate values for solutions from limed and unlimed Hilo series soils.

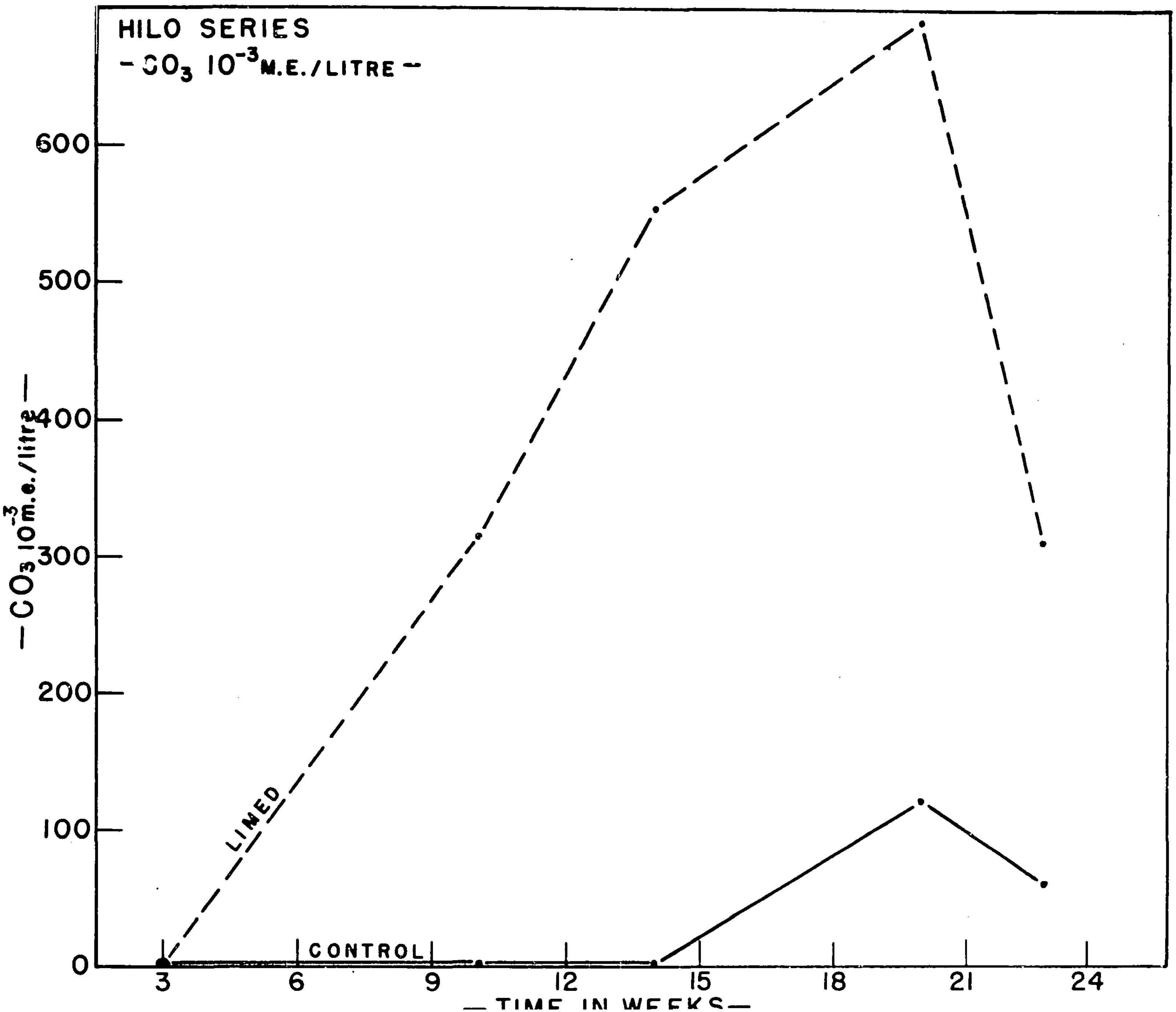

HILO SERIES
- CO_3 10^{-3} M.E./LITRE -
600
500
400
300
200
100
0
- CO_3 10^{-3} m.e./litre -
LIMED
CONTROL
3
6
9
12
15
18
21
24
— TIME IN WEEKS —

Figure 10. Progressive changes, over a six-month period, in mean bicarbonate values for solutions from limed and unlimed Hilo series soils.

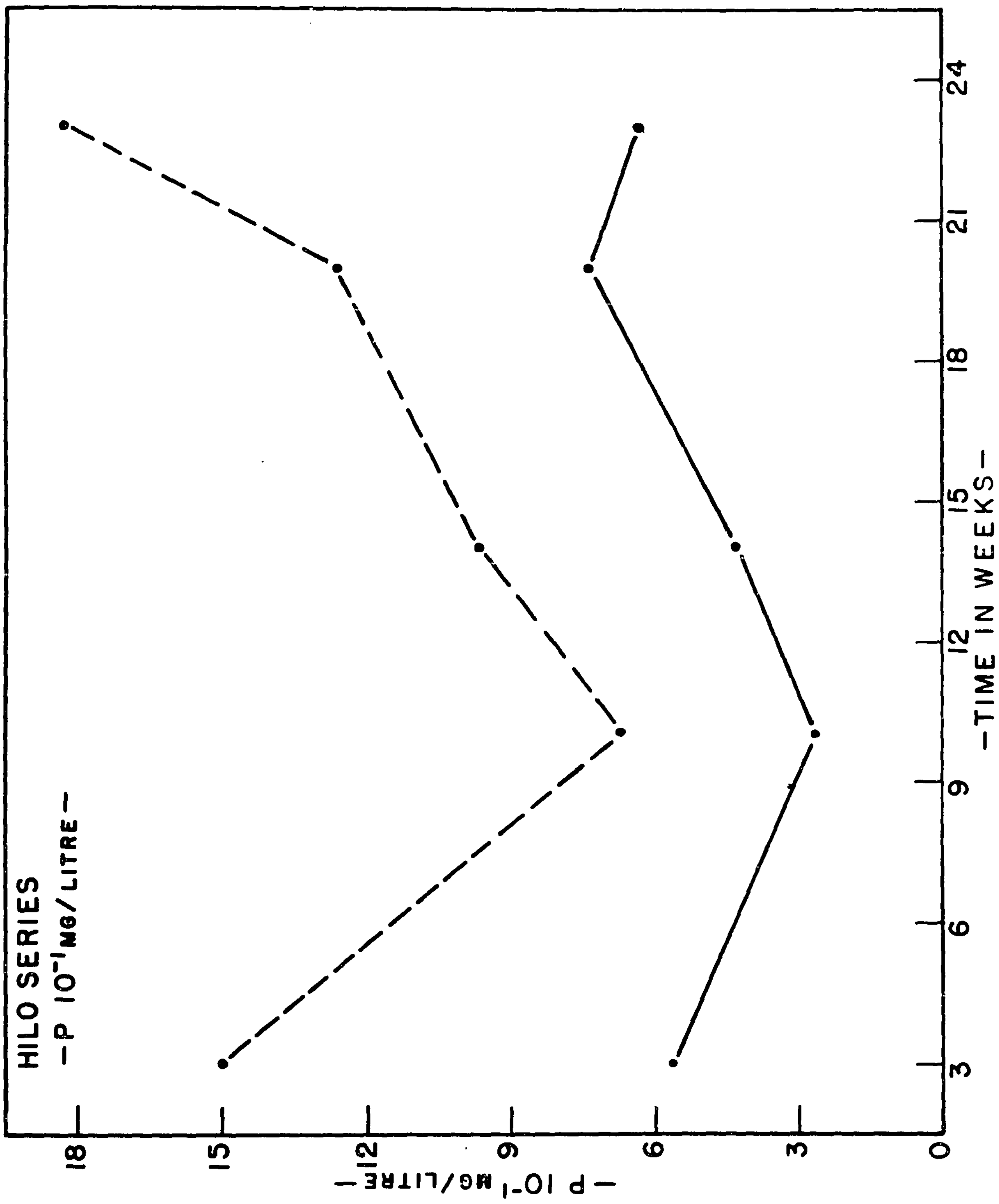

HILO SERIES
—P 10⁻¹ MG/LITRE—
— P 10⁻¹ MG/LITRE —
18
15
12
9
6
3
0
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 11. Progressive changes, over a six-month period, in mean phosphorus values for solutions from limed and unlimed Hilo series soils. (The control values are represented by a solid line and values for limed soils by a broken line.)

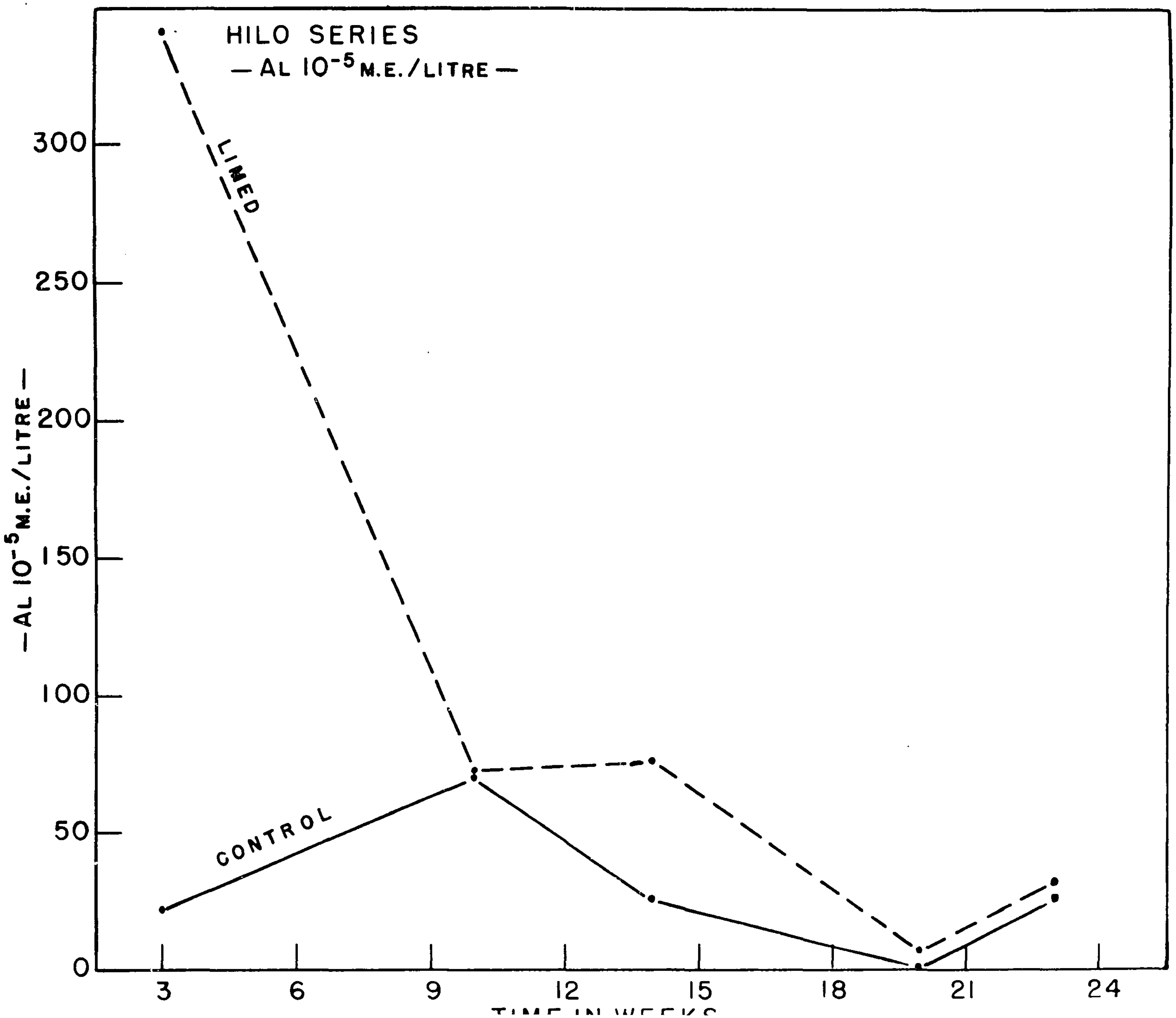

HILO SERIES
— AL 10^{-5} M.E./LITRE —
LIMED
CONTROL
— AL 10^{-5} M.E./LITRE —
300
250
200
150
100
50
0
3
6
9
12
15
18
21
24

Figure 12. Progressive changes, over a six-month period, in mean aluminum values for solutions from limed and unlimed Hilo series soils.

