EFFECT OF SOIL pH, LIMING MATERIALS AND PHOSPHORUS ON GROWTH AND NUTRIENT UPTAKE OF SUGARCANE

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By

Awad El-Hag M. El-Tahir

Dissertation Committee:

James A. Silva
Beatrice H. Krauss
Robert L. Fox
Peter P. Rotar
Yusif N. Tamimi

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

DISSERTATION COMMITTEE

James A. Silva
Chairman

Peter P. Rotar

Robert L. Fox

Yusuf N. Tamimi

Beatrice H. Krauss

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ABSTRACT

Sugarcane (Variety H59-3775) yield and nutrient composition was studied in relation to soil pH, liming with $CaCO_3$ and $CaSiO_3$, and P fertilization. The pH levels investigated were 4.7, 5.0, 5.2, 5.6, 5.8, 6.0 and 6.7 obtained with either $CaCO_3$ or $CaSiO_3$. Two P levels, 0.006 and 0.025 ppm P in solution, were also included in the study as the main plots.

Liming Wahiawa soil (Tropeptic Eutrustox) significantly increased sugarcane yield. Maximum yield was obtained at pH 5.8 in the $CaCO_3$ system and at pH 6.0 in the $CaSiO_3$ system. In general, an optimum soil pH for sugarcane was about 5.8.

Liming resulted in a significant increase in Ca, Mg, and N concentrations in various plant tissues. Besides supplying Ca and some Mg, the liming materials substantially improved the retention of these elements within reach of plant roots. This was due to the marked increase in CEC obtained with increasing soil pH. This can be of practical importance since the well aggregated condition of Wahiawa soil can result in rapid leaching of the basic cations under acid conditions. In the unlimed treatment, and at the low liming rates (pH 5.2 and 5.6) large amounts of K moved down the soil profile to the 45 cm depth. Potassium extracted from the surface was 30% greater from the high lime treatments (pH 6.7) than from the control (pH 4.7).

Increasing soil pH significantly reduced soil Al and Mn in the surface. Mn was also reduced markedly in the soil profile down to the 30 cm depth in the high liming treatments.

Phosphate sorption studies suggested that the first rates of liming decreased P sorption by reducing Al activity which otherwise could immobilize P by precipitation as Al-phosphate or adsorption on the surface of hydrous Al oxide. The silicate applications at the high rates decreased P sorption markedly by anion exchange.

An attempt was made to study the direct effect of H ion concentration on sugarcane growth in a nutrient solution culture using a split-root technique. In the pH range investigated (3.0, 4.0, 5.5, 6.5, and 8.5) supplied with 45 ppm Ca in solution, the maximum yield of cane was obtained at solution pH 5.5 and 6.5. Yield declined slightly at pH 8.5 and significantly at pH $\leq$ 4.0. Absorption of nutrients was severely curtailed at pH 3.0 and 4.0, probably due to the high H ion concentration. Symptoms of Fe deficiency occurred at pH 8.5, and it appeared that the Fe absorbed was precipitated in the stalks. In general, growth and nutrient absorption of sugarcane was best in the pH range 5.5 - 6.5.

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INTRODUCTION

Intensive chemical weathering and high rainfall in the humid tropics lead to depletion of soil bases and to accumulation of hydrated aluminum and iron oxides. These soils tend to be acidic and are of limited productivity. Application of liming materials, under such conditions, can improve crop production by providing a favorable balance of plant nutrients, by increasing the availability of certain nutrient elements, and by depressing the solubility of toxic elements.

Besides supplying Ca, liming materials such as $CaCO_3$ and $CaSiO_3$, can increase cation exchange capacity (CEC), especially in soils with a high amount of pH-dependent charge. This improves retention of cations such as Ca, K and Mg keeping them within reach of plant roots. Increasing soil pH decreases the solubility of heavy metals such as Al and Mn which could be toxic to plants under acid conditions. Also, some reports indicate that at very low pH, H ion concentration, per se,can adversely affect plant growth, i.e., by root injury (Arnon,1942) and by decreasing plant uptake of basic cations through ion competition (Black, 1968). However,due to the difficulties involved in determining such direct effects of pH, work done on this subject is limited. One such difficulty is that usually, at the pH levels where the H ion concentration is expected to be harmful, Al, Mn and perhaps other elements are present in toxic concentrations.