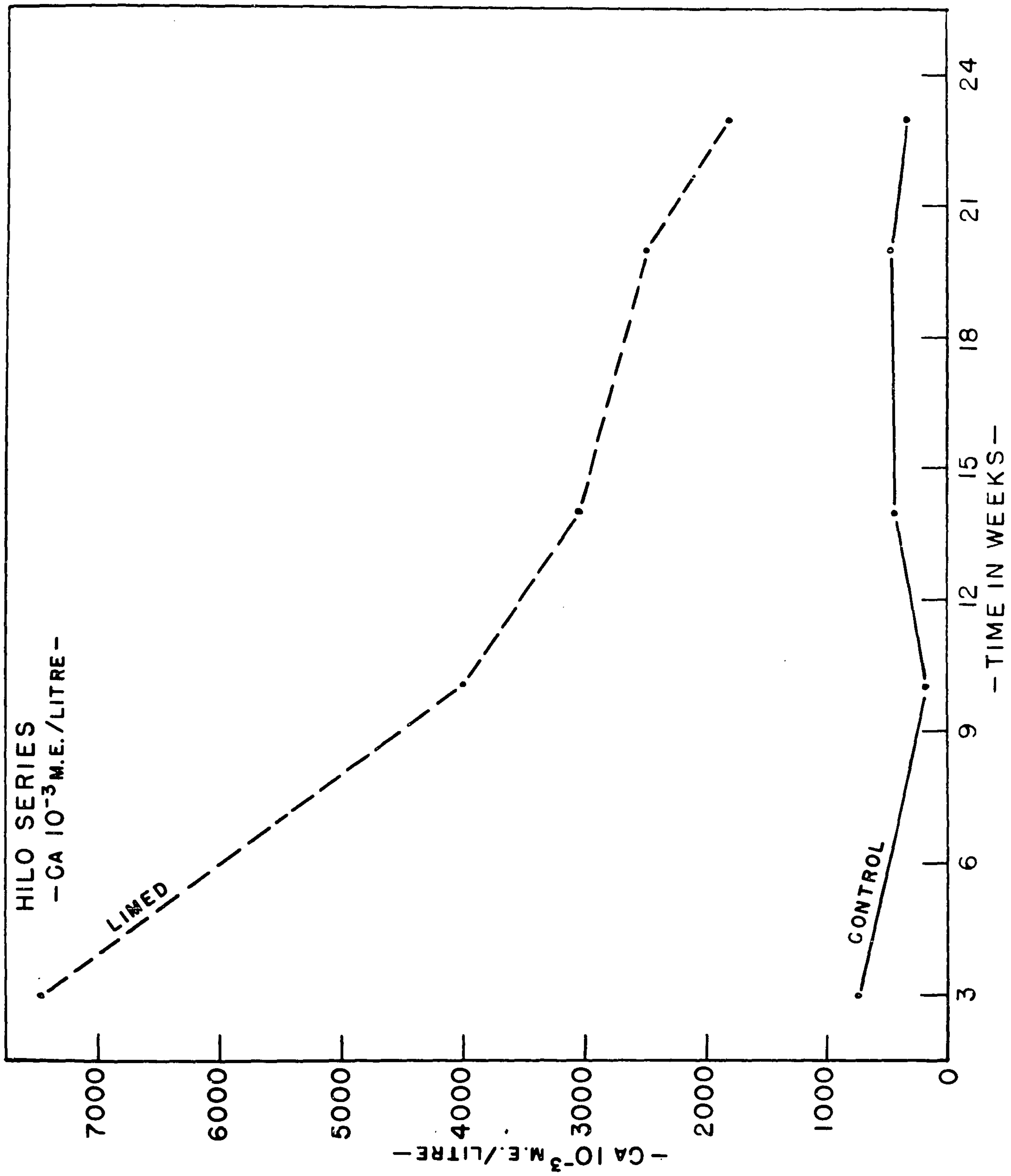

HILO SERIES
-CA 10^{-3} M.E./LITRE-
LIMED
CONTROL
7000
6000
5000
4000
3000
2000
1000
0
-CA 10^{-3} M.E./LITRE-
3
6
9
12
15
18
21
24
-TIME IN WEEKS-

Figure 13. Progressive changes, over a six-month period, in mean calcium values for solutions from limed and unlimed Hilo series soils.

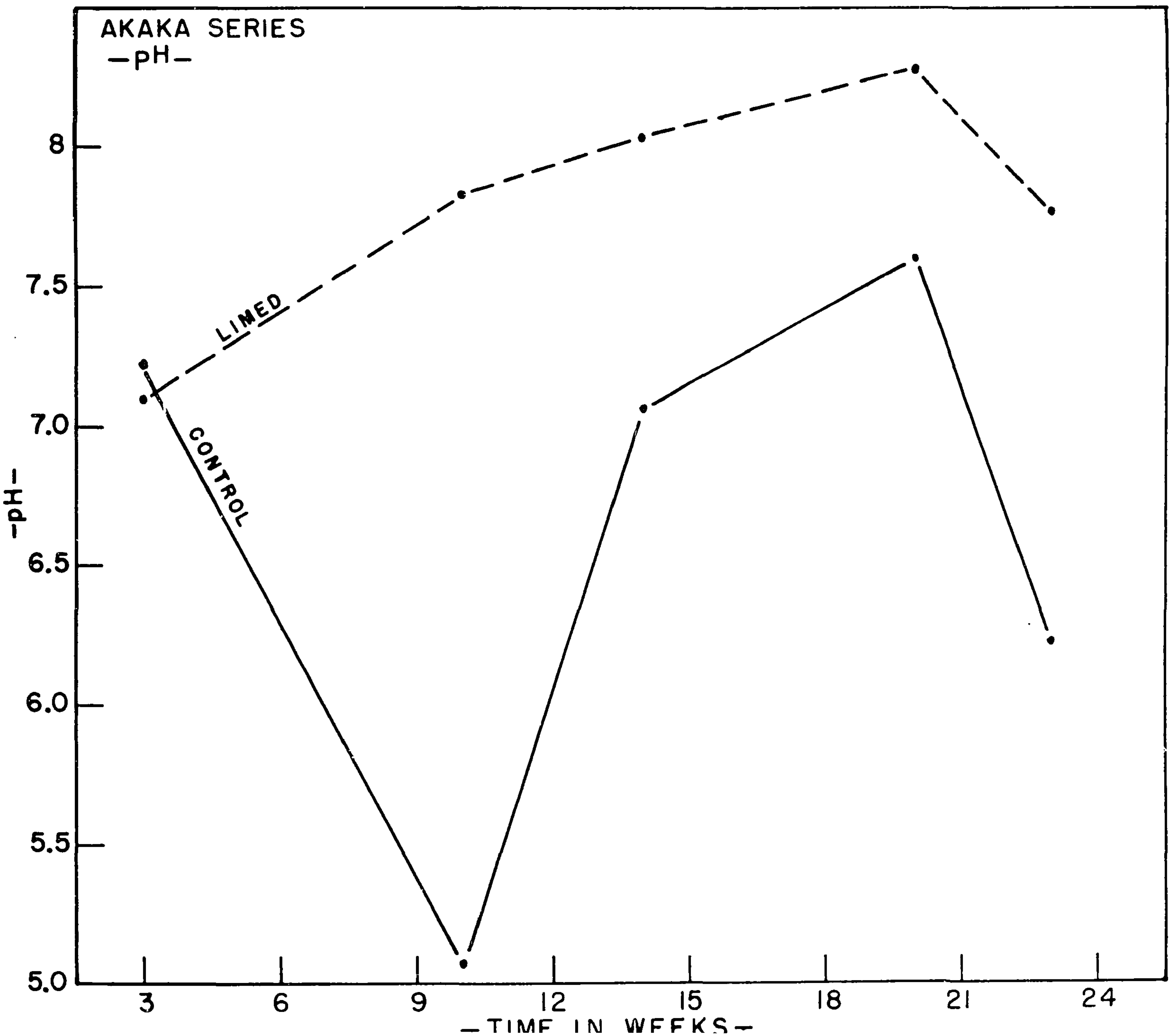

AKAKA SERIES
—pH—
LIMED
CONTROL
-pH-
8
7.5
7.0
6.5
6.0
5.5
5.0
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 14. Progressive changes, over a six-month period, in mean pH values for solutions from limed and unlimed Akaka series soils.

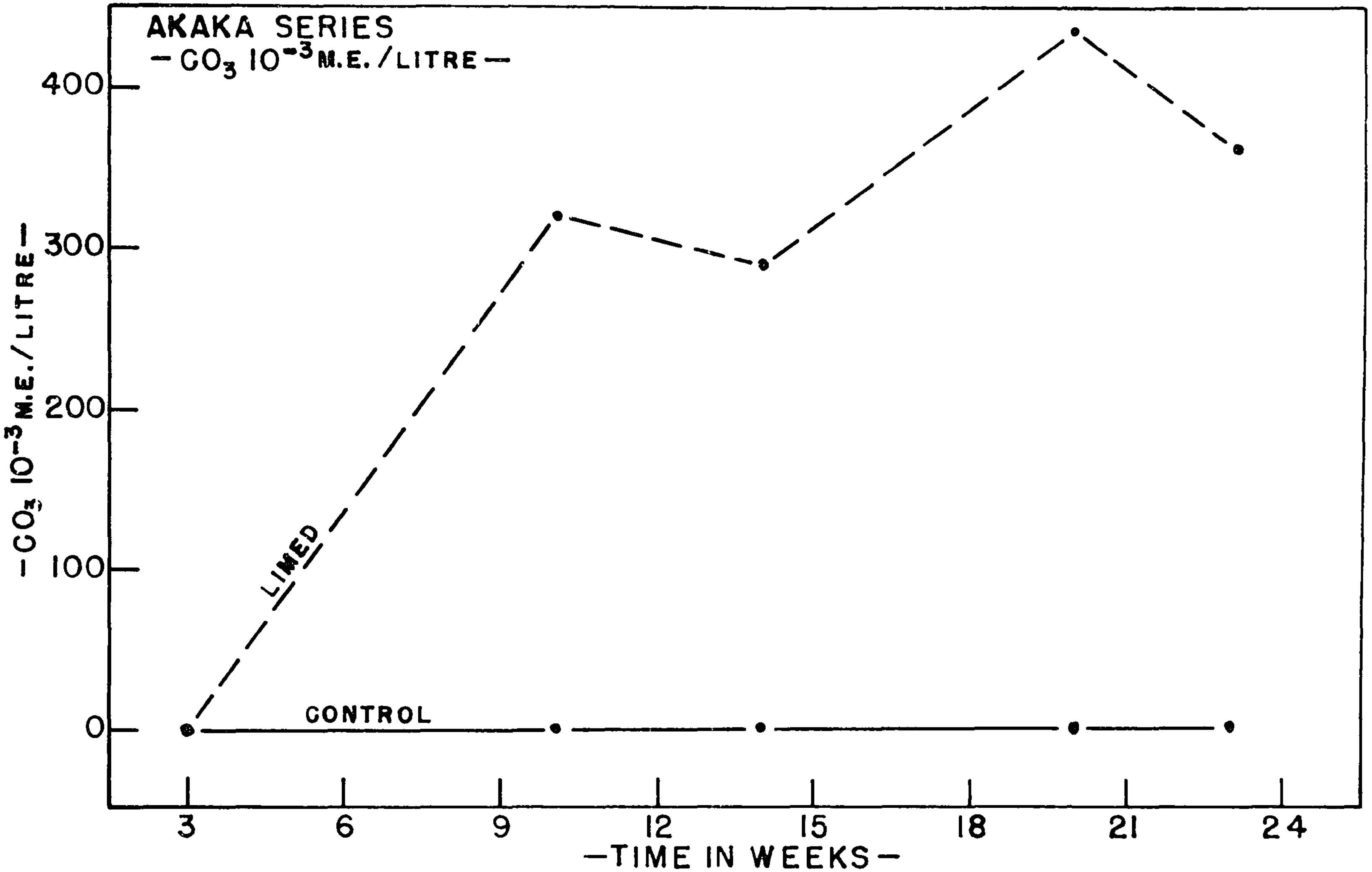

AKAKA SERIES
— CO_3 10^{-3} M.E./LITRE —
400
300
200
100
0
— CO_3 10^{-3} M.E./LITRE —
LIMED
CONTROL
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 15. Progressive changes, over a six-month period, in mean carbonate values for solutions from limed and unlimed Akaka series soils.

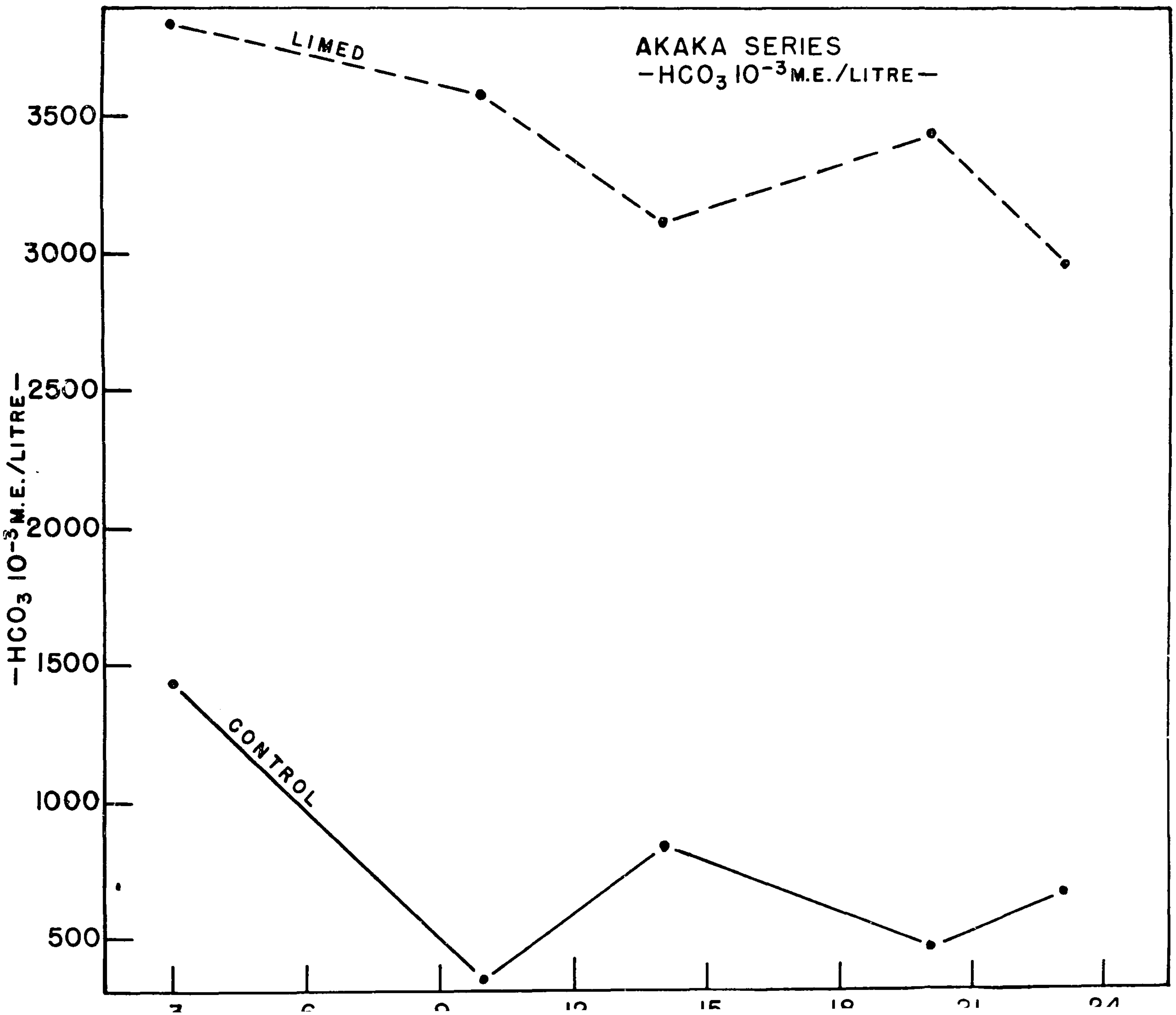
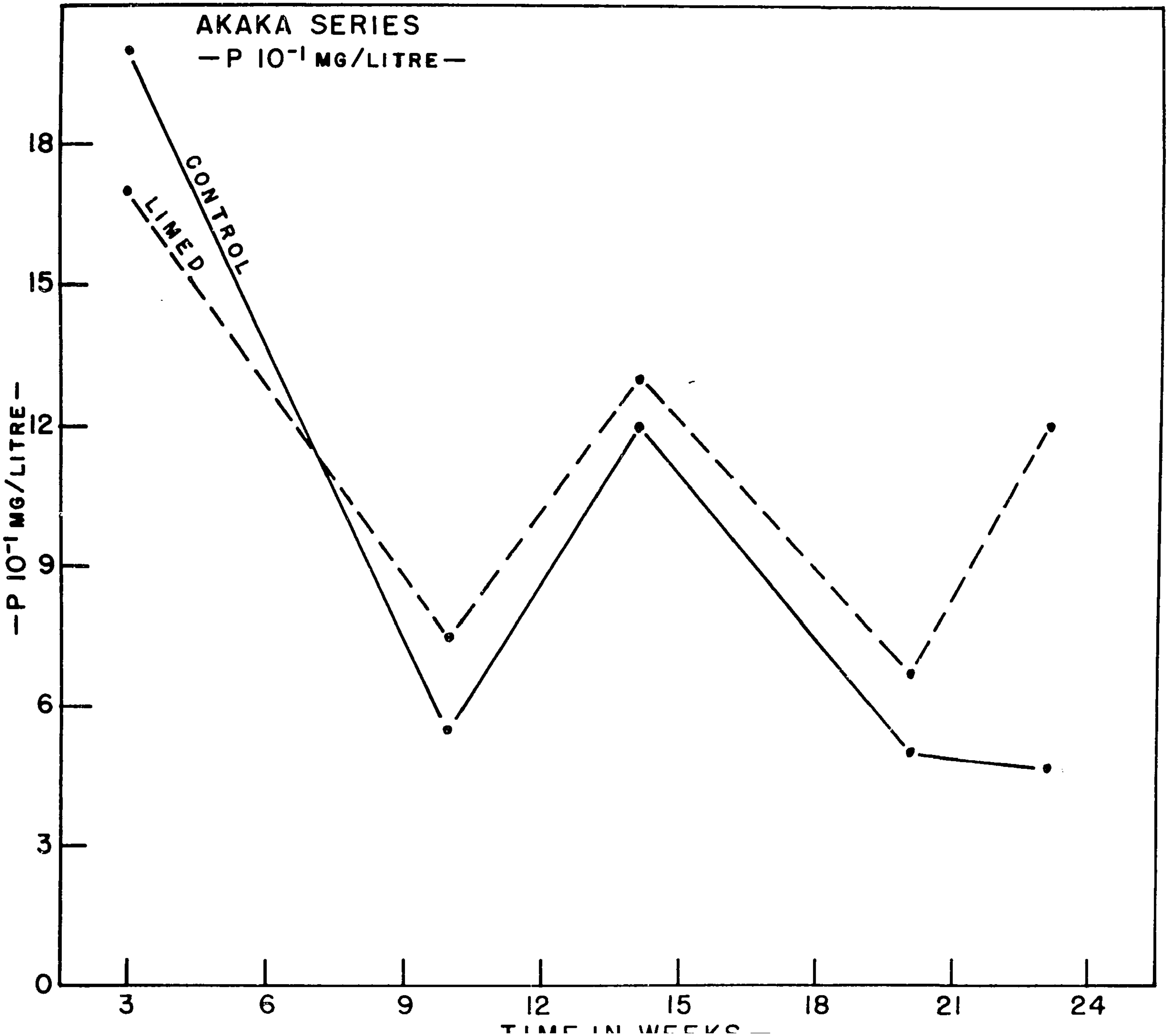

AKAKA SERIES
-HCO3 10-3 M.E./LITRE-
LIMED
CONTROL
3500
3000
2500
2000
1500
1000
500
-HCO3 10-3 M.E./LITRE-

Figure 16. Progressive changes, over a six-month period, in mean bicarbonate values for solutions from limed and unlimed Akaka series soils.


AKAKA SERIES
—P 10⁻¹ MG/LITRE—
CONTROL
LIMED
—P 10⁻¹ MG/LITRE—
0
3
6
9
12
15
18
3
6
9
12
15
18
21
24

93

Figure 17. .rogressive changes, over a six-month period, in mean phosphorus values for solutions from limed and unlimed Akaka series soils.

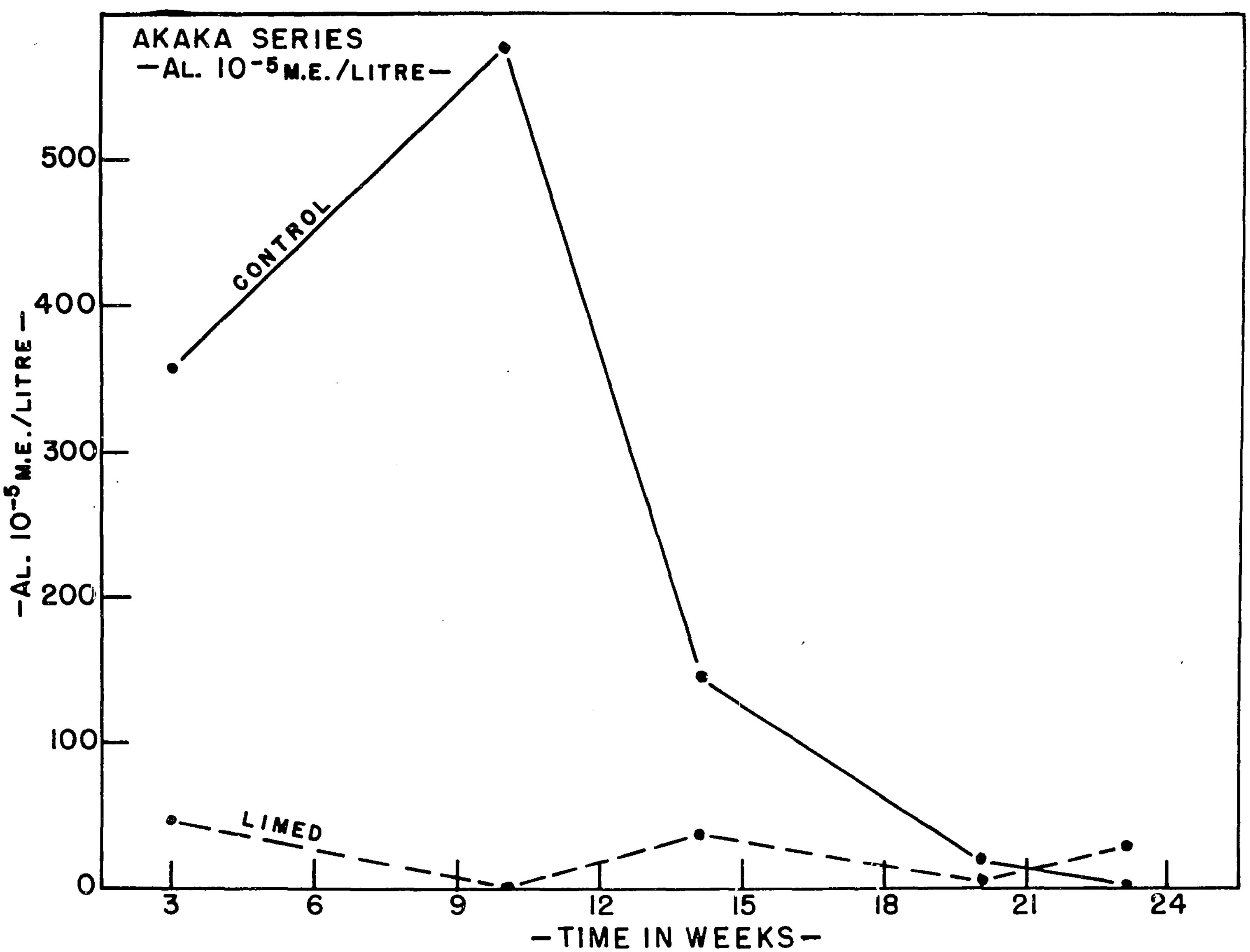

AKAKA SERIES
—AL. 10⁻⁵ M.E./LITRE—
CONTROL
LIMED
500
400
300
200
100
0
3
6
9
12
15
18
21
24
—TIME IN WEEKS—
—AL. 10⁻⁵ M.E./LITRE—

Figure 18. Progressive changes, over a six-month period, in mean aluminum values in solutions from limed and unlimed Akaka series soils.