The effect of liming on P availability, although frequently mentioned, is not well defined. Under highly leached conditions soils consist largely of amorphous hydrated Al and Fe oxides (Jones et al.,1969). These soils tend to sorb more P per unit surface area and with greater bonding energy than limed soils. Bache (1964) indicated that P was held less tightly as pH was raised. On the other hand, Brams (1971) working with soils low in Al did not find any interaction between P availability and liming. In other reports increasing Ca concentrations in oxidic soils were significantly related to lower P solubility and as a result lower P uptake by Sudangrass (Stoop, 1974). However, there is evidence that the effect of liming on improving plant P availability is largely indirect, i.e. by alleviating growth limiting conditions, liming increased the ability of plant roots to absorb more P.

Sugarcane is an important crop in the humid tropics. Its production is reported to be limited by the acid conditions that prevail in some areas of this climatic region. Nevertheless, there is no consistency in reports regarding the effect of liming on sugarcane. While it responded favorably to coral stone applications in Hawaii (Clements, 1962), no response to $CaCO_3$ was obtained in Queensland (Haysom and Chapman, 1975). Recently many workers seem to prefer applications of calcium silicate to crops such as sugarcane over other liming materials.

The current study was initiated to further our knowledge of the effects of liming on crop production with the following objectives:

(i) Evaluate the two liming materials; $CaCO_3$ and $CaSiO_3$ for their ability to maintain soil pH at a desirable level and their effect on soil nutrient supply;

(ii) Determine the optimal pH range for the sugarcane variety H59-3775;

(iii) Determine the P and pH interaction with the two liming materials; and

(iv) Determine the direct effect of H ion concentration by separating other pH effects in a solution culture experiment.

REVIEW OF LITERATURE

Liming

Beneficial effects of liming acid soils on crop production have been documented for many years. Crop response has been variably attributed to the effect of lime application on the physical, chemical and biological conditions of the soil which influence Cu, P. and K; and the solubility and toxicity of other elements such as Mn, Al and H ions (Kamprath, 1970, Tisdale and Nelson, 1969). Lime has been applied to supply or correct various factors of plant nutrition, i.e., to supply calcium under high leaching conditions (Ayres, 1961, Coleman & Thomas, 1967, Silva, 1971), to alleviate toxicity of elements such as Al and Mn (Kamprath, 1970), or to raise soil pH to a favorable range for plant nutrient availability (McLean, 1973).

Effect of Liming on Ca Availability

Factors affecting the availability of calcium to plants include total Ca supply, soil pH, percent Ca saturation of the CEC of soil colloids, and the ratio of Ca to other cations in solution (Adams and Pearson, 1967). Functions of calcium in plants include a role in the formation and maintenance of cell membrance systems (Marinos, 1962) and preventing toxic effects of other mineral elements (Bonds and O'Kelly, 1969; and Gauch, 1972).

Most soils are reported to have adequate Ca except highly leached acid soils or very sandy soils with low CEC. Therefore, addition of soluble salts of calcium, other than liming materials, does not increase plant yields in most cases (McCart and Kamprath, 1965). Lime ($CaCO_3$) and gypsum ($CaSO_4$) were used by Fried and Peech (1946) to study the effects of liming acid soils on Ca nutrition using $CaSO_4$ to supply Ca and they concluded that gypsum in spite of its ability to supply Ca, did not compare favorably with lime. However, there is a risk of intensifying Ca deficiency when $CaSO_4$ alone is used to supply Ca in acid soils because of the Al brought into solution when Ca ions exchange with Al ions. Although most soils contain reasonable amounts of calcium, it is postulated that the absolute amount of exchangeable Ca is not as important in plant nutrition as the amount present in relation to the quantities and kinds of other cations held by the clay, i.e., the degree of Ca saturation. Mehlich and Colewell (1944) concluded that in acid mineral soils Ca was not readily available to plants at low base saturation and indicated that percent saturation was more important than total calcium present in the growing medium. The magnitude of Ca saturation recommended by various investigators varies over a wide range according to the soils tested, the type of clays, and weathering conditions. Adams et al.(1967) working with acid Norfold, Magnolia and Greenville soils found that cotton yields were reduced at Ca saturation in the range of 30-40% and at Al saturation of 40-60%. Al concentrations of only .002 to .003 me/1 inhibited cotton root growth. On the other extreme, according to Mahilum, et al.(1970) only 12% Ca saturation supported normal growth of sugarcane in volcanic ash soils of

Hawaii. Therefore, overliming problems could arise in these soils when lime is applied only to raise Ca saturation.