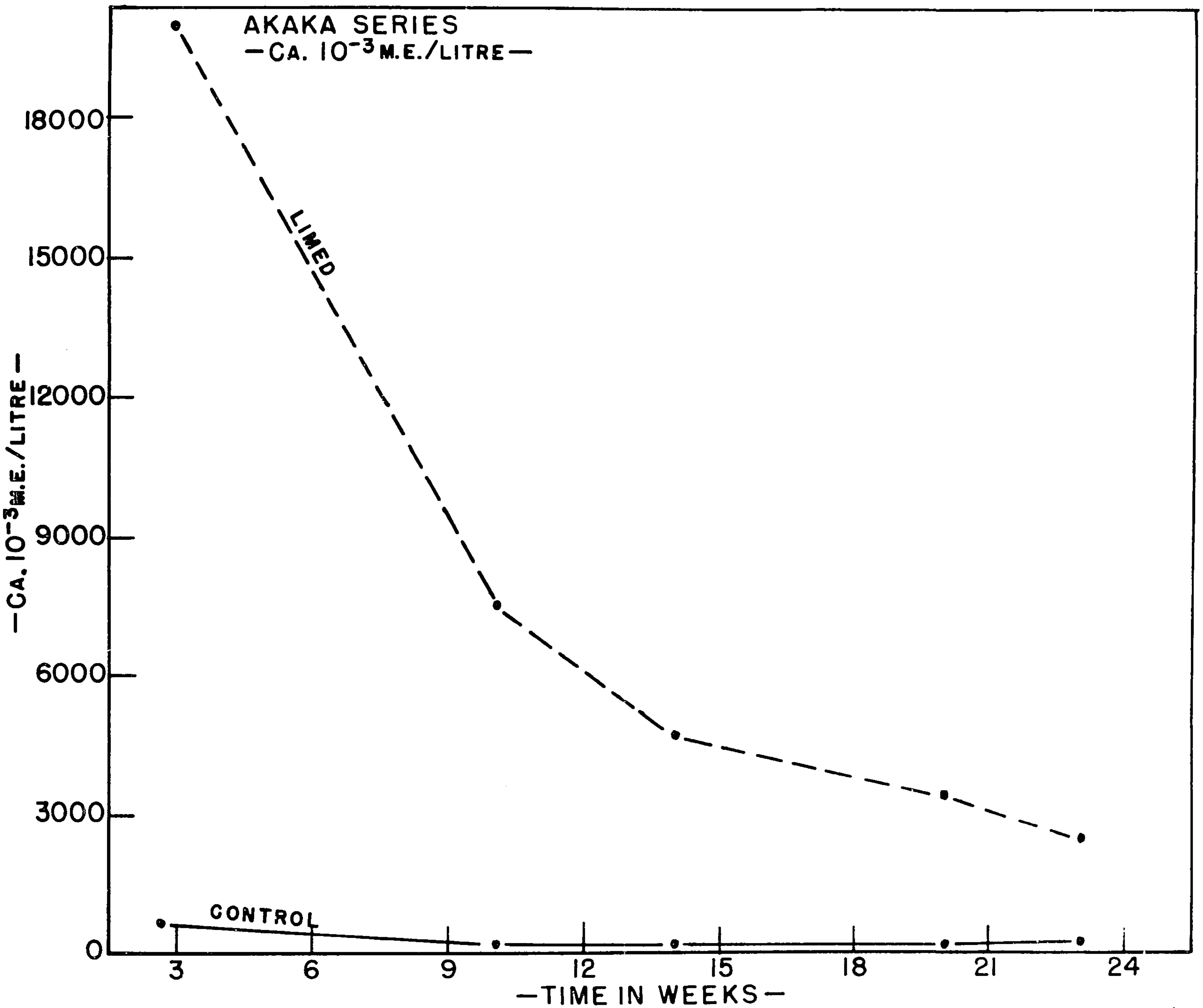

AKAKA SERIES
—CA. 10^{-3} M.E./LITRE—
LIMED
CONTROL
18000
15000
12000
9000
6000
3000
0
—CA. 10^{-3} M.E./LITRE—
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 19. Progressive changes, over a six-month period, in mean calcium values for solutions from limed and unlimed Akaka series soils.

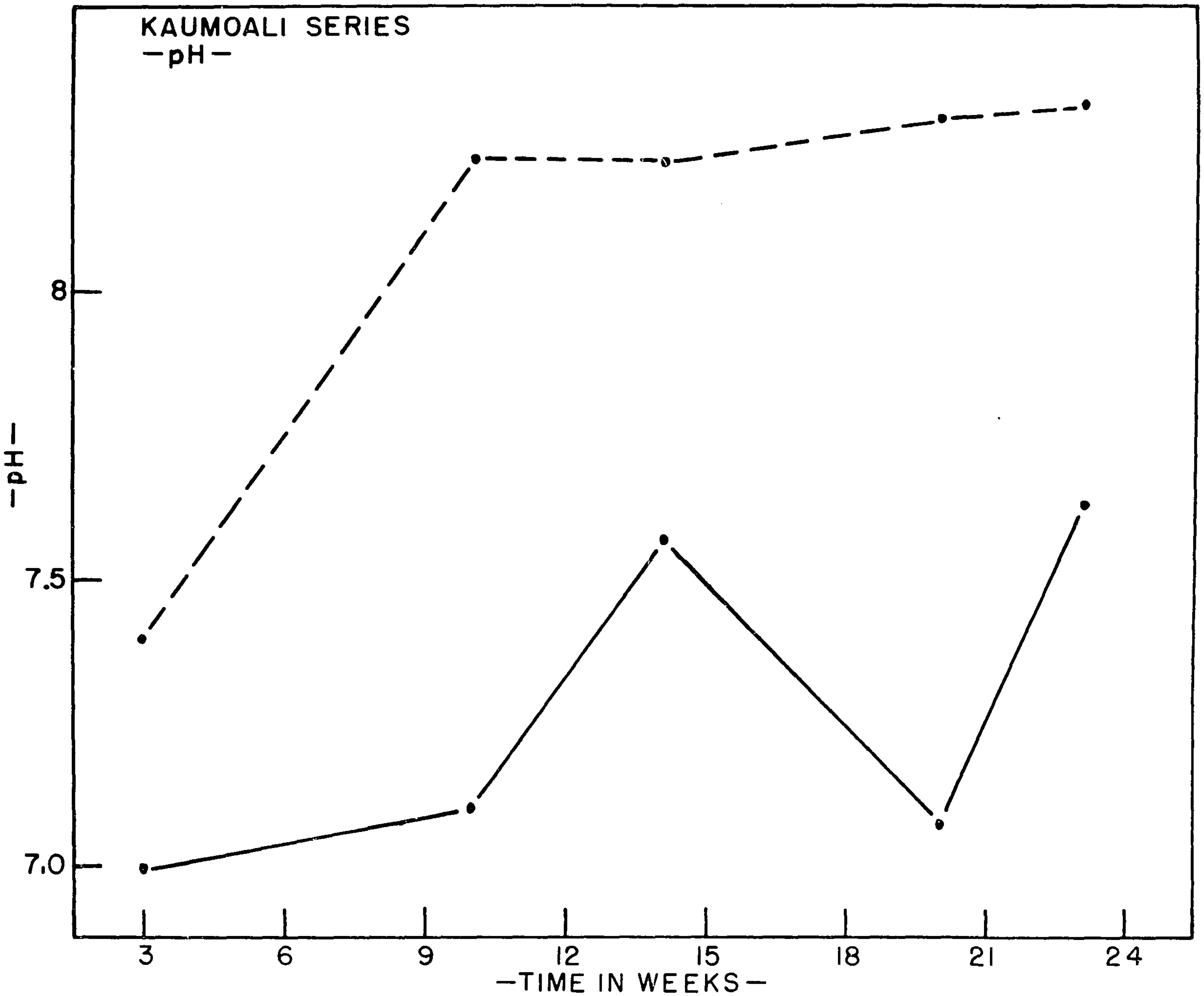
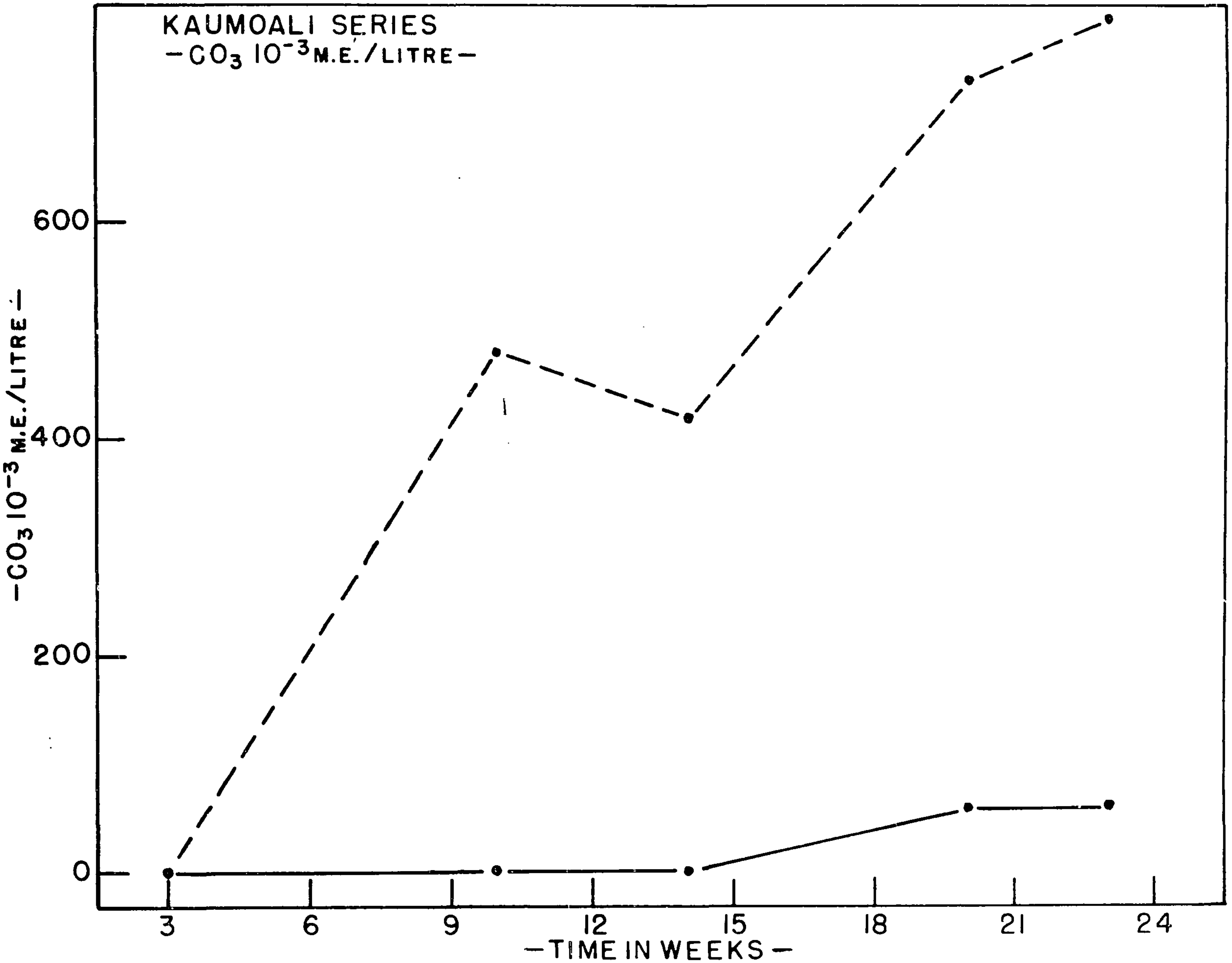

KAUMOALI SERIES
—pH—
—pH—
8
7.5
7.0
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 20. Progressive changes, over a six-month period, in mean pH values for solutions from limed and unlimed Kaumoali series soils. (The control values are represented by a solid line and values for limed soils by a broken line.)


KAUMOALI SERIES
$-CO_3\ 10^{-3}$ M.E./LITRE$-$
600
400
200
0
3
6
9
12
15
18
21
24
$-$TIME IN WEEKS$-$
$-CO_3\ 10^{-3}$ M.E./LITRE$-$

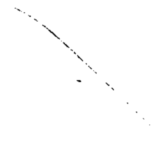


Figure 21. Progressive changes, over a six-month period, in mean carbonate values for solutions from limed and unlimed Kaumoali series soils. (The control values are represented by a solid line and values for limed soils by a broken line.)

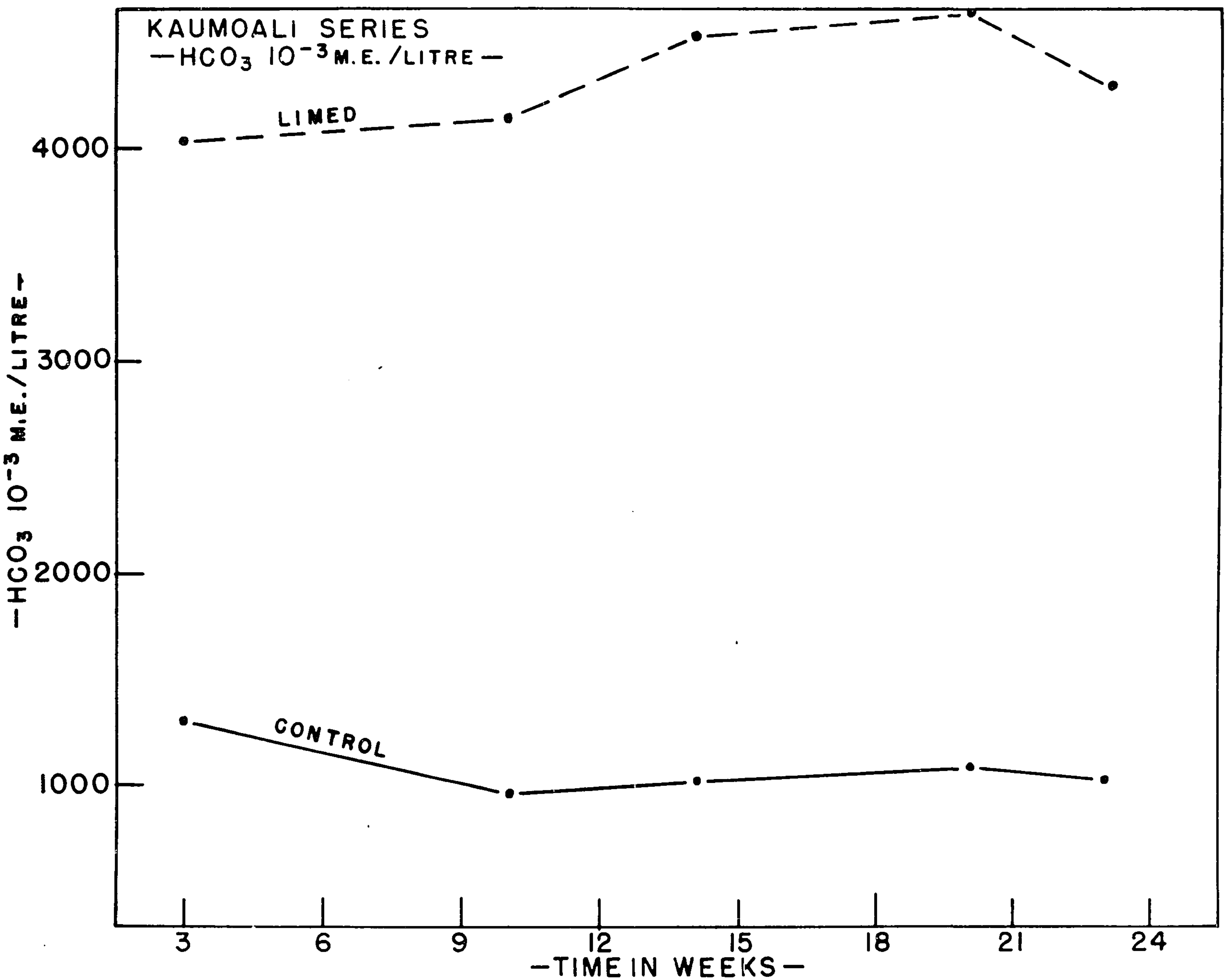

KAUMOALI SERIES
—HCO_3 10^{-3} M.E./LITRE—
LIMED
CONTROL
4000
3000
2000
1000
—HCO_3 10^{-3} M.E./LITRE—
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 22. Progressive changes, over a six-month period, in mean bicarbonate values for solutions from limed and unlimed Kaumoali series soils.

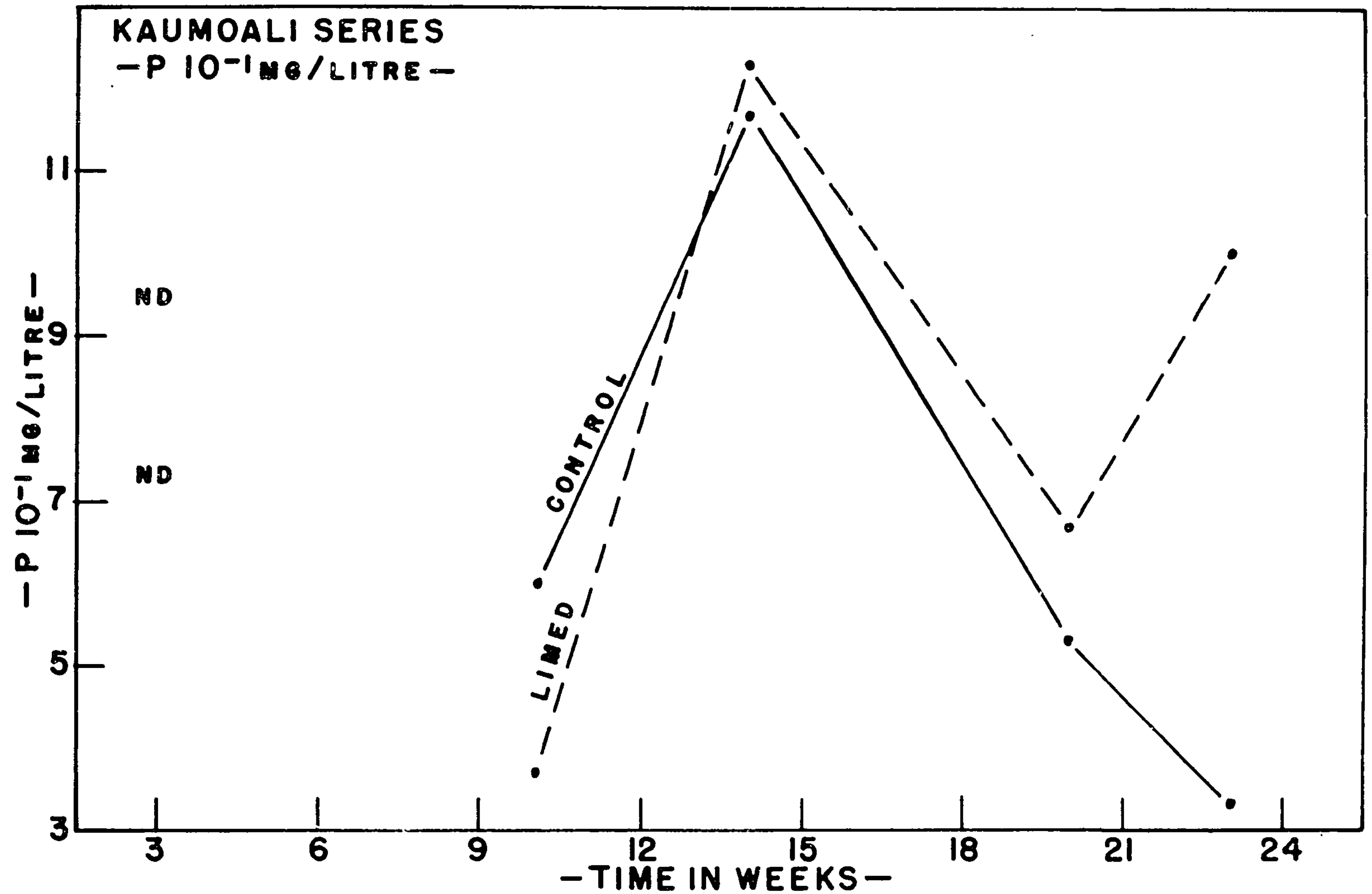

KAUMOALI SERIES
—P 10⁻¹ MG/LITRE—
ND
ND
CONTROL
LIMED
—P 10⁻¹ MG/LITRE—
11
9
7
5
3
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 23. Progressive changes, over a six-month period, in mean phosphorus values for solutions from limed and unlimed Kaumoali series soils.

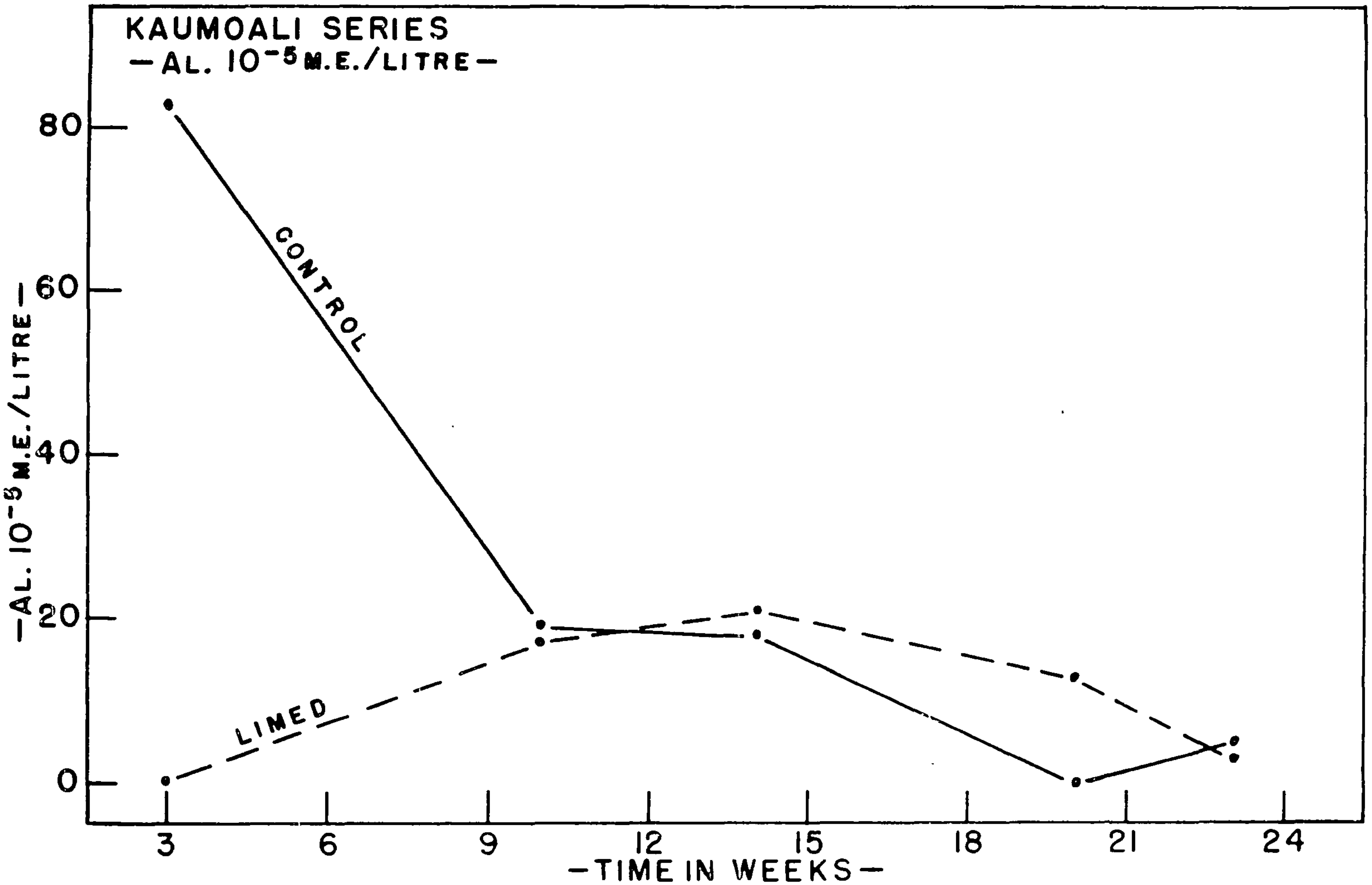

KAUMOALI SERIES
—AL. 10⁻⁵ M.E./LITRE—
CONTROL
LIMED
80
60
40
20
0
—AL. 10⁻⁵ M.E./LITRE—
3
6
9
12
15
18
21
24
—TIME IN WEEKS—

Figure 24. Progressive changes, over a six-month period, in mean aluminum values for solutions from limed and unlimed Kaumoali series soils.