An important factor affecting Ca availability is the level of the exchangeable and soluble Al in the soil. Lance and Pearson (1969) found that reduced Ca uptake was one of the first symptoms of Al-damaged cotton seedlings which were exposed to 0.3 ppm Al in solution. Inhibition of Ca uptake was amended by increasing Ca concentration in the nutrient solution. Similar observations were reported by Evans and Kamprath (1970). Lund (1970) noted increased cotton root elongation when Ca:(Ca + Mg + K) ratios were between 0.10 to 0.20. Lower ratios were effective when K substituted for ½Mg. In another observation, Misra (1970), comparing the effect of liming under two K levels (5% and 1% K saturation), concluded that liming was effective in increasing sugarcane yield at the high K level. He therefore suggested the need for additional Ca when soil K is very high. These observations agree with those of Schmehl, Peech and Bradfield (1950) who evaluated Ca:Al and Ca:Mn ratios in alfalfa and suggested lime addition when Ca:Mn ratio was below 75.

Liming acid soils increases pH, deprotonates surfaces, and can increase the pH-dependent charge and hence increase CEC (Mekaru and Uehara, 1972) and reduce leaching of cations (Mahilum et al., 1970). Recently, McLean and Bittencourt (1974) reported marked complementary ion effects on K and Ca displacement from exchange sites of the pH-dependent charges. Displacement of a given cation, i.e., K, varies greatly depending on the accompanying cation on the exchange site of the clay, and the magnitude of this complementary ion effect was greatest when the charge was pH-dependent.

Effect of Liming on P Availability

The bulk of inorganic P in soil is reported to be present as sparingly-soluble phosphate compounds and adsorbed P. Phoshpate adsorption has received considerable attention by many workers (Coleman et al., 1960; Olsen and Watanabe, 1963; Fox et al., 1968; Soundararajan, 1971; and Bartellett and Pecerelli, 1973), and they generally agree that P sorption occurs on the surfaces of clay minerals, aluminum hydroxides and hydrated iron oxides in acid soils, and largely on $CaCO_3$ in calcarious soils. Acid soil contain appreciable amount of exchangeable Al and hydroxyl Al (Coleman et al., 1960), and under highly leached conditions most of the inorganic colloidal complex is poorly crystalized and consists largely of amorphous hydrate Al and Fe oxides (Jones et al., 1969). Such soils tend to sorb more phosphate per unit surface area and with greater bonding energy than limed soils. Bache (1964) calculated the bonding energy of P sorption by Al and indicated that P was held less tightly as pH was raised. On the other hand, Fox (1974) reported that when soil pH was adjusted in the range 5.0 to 6.5 with $Ca(OH)_2$ and added Ca was kept constant with $CaCl_2$ one P sorption isotherm described all of the data points.

In general, liming is reported to affect phosphate availability by (i) neutralizing exchangeable Al. Since phosphate solubility decreased with the accompanying cation valency as follows: $K < Mg \leq Ca$, (Stoop, 1974), phosphate solubility would probably be increased when the divalent Ca ions replaces the trivalent Al ions, (ii) reducing the reactivity of hydrous oxides of Al and Fe by increasing soil pH. As mentioned above these hydrous oxides can sorb appreciable amounts of P in acid soils, (iii) increasing Ca saturation. Calcium can decrease P sorption by its effect on Al, but at high concentrations can depress P solubility by forming the relatively less soluble dicalcium phosphates.