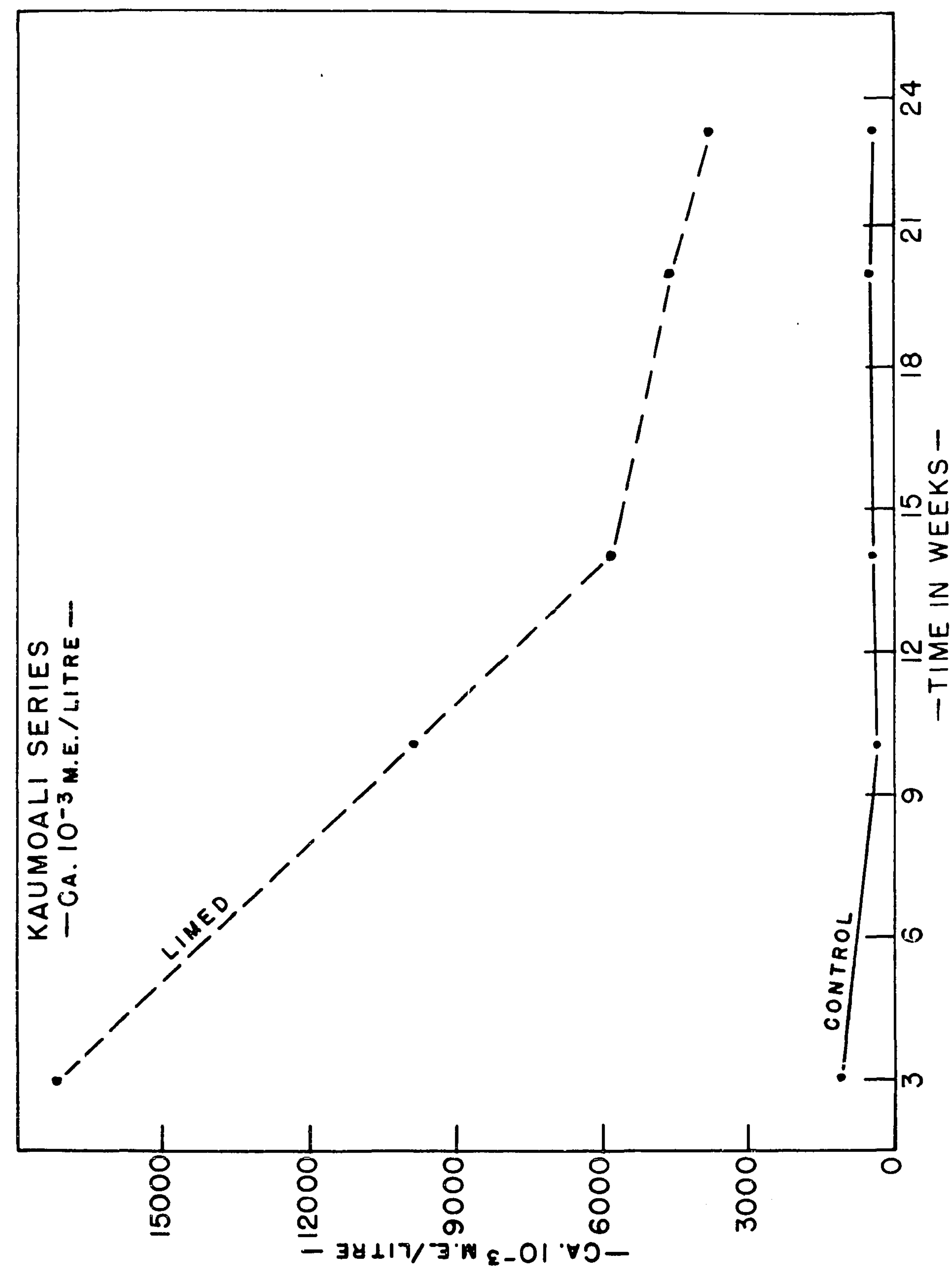

KAUMOALI SERIES
—CA. 10^-3 M.E./LITRE—
LIMED
CONTROL
—TIME IN WEEKS—
3
6
9
12
15
18
21
24
—CA. 10^-3 M.E./LITRE—
0
3000
6000
9000
12000
15000

Figure 25. Progressive changes, over a six-month period, in mean calcium values for solutions from limed and unlimed Kaumoali series soils.

presented in figures 8-12. The values for the Akaka series soils are presented in figures 13-19 and for the Kaumoali series soils in figures 20-25. Each value is the mean of three replicates.

Table 33 contains the analysis of variance of calcium content of leaching solutions from limed and unlimed Hilo series, Akaka series and Kaumoali series soils.

Analysis of variance of aluminum content of leaching solutions from limed and unlimed soils of the Hilo series, Akaka series and Kaumoali series is presented in table 34. Analysis of variance of phosphorus concentrations in solutions from limed and unlimed Hilo series soils is presented in table 35.

Discussion

To prevent dehydration of the soils used in this leaching experiment, a very liberal daily quantity of water was added. With a one-inch internal radius for the tubes the soils had a surface area of 3.1416 square inches. This is the equivalent of 6.45 square cm. The daily addition of 50 cm. water would give a depth of 7.75 cm. This is the equivalent of 3.05 inches per day. Occasionally rainfall similar to this would have been recorded for field areas but certainly not continuously. Thus, the leaching tubes would have greatly accelerated rates of movement compared with field situations. Nevertheless these studies have supplied useful information about the concentration of constituents in the soil solution and some idea of their rates of downward movement.

Calcium: The general behavior pattern for calcium was the same for the three soil series. For the control soil solutions the largest values were obtained for the first period. The calcium values were relatively

Table 33. Analysis of variance of calcium contents of leaching solution from limed and unlimed soils of the Hilo Series, Akaka Series, and Kaumoali Series, from Island of Hawaii

Source	Degrees of freedom	Sum of squares	Mean square
Replicates	2	1,032	
Treatments	(5)	514,207	102,841**
Series	2	2,382	1,191
Liming	1	425,349	425,349**
Series x liming	2	86,476	43,238**
Error	10	8,365	836
Total	17	523,604	

Table 34. Analysis of variance of aluminum content of leaching solutions from limed and unlimed soils of the Hilo Series, Akaka Series, and Kaumoali Series, from Island of Hawaii

Source	Degrees of freedom	Sum of squares	Mean square
Replicates	2	54,168	
Treatments	(5)	2,487,611	497,522**
Lime	1	28,939	28,939
Series	2	128,423	64,211
Lime x series	2	2,330,251	1,165,125**
Error	10	261,439	26,144
Total	17	2,803,217	

Table 35. Analysis of variance for phosphorus content of solutions from limed and unlimed Hilo Series soils, from Island of Hawaii.

Source	Degrees of freedom	Sum of squares	Mean square
Replicate	2	561	
Treatment	1	1873	1873*
Error	2	197	98.5
Total	5	2631	

constant for the remaining periods.

For the solutions from limed soils the peak contributions of calcium were obtained for the first period. There was a progressive decrease in calcium for the following time periods. The highly significant interaction shown in table 33, between lime and series for calcium values signified that the three soils did not respond in the same manner to applied lime.

For the April period the solution for limed Akaka series soils had almost three times as much calcium as the solution from the limed Hilo soils. The same lime levels had been applied to these soil series. The Kaumoali series soil had received twice as much lime as the Akaka series soil. The Kaumoali series soil did not have as much calcium in the soil solution for this first period as the solution from limed Akaka series soil. It appeared that the Akaka series soils had a much greater capacity than the other two soil series to promote the mobility of calcium. Thus, mechanisms that can increase the mobility of calcium are of interest in understanding these observations. Simmons (112) studied the effects of carbon dioxide pressure on the calcium and hydrogen ion concentrations of aqueous solutions of calcite at 25°C. It was found that as the pressure of carbon dioxide is increased, the concentration of both calcium and hydrogen ions is increased. However, the hydrogen ion concentration increases more rapidly than the calcium ion concentration. Bradfield (8) concluded from these studies that due to the increasing competition from hydrogen ions the amount of calcium absorbed by the clay will decrease as the carbon dioxide pressure rises.

<u>Aluminum</u>: The interaction between lime and series shown in table 34, for aluminum values was highly significant, and indicated that the

three series did not behave similarly when limed. There were substantial quantities of aluminum in solution from the unlimed Akaka series. In contrast there were negligible amounts of aluminum in solutions from the limed soils. In the unlimed soil solutions the aluminum was presumed to be in the AL^{+++} or closely related form. Brosset (9, 10) suggested that as the pH of solutions rise, there was a complexing of the aluminum ion accompanied by a decrease in net charge per aluminum atom. The reactions were considered to occur according to the following scheme.

$$AL^{3+} + AL^{3+} + 3H_2O \rightleftharpoons AL_2(OH)_3^{3+} + 3H^+$$

$$AL_2(OH)_3^{3+} + AL^{3+} + 3H_2O \rightleftharpoons AL_3(OH)_3^{3+} + 3H^+$$

Low concentrations of aluminum were present in Hilo series control. The increase in aluminum with liming was possibly due to the production of the aluminate ion.

Both limed and control Kaumoali series soils produced low concentrations of aluminum in the soil solutions. Thus, it appeared that water soluble aluminum was a very minor component of the high extractable aluminum values obtained for this soil series.

Phosphorus: Liming resulted in a significant increase, shown in table 35, for phosphorus concentrations in the solution from Hilo series soils. There was a slight but not significant increase due to liming in phosphorus concentration for the soil solution from the Akaka series and Kaumoali series.

Silica: The analytical figures for the August samples were of great interest. There was a threefold increase in silica in the soil solution as a result of liming for the Hilo series and Kaumoali series.

Liming the Akaka series soil resulted in a sixfold increase in silica in the soil solution. In the past the possible effects of increased soluble silica on phosphate availability has received attention. In his studies with sugar cane producing soils of Hawaii, McGeorge found that phosphate availability was usually associated with a higher solubility of silica. Sherman et al (111) reported that the yield of sudan grass was increased threefold when 1000 pounds of sodium silicate were added to a Humic Latosol from Hawaii. The typical phosphate deficiency symptoms of sudan grass were eliminated in the process. The greatly accelerated rate of downward movement of silica with liming is also of importance in regard to the pedogenesis and modification of soil properties. Hough, et al (49) reported that the Hilo series profile, which they analyzed, had approximately 10 per cent silica, approximately 25 per cent for aluminum and approximately 25 per cent for iron. The removal of silica is an important process in the formation of laterite and lateritic soils. A widely accepted hypothesis is that laterite is the result of leaching with a basic soil solution. The silica data for the leaching solutions from these Hawaiian soils support this hypothesis. Correns (24) concluded that silica solubility increased continuously with increased pH over a range from pH 2.0 to pH 11.0. The solubility curve included an increase from 2 millimoles per liter for pH 5.0 to 5.5 millimoles per liter for a pH of 8.0. However, there is a second much discussed hypothesis that acidic groundwater favors the removal of silica and promotes lateritization. Pickering (88) concluded from his leaching studies that the rate of dissolution of silica from quartz-free silicate rocks increases substantially with decreasing pH of the dissolving solution.

Carbonate: During the first period carbonates were absent for all soils. For later periods carbonate values were recorded for all soils. The presence of carbonates in solutions from unlimed soils belonging to the Hilo series and Kaumoali series was difficult to explain.

Bicarbonates: Bicarbonates are of importance in the dissolution of calcium carbonate. Johnston and Williamson (52) established a calcium carbonate solubility curve for a series of partial pressures of carbon dioxide. At 3.7×10^{-7} atmospheres partial pressure of carbon dioxide there is a point of minimum calcium concentration which corresponds to a solubility of about 16 mg. $CaCO_3$ per liter. On either side of this point the solubility increases owing to formation in solution of hydroxide with decreasing partial pressures and bicarbonate on the other side with increasing partial pressures of carbon dioxide. Along the whole course of the graph all three ions OH^-, CO_3^{--}, HCO_3^-, are present at relative concentrations according to the partial pressure of carbon dioxide. Bradfield (8) considered that practically all of the calcium in solution under soil conditions is in the form of the bicarbonate. The range of partial pressure usually encountered in soils is from 0.0003 atmospheres to 0.1 atmosphere. The increased bicarbonate values in the solutions from limed soils as compared with those from unlimed soils are considered to be associated with increased calcium content of the former solutions. For the duration of the leaching studies all soil series, when limed, had a relatively constant bicarbonate value in their solutions. On the other hand, calcium had an extensive range of values for the duration of the experiment. The classical lime equation is as follows:

$$CaCO_3 + H \overset{\text{soil}}{\text{colloid}} H \rightleftharpoons Ca \overset{\text{soil}}{\text{colloid}} + CO_2 + H_2O$$

It is suggested that some of the original carbonate was transformed and given off as CO_2.

Soil Analysis: The exchangeable calcium and extractable aluminum figures are generally in agreement with values obtained for field plot experiments. The soil pH values in the leaching study were a little higher than the field plot values. This was attributed mainly to the use of calcium carbonate for the leaching studies. There was an increase in available phosphate from liming with the Hilo series. The value for the initial soil of the Akaka series is difficult to explain. Hawaiian Hydrol Humic Latosols have a high total phosphorus content and this must have been modified due to heavy water applications and subsequent leaching.