Effect of Liming on Exchangeable and Soil Solution Al

Soluble aluminum is widely held to be the major toxic element in acid soils (Ragland and Coleman, 1959; Stoop et al., 1961; Abruna et al., 1964; and Kamprath, 1972). The amount of Al present in the soil solution is reported to be largely dependent on the nature of aluminum compounds and on soil pH. Magistad (1925) developed a curve which showed the relationship between soil pH and the level of Al in soil and culture solutions. As pH increased in soil, in a culture solution or in a solution of $Al_2(SO_4)_3$ in water, the level of Al in solution decreased rapidly to less than 1 ppm at pH 5.0 and above. The solubility of Al again increased above pH 9.0. The negative relationship between soil pH and exchangeable and soluble Al has been confirmed in numerous observations in tropical areas. Brams (1971) observed that exchangeable Al in two soils from West Africa (a Plinthic Haplustox and a Typic Haplustox) decreased rapidly as soil pH was raised to 5.3. An aluminum saturation of 26% at pH 4.3 was reduced to only 8% at pH 5.3 This striking reduction in Al concentration with an increase in soil pH confirms the views expressed by Kamprath (1972). Barium chloride-extractable Al in Hawaiian Latosols reached minimal levels at pH 5.5 as reported by Fox et al. (1962), and in three Latosols from Brazil as found by Soares et al. (1974).

Al is believed to precipitate as Aluminum hydroxide ($Al(OH)_3 \cdot 3H_2O$) as pH increases (Jackson, 1961). The trivalent Al that exists as the cation $Al(H_2O)$ in acid solutions is polymerized by the loss of H ions as pH increases (McLean, 1965). When lime is applied to soil, exchangeable Al is preapitated first followed by neutralization of non-exchangeable acidity. At pH above 5.5 $\underline{H^+}$ from hydroxy Fe and Al compounds and organic matter begins to ionize. McLean (1965) and Kamprath (1970) found that exchangeable Al was rapidly neutralized by the first increments of lime, but that neutralization of non-exchangeable acidity was slow and required more lime. Kamprath (1970) believes that exchangeable Al is a valid criterion for determining lime requirements and suggested that an adequate liming rate would be the amount that would neutralize 1.5 x me of exchangeable Al per 100 g soil. This should reduce aluminum saturation to a tolerable level for most crops.

Response of many crops to liming has been attributed to the reduction in the level of exchangeable Al that results from liming. Reeve and Sumner (1970) working with Sorghum growing on some Oxisols from Natal observed marked growth response to amelioration by lime and Ca silicate which they reasoned to be due to the elimination of Al toxicity. The response increased to the point of neutralizing exchangeable Al after which a significant decline in growth occurred. The first increment of lime leiminated the influence of Al and Mn. Silene (a commercial form of Ca silicate) decreased Al and Mn gradually, while gypsum increased Mn but also decreased Al which they thought to be due sulfate induced Al polymerization. Likewise, lack of response of maize to lime in West Africa was attributed to the relatively low level of exchangeable Al (Brams, 1971). His findings also did not show an interaction between lime and P because Al was not high enough to interfere with P supply.

Manganese Toxicity in Plants

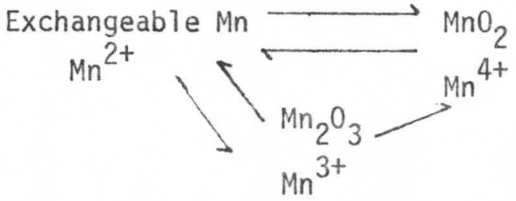
Manganese, like many other micronutrients, is required in small quantities as a co-enzyme and catalyst in plant metabolism. Its abundance is considered to be a principal contributing factor to poor plant growth in some acid soils (Adams and Pearson, 1967). Manganese toxicity has been observed in numerous plant species growing under high levels of soluble Mn. These include cauliflower, potato, cotton, barley, sugarcane and rice (Adams and Wear, 1957; Vlamis and Williams, 1967; and Clements, 1965). Furthermore, plant species differ widely in Mn uptake and sensitivity to toxic levels of this element. For example, Vlamis and Williams (1967) working with barley and rice in standard Hoagland's solution with increasing levels of Mn observed Mn toxicity symptoms when solution Mn increased above 0.5 ppm and tissue manganese levels were 1200 and 7000 ppm in barley and rice, respectively. In other reports, sweetclover was found to be much more sensitive to Mn than either cowpeas or soybeans (Morris and Pierre, 1949). Yield of sweetclover decreased 66% compared to yield of control plants, when the concentration of Mn was raised from 0.1 ppm to 1 ppm, while cowpeas and soybeans were affected only at Mn concentrations above 2.5 ppm. Likewise, Rees and Sidrak (1961) observed that yield of spinach decline 11% compared to the control treatment, while yields of barley and atriplex were reduced by 21 and 50 percent, respectively, as Mn concentration increased from 0 to 5 ppm in the culture medium.

Symptoms of toxicity also vary in different plant species. In general, while Al toxicity frequently affects plant roots, Mn toxicity is reported to manifest itself on the aerial parts of plants. Stunted growth of cotton with characteristic necrotic spots known as crinkle leaf of cotton has been related to water soluble and exchangeable Mn (Adams and Wear, 1957). Leaf extracts of snap beans showing Mn toxicity symptoms contained higher than normal levels of isocitric dehydrogenase and malic enzymes than healthy plants. This over activiation of enzymes is believed to induce a metabolic imbalance (Anderson and Evans, 1956). The characteristic leaf freckle of sugarcane due to Mn toxicity observed by Clements (1965) was also reported recently in Queensland by Haysom and Chapman (1975), who observed that younger leaves of sugarcane growing in acid soils showed dark-red freckles starting at the tips of leaf blades and midribs. At severe stages of Mn toxicity these freckles coalesced.

Effect of Liming on Mn Toxicity

Absorption of Mn by plants depends primarily upon the amount of available Mn in the soil. Soil manganese is present in three oxide forms, (MnO, Mn_2O_3, MnO_2) whose relative amounts are governed by the oxidation-reduction status of the soil (Fujimoto et al., 1948).

These authors also reported that acid conditions favor reduction and alkaline conditions bring about oxidation. Tisdale and Nelson (1969) states that the manganous ion (Mn) is the most readily available to plants and is in equilibrium with the higher Mn oxides as shown below.



This view is also held by Pearson (1975) who believes that manganese uptake depends on the activity of divalent Mn in the soil solution, which is dependent upon the presence of reducible Mn in the soil. The equilibrium between the forms of Mn is reported to be influenced mainly by pH. Mulder and Gerretsen (1952), contend that acid soils with pH below 5.5 contain most of their manganese in water soluble and exchangeable forms. As pH increases manganous oxide (MnO) is readily converted into the higher manganic oxides. (Mn_2O_3, MnO_2).

Liming acid tropical soils, therefore, effectively reduces plant available forms of manganese. Brenes and Pearson (1973) working with an acid Tropeptic Haplorthox from Puerto Rico observed marked reduction from an original manganese concentration of 3.3 me Mn/l soil solution when liming raised soil pH from 4.05 to 4.75. Similarly, Mn uptake by Sorghum was drastically reduced as was the soil extractable Mn when some Oxisols from Natal were limed (Reeve and Sumner, 1970).

Besides lowering Mn uptake, liming also brings about some reportedly favorable plant nutrient ratios, i.e., Ca:Mn ratio (Pearson

1975) and Si:Mn ratio (Clements, 1965; and Haysom and Chapman, 1975). Pearson (1975) noticed that beans responded favorably to liming in some Oxisols from Puerto Rico. No relationship could be found between leaf Ca content and yield, nor between leaf Mn content and yield, but the relationship was striking when the Ca:Mn ratio was considered. Yield was positively correlated ($r = 0.91^{**}$) with Ca:Mn ratio in chemical equivalents. The idea that a correct balance between Si and Mn is required for best growth has been proposed by Halais and Parish (1963) as reviewed and substantiated by Clements (1965) who stated that sugarcane growth response to liming was affected by the Mn/silica ratio. He further suggested that where silica is low and manganese is high, heavy silicate applications are required to lower Mn uptake and provide Si to effect a favorable Mn/silica ratio.

Hydrogen Ion Concentration

Of the extensive work done on the effect of soil pH on plant growth very few refer to the direct effect of the H ion concentration per se. This might be due to the difficulties involved in determining such direct effects in soils (Kamprath & Foy, 1971). Usually, at pH levels where the H ion is expected to be harmful, Al, Mn and perhaps other elements are present in toxic concentrations. Furthermore, Coleman & Thomas (1967) believe that within the pH range normally encountered in acid soils (pH 4.5 to pH 6.0) exchangeable hydrogen is not found in appreciable quantities. However, the hydrolysis of aluminum results in hydrogen being present in the soil solution.

Some of the early evidence of the direct effects of H ion concentration has been reported by Arnon (1942), and Arnon and Johnson (1942) from pot experiments. Tomato plants showed restricted growth at pH 4.0 and completely failed below that. Absorption of Ca, Mg and K was drastically reduced at this pH level. These authors reasoned that H ions might be competing with the cations for absorption. In some instances