C. SUGAR CANE TISSUE ANALYSIS

Results

The concentration of constituents is expressed as parts per million (P.P.M.) on an oven dry basis. The results of the chemical analyses of the nodal material from Hilo series field plots are presented in table 36. The results of the chemical analyses of sugar cane roots from Hilo series field plots are set out in table 37.

Tha Akaka series sugar cane node chemical analyses are set out in table 38. The chemical analytical figures for sugar cane roots from the same source are presented in table 39.

The chemical analyses of the Kaumoali series field plot sugar cane nodes are presented in table 40. The chemical analysis of sugar cane roots from the same source is presented in table 41.

Results and Discussion

Phosphorus. The various treatments had no appreciable effect on phosphate concentration in either node or root sugar cane tissues from any of the field plots that were studied. Heavy lime combined with nil phosphate treatment gave a slightly higher concentration of phosphorus in roots of the Kaumoali series field plots. In general the Hilo series field plot sugar cane tissues have the lowest and the Kaumoali series field plot sugar cane tissues have the highest concentration of phosphorus.

Calcium. There was a progressive decrease in calcium content of the sugar cane nodes with each increment of lime added to the Hilo series soils. Liming greatly increased the calcium content of sugar cane nodes produced on phosphate-treated Hilo series and Akaka series soils. There was twice as much calcium in the sugar cane roots for the limed as compared with the unlimed Hilo and Kaumoali series field plots. The limed Akaka series field plots sugar cane roots had six times as much calcium

Table 36. Mean concentration values of calcium, aluminum, iron and phosphorus in two basal sugar cane nodes grown on experimental field plots on Hilo series soils, Hilo plantation, Island of Hawaii.

Treatment Pounds per acre		No. of replicates	Mean concentration in P.P.M.				
			P	Ca	Si	AL	Fe
nil P_2O_5	nil coral	4	812	1800	2650	15.5	27.5
nil P_2O_5	4,000 coral	4	630	1600	3888	17.5	25.5
nil P_2O_5	11,000 coral	4	675	1550	2912	29.0	24.8
nil P_2O_5	22,000 coral	4	775	1200	2528	25.2	36.0
200 P_2O_5	nil coral	2	612	900	3300	12.5	26.5
200 P_2O_5	22,000 coral	2	812	1750	3475	25.0	35.0
400 P_2O_5	nil coral	2	788	1050	3175	27.0	25.0
400 P_2O_5	22,000 coral	2	788	1700	3425	25.5	26.0

Table 37. Concentrations of phosphorus, calcium, silica, aluminum and iron in sugar cane roots grown in Hilo series field plots, Hilo Plantation, Island of Hawaii.

Treatment		Concentration in P.P.M.				
Pounds coral per acre	Plot	P	Ca	Si	AL	Fe
nil coral	30	390	1,800	18,250	2,050	403
nil coral	42	450	1,600	18,700	2,050	428
22,000 coral	15	500	3,400	14,700	900	428
22,000 coral	27	502	3,000	16,500	920	441

Table 38. Mean* concentration values of phosphorus, calcium, silica, aluminum and iron in the two basal nodes of sugar cane grown on Akaka series field plots, Hakalau plantation, Island of Hawaii. Moisture percentage of fresh material is included.

Treatment Pounds per acre		Moisture percentage	Mean concentration values in P.P.M.				
			P	Ca	Si	Al	Fe
nil P_2O_5	nil coral	66.8	847	1675	2500	55.5	68.5
nil P_2O_5	4,000 coral	67.6	675	1300	3225	43.5	48.0
nil P_2O_5	11,000 coral	69.2	550	1500	4400	35.5	46.0
nil P_2O_5	22,000 coral	70.0	617	1700	3075	29.0	46.5
200 P_2O_5	nil coral	67.8	737	1750	3350	37.5	47.0
200 P_2O_5	22,000 coral	71.2	687	2225	3725	37.5	65.0
400 P_2O_5	nil coral	67.4	775	1450	2825	46.5	60.0
400 P_2O_5	22,000 coral	69.9	710	2100	3525	37.5	58.0

*Each value is the mean of two replicates.

Table 39. Concentration of phosphorus, calcium, silica, aluminum and iron in the roots of sugar cane grown on Akaka series field plots, Hakalau Plantation, Island of Hawaii.

Pounds coral per acre	Plot No.	Concentration in P.P.M.				
		P	Ca	Si	AL	Fe
0	20	725	1,000	6,150	4,650	424
0	23	725	800	6,800	4,350	589
22,000	8	725	4,800	6,900	750	519
22,000	11	700	4,700	5,035	800	505

Table 40. Mean* concentration values of phosphorus, calcium, silica aluminum and iron in the two lowest nodes of sugar cane grown on Kaumoali series field plots, Paauhau plantation, Island of Hawaii.

Treatment Pounds per acre		Concentration mean values in P.P.M. P	Ca	Si	AL	Fe
nil P_2O_5	nil coral	800	2100	1625	56.0	98
nil P_2O_5	12,000 coral	725	1400	1825	35.5	100
nil P_2O_5	30,000 coral	862	1450	1900	36.5	120
nil P_2O_5	46,000 coral	825	1550	1625	45.0	104
200 P_2O_5	nil coral	887	1200	1500	61.5	105
200 P_2O_5	46,000 coral	712	1550	1450	42.5	126
400 P_2O_5	nil coral	730	1500	2225	37.5	108
400 P_2O_5	46,000 coral	905	1600	1150	40.5	75

*Each value is the mean of two replicates.

Table 41. Concentration of phosphorus, calcium, silica, aluminum and iron in the roots of sugar cane grown on Kaumoali series field plots, Paauhau plantation, Island of Hawaii.

Treatment in Pounds per acre		Plot No.	Concentration in P.P.M.				
			P	Ca	Si	AL	Fe
nil P_2O_5	nil coral	11	850	2200	6150	3850	473
nil P_2O_5	nil coral	23	875	1800	6670	3500	547
400 P_2O_5	nil coral	2	778	1600	6250	2952	553
400 P_2O_5	nil coral	14	1075	1900	7050	3550	773
nil P_2O_5	46,000 coral	8	900	3700	6300	1600	633
nil P_2O_5	46,000 coral	20	1100	2500	6000	900	785

as the sugar cane roots from the unlimed Akaka series field plots. This is very significant and suggests the possibility of the sugar cane root tissues being deficient in calcium for these unlimed soils. It is noteworthy that these calcium figures are considerably lower than the calcium concentration of sugar cane roots from the Hilo series and Kaumoali series.

Silica. The sugar cane nodes grown on the Hilo series and Akaka series field plots had very similar values for silica. The sugar cane nodes grown on the Kaumoali series field plot were slightly lower than the above mentioned soil series in silica content. There was no definite pattern of response in silica content to any field treatment for any soil series. However, there was a significant negative correlation value of -0.729 for the relationship between silica and phosphorus content for the sugar cane nodes produced on the Akaka series soils. The sugar cane roots of the Akaka series and Kaumoali series had a similar silica content. The sugar cane roots of the Hilo roots had three times as much silica as in the sugar cane roots for the other soil series. This high silica content of the Hilo series sugar cane is notable.

Aluminum. The pattern of aluminum concentrations in response to field plot applications varies considerably from one soil series to the next.

a. Hilo Series: There was an increase in aluminum concentration in sugar cane nodes as a result of liming. The highest aluminum figures were from the plots that had received 11,000 pounds lime per acre. There was approximately twice as much aluminum in the sugar cane roots in the unlimed compared with the limed field plots.

b. Akaka Series: There was a progressive decrease of aluminum concentration in sugar cane nodes with each increment of lime. Heavy liming reduced the aluminum content of sugar cane roots to one sixth of the value for sugar cane roots from unlimed field plots. There is a negative correlation value of -0.996, which is highly significant, for the relationship between calcium content and aluminum content for the sugar cane roots produced in this soil series.

This presents three possible situations for the unlimed Akaka soils. (1) That this soil is very low in exchangeable calcium is shown in table 10. (2) There was insufficient calcium present to prevent the large intake of aluminum. (3) The high aluminum concentration in the soil solution may have depressed the intake of calcium. These effects are closely related to each other.

c. Kaumoali Series: Except where 400 pounds phosphate per acre were applied, all the non-limed field plots had the higher aluminum content in sugar cane nodes than did limed plots (table 40). Application of lime decreased the aluminum content in sugar cane nodes but the values were somewhat similar for all levels of applied lime. Compared with the limed plots the unlimed plot sugar cane roots had more than twice as high a concentration of aluminum. Phosphate applications slightly reduced the aluminum concentration in root tissue.

Moisture Percentage. The moisture percentage values were recorded for the sugar cane nodes grown on Akaka series but not for the other two soil series. There was a progressive increase in moisture content in this tissue with each liming increment. There was a significant correlation value of -0.82 for the relationship between aluminum content and moisture percentage of nodal tissue. It is proposed that the partial plugging with aluminum of vascular vessels in the roots and extreme basal portions of the stem, may modify the free movement of solutions within these tissues. This in turn may be responsible for the lower moisture percentage found in the basal nodes. Hoffer and Carr (48) found aluminum was especially active in plugging the vascular bundles of corn tissue.

Iron. Disregarding treatments each soil series had a characteristic range of values for iron concentration in sugar cane nodal tissue. The Hilo series had a range of 17-52 P.P.M. Fe. The Akaka series had a range of 31-99 P.P.M. Fe. The Kaumoali series had a range of 59-161 P.P.M. Fe.

a. Hilo Series: Field applications had no effect on the concentration of iron in sugar cane nodes on sugar cane roots.

b. Akaka Series: When phosphate was omitted there was a decrease in iron content in sugar cane nodes with liming. The iron concentration was similar for any level of applied lime. Irregularities were present in the 200 pounds P_2O_5 per acre replicates. It is of interest that the 400 pounds phosphate per acre did not reduce the iron content. This treatment combined with 22,000 pounds lime per acre gave practically the same value for iron concentration in the sugar cane nodes.

c. Kaumoali Series: The replicates for sugar cane nodes had a disconcerting amount of variation. In general there was no great response in iron concentration in sugar cane nodes to field application. The highest iron content in sugar cane roots was associated with high lime applications. No lime, no phosphate plots had the lowest concentration of iron in the roots. There was a substantial increase in iron content in sugar cane roots due to applied phosphate. There was a significant correlation value of 0.90 for the relationship between iron and phosphorus content in the roots of sugar cane grown on Kaumoali series soils. When all the root samples grown on the Kaumoali series soils were considered, the correlation value between aluminum and iron was not significant. However, when this same relationship was considered in the absence of values for phosphate treated plots, a significant negative correlation of -0.95 was obtained.

D. FIELD PLOT HARVESTING DATA

Introduction

Harvesting data for field plots, which have been studied, have been supplied by the respective sugar plantations. The data were accompanied by statistical analysis.

Results

For the sugar cane from each field plot the Brix, Pol., Pur., F%C, T.C.A., PR, P%C and TPA were measured. TCA means tons cane per acre and TPA means tons pol. (sugar) per acre. These two measurements were taken as harvesting data for comparison of effects of field treatments. The harvesting data for the field plots which have been studied, are included in the tables of results. In addition the values for each field plot application are included.

Hilo Series: Harvesting data consisting of TCA and TPA mean values are presented in table 42. The statistical analysis of harvesting data is presented in tables 43 and 44. There was an interaction between applied phosphate and lime which gave a significant increase in tons cane per acre.

Table 42. Harvesting data for sugar cane from Hilo series field plots, Hilo Plantation, Island of Hawaii.

Treatment Pounds per acre		Mean yield values of 4 replicate plots	
		Tons cane per acre	Tons sugar per acre
nil P_2O_5	nil coral	109.7	12.5
nil P_2O_5	4,000 coral	112.2	12.1
nil P_2O_5	11,000 coral	117.6	13.1
nil P_2O_5	22,000 coral	108.9	12.1
200 P_2O_5	nil coral	100.1	11.5
200 P_2O_5	4,000 coral	108.8	12.0
200 P_2O_5	11,000 coral	117.1	12.3
200 P_2O_5	22,000 coral	123.0	12.7
400 P_2O_5	nil coral	113.8	12.9
400 P_2O_5	4,000 coral	115.9	12.5
400 P_2O_5	11,000 coral	108.7	12.9
400 P_2O_5	22,000 coral	115.6	11.9

Table 43. Analysis of variance of harvesting data from Hilo series field plots, Hilo Plantation, Island of Hawaii.

Source	D.F.	Mean squares	
		Tons cane per acre	Tons sugar per acre
Blocks	3	81.16	1.87
AP	2	8.81	0.75
ACaO	(3)	141.93	0.94
CaOL	1	339.46*	0.01
CaO Dev.	2	43.16	1.41
AP x CaO	6	175.78*	0.94
Error	33	64.07	1.22
Total	47		

Table 44. Interaction between applied phosphate and coral dressings in Hilo series field plots, Hilo Plantation, Island of Hawaii.

pounds per acre	Tons cane per acre			Tons sugar(pol) per acre		
	nil P_2O_5	200 P_2O_5	400 P_2O_5	nil P_2O_5	200 P_2O_5	400 P_2O_5
0	109.7	100.4	113.8	12.5	11.5	12.9
4,000	112.2	108.8	115.9	12.1	12.0	12.5
11,000	117.6	117.1	108.7	13.1	12.3	12.9
22,000	108.9	123.0	115.6	12.1	12.7	11.9
H.S.D.	N.S.	19.9	N.S.	N.S.	N.S.	N.S.

Akaka Series: The Akaka series field plots on Field 20, Hakalau plantation were harvested on the 6th and 7th February 1961. Harvesting data comprising T.C.A. and T.P.A. individual field plot and mean values are presented in table 45. Analysis of variance of harvesting data is presented in table 46. Applied lime resulted in significant increases in tons can per acre.

Harvesting Data Discussion

Hilo Series: A significant increase in tons cane per acre was obtained with the lime applied phosphate treatments. An increase in phosphate concentration in soil solution with liming was noted for this soil series. Soils used in this leaching studies had an increased available phosphate value with liming. It was concluded that liming enhanced the efficiency of phosphatic fertilizer applications.

When the Hilo series soils were limed, there was a moderate increase in concentration of aluminum in the soil solution. The improved availability of phosphorus probably compensated for any adverse effects due to increased aluminum concentration.

Akaka Series: The concentration of aluminum in the soil solution of the Akaka series was reduced tremendously as a result of liming. This was directly related to concentrations of aluminum within sugar cane tissues, and this was especially noticeable for the roots. This pattern of response to liming for this soil series was further shown by the significant increase in tons cane per acre.

In this study the principal response to heavy applications of lime to the Akaka series soils has been shown to be a definite pattern of aluminum values in the soil, in sugar cane tissues, and in tons sugar

Table 45. Harvesting data for sugar cane from Akaka series field plots, Hakalau plantation, Island of Hawaii.

Treatment pounds per acre		Plot No.	Tons cane per acre	Tons sugar (pol) per acre
nil P_2O_5	nil coral	20	77.0	10.0
" "	" "	23	71.8	9.7
" "	" "	Mean	74.4	9.8
nil P_2O_5	4,000 coral	14	104.4	12.8
" "	" "	17	87.1	11.1
" "	" "	Mean	95.7	11.9
nil P_2O_5	11,000 coral	2	113.1	12.2
" "	" "	5	103.0	13.1
" "	" "	Mean	108.1	12.7
nil P_2O_5	22,000 coral	8	113.0	13.4
" "	" "	11	92.3	10.0
" "	" "	Mean	102.7	11.7
200 P_2O_5	nil coral	4	85.6	10.5
" "	" "	15	99.0	12.2
" "	" "	Mean	92.3	11.4
200 P_2O_5	4,000 coral	1	105.5	12.0
" "	" "	6	107.3	13.8
" "	" "	Mean	106.4	12.9
200 P_2O_5	11,000 coral	10	103.6	13.0
" "	" "	21	98.6	12.4
" "	" "	Mean	101.1	12.7

Table 45 (continued)

Treatment pounds per acre		Plot No.	Tons cane per acre	Tons sugar (pol) per acre
200 P_2O_5	22,000 coral	19	112.2	12.2
" "	" "	24	97.1	12.6
" "	" "	Mean	104.7	12.4
400 P_2O_5	nil coral	7	86.7	10.2
" "	" "	12	74.9	10.2
" "	" "	Mean	80.8	10.2
400 P_2O_5	4,000 coral	9	96.7	11.4
" "	" "	22	91.6	12.6
" "	" "	Mean	94.2	12.0
400 P_2O_5	11,000 coral	13	99.3	12.6
" "	" "	18	99.4	12.7
" "	" "	Mean	99.3	12.7
400 P_2O_5	22,000 coral	3	107.2	12.3
" "	" "	16	116.8	12.3
" "	" "	Mean	112.0	12.3

Table 46. Analysis of variance of harvesting data from Akaka series field plots, Hakalau plantation, Island of Hawaii

Source	D.F.	Mean squares	
		Tons cane per acre	Tons sugar per acre
Blocks	1	48.74	4.42
ACaO	3	669.53*	5.69
Error (a)	3	42.20	0.67
AP	2	76.34	1.34
P x CaO	6	89.24	0.25
Error (b)	8	74.96	0.66
Total	23		

Table 47. Correlation coefficient values for relationships between tons sugar cane per acre and soil extractable aluminum values at 5 months, one year and two years after installation of Akaka series field plots on Hakalau plantation, Island of Hawaii.

Time since installation	Correlation coefficient
5 months	0.76*
1 year	0.92**
2 years	0.68

P (0.01) = 0.83 n = 8, for all periods
P (0.05) = 0.71

per acre. There was a significant negative correlation value of -0.57 for the relationship between aluminum values for sugar cane nodes and tons sugar per acre. For this relationship n = 16. There was a highly significant negative correlation value of -0.66 for relationship between tons sugar cane per acre and the extractable aluminum values of samples taken at 5 months after installation of field plots. For this relationship n = 24. The correlation value of 0.79 for the relationship between concentration of aluminum in sugar cane nodes and extractable aluminum at two years, was significant. For this relationship n = 8. The correlation values for tons sugar cane per acre and extractable aluminum values for the three points in time at which soil samples were taken are presented in table 47.

The time studies for the field plots reveal the disturbing capacity, of this soil series, to return to the former condition after heavy liming. Compared with the Hilo series and Kaumoali series, there was a threefold increase in the initial contribution of calcium to the solution from limed soils for the Akaka series. This indicated that the Akaka series soils have a capacity to increase the solubility of calcium carbonate. This capacity may be called "inherent acidity." It is necessary to take this factor into account when considering persistence of liming effects as well as liming rates.

Kaumoali Series: The harvesting data for Paauhau plantation are presented in table 48. There was no significant response to any soil treatment. The soil solutions chemical analysis showed no striking differences for either aluminum or phosphorus, due to liming. This soil series has a comparatively high exchangeable calcium content for soils from a humid climate.

Table 48. Harvesting data for sugar cane from Kaumoali series field plots, Paauhau plantation, Island of Hawaii

Treatments pounds per acre	No. of Replicates	Tons cane per acre	Tons sugar (pol) per acre
0 phosphate	8	65.2	7.8
200 phosphate	8	67.2	7.6
400 phosphate	3	70.3	8.0
0 ground coral	6	68.6	8.3
12,000 ground coral	6	66.8	7.7
30,000 ground coral	6	67.7	7.5
46,000 ground coral	6	67.2	7.9

SUMMARY

Effects of heavy lime applications to soils derived from volcanic ash on the Island of Hawaii have been studied. Three soils series were included in the investigation. The Hilo series and the Akaka series are Hydrol Humic Latosols. The Kaumoali series is a Humic Latosol. A series of lime phosphate field plot experiments were installed on these soil series at sugar plantations. Four levels of lime, applied as crushed coral stone, and three levels of phosphate, applied as superphosphate were used. Sugar cane was grown in these experimental plots. Soil samples, collected at three different times after the installation, were chemically analyzed. A leaching study for the three soil series was conducted with unlimed and heavily limed soils. Plant analysis of two sugar cane tissues, (1) the two lowest nodes, (2) roots, was conducted approximately two years after the field plots had been installed. Harvesting data and accompanying statistical analysis were supplied by the sugar plantations.

Effects of heavy applications of lime on some soil constituents and soil properties are as follows: Exchangeable calcium values were greatly increased and extractable aluminum values were greatly reduced for all the soils that were studied. There was a general increase in soil pH values but pH 7.0 was the highest recorded soil reaction value. Highly significant positive correlations between logarithm of exchangeable calcium values and pH were found for the three soil series. There were highly significant negative correlations between exchangeable calcium and extractable aluminum and between pH and extractable aluminum for the three soil series. Examples of reduced cation exchange

capacity due to phosphate treatments in the presence of lime were found in the Hilo series soils. After two years there was a reduction in cation exchange capacity for the limed Akaka series soils.

The increased exchangeable calcium values and decreased extractable aluminum values due to liming showed little change over a two-year period for soils belonging to the Hilo series and Kaumoali series. On the other hand, there was a continuous decline in exchangeable calcium and general increase in extractable aluminum over the two-year period for the limed Akaka series soils. Time studies indicated that a maximum value for exchangeable calcium was attained for all soils within two years after the installation of the field plots. It was concluded, from the long term studies, that the pH values of field plots were unlikely to increase in the immediate future.

Compared with the other soil series the contribution of calcium from limed Akaka series to the soil solution was three times greater. This factor plus the rapid decline in exchangeable calcium for limed Akaka series soils over a two-year period indicated that soils belonging to this soil series have a greater capacity than the other two soil series to affect the solubility of calcium carbonate. It was suggested that this factor be called inherent acidity. In investigating liming rates, or persistence of liming effects for the Akaka series soils, inherent acidity should be considered.

As compared with the solutions from unlimed soils, the bicarbonate values in the solutions from limed soils for all series were greatly increased. This was considered to be principally due to the association of this anion with calcium which was greatly increased. For all periods of the leaching study the bicarbonate concentration of solutions from limed soils was relatively constant. This was in contrast to the fluctuations in calcium content for these solutions, and it was suggested that a considerable amount of the original carbonate ion was transformed and given off as carbon dioxide.

Soluble aluminum was greatly reduced by liming in the Akaka series. For the Hilo series there was a moderate increase in soluble aluminum with liming. Liming had no appreciable effect on the soluble aluminum content of the Kaumoali series.

Plant analysis showed a big decrease in aluminum content in sugar cane tissues produced on limed Akaka series plots. There was six times as much aluminum in sugar cane roots from control as there was in roots from limed plots. The control plot roots had approximately 4,500 P.P.M. aluminum and the sugar cane roots from the heavily limed Akaka series plots had 750-800 P.P.M. aluminum. There was a slight increase in aluminum content of nodes with liming in the Hilo series soils. However, there was a decrease in aluminum content in the roots from limed Hilo series soils. There was a very slight decrease in aluminum content in the nodes and a decrease in the roots of sugar cane grown on limed Kaumoali series soils.

There was a significant increase in soluble phosphate in the limed Hilo series soils. There was a very slight increase in soluble phosphate for the Akaka series and Kaumoali series soils.

The phosphorus content of sugar cane nodes was similar for all treatments. The Hilo series sugar cane nodes had slightly less phosphorus than the Kaumoali series sugar nodes. The Akaka series sugar cane nodes were intermediate between the other soil series. For sugar cane grown on Hilo series the root had slightly less phosphorus than the nodes. Similar phosphorus values in the nodes and roots were found in the sugar cane grown on Akaka series. There was an increased phosphorus concentration in the roots of the sugar cane from the limed Kaumoali series.

Liming produced an increase that was at least threefold in the downward movement of silica for the three soil series.

Liming had no effect on the concentration of silica in sugar cane nodes from the Hilo series soils. There was an increase in silica concentration of sugar cane nodes with applied phosphate for Hilo series. The very high root silica concentration values, with a range from 14,700-18,700 P.P.M. were notable. They were three times greater than the silica concentration for sugar cane roots grown on Akaka series and Kaumoali series. Field plot treatments had no appreciable effects on the silica content of sugar cane nodes and roots grown on the Akaka series and Kaumoali series. The Akaka series sugar cane nodes had a similar concentration in silica to the sugar cane nodes of the Hilo series. The sugar cane nodes from the Kaumoali series plots had about half the silica concentration that was present in the nodes from the other two soils.

Liming had no significant effect on the iron concentration in sugar cane nodes and roots grown on the Hilo series. A decrease in iron content of sugar cane nodes with liming was obtained with Akaka series soils. The iron content of sugar cane roots grown on Kaumoali series soils was increased with liming. There was a characteristic range in iron concentration in sugar cane nodes for each soil series. For Hilo series the range was 17-52 P.P.M. Akaka series range was 31-99 P.P.M. The Kaumoali series range was 59-161 P.P.M.

There were no examples of adverse effects on sugar cane growth due to heavy lime application.

The Akaka series produced a significant increase in tons cane per acre with liming. This was attributed to a substantial decrease in aluminum concentration in the soil solution.

The Hilo series lime-applied phosphate field plots produced a significant increase in tons cane per acre. This was attributed to the enhanced efficiency of applied phosphate in the presence of lime.

There was no significant response to any treatments for Kaumoali series soils.

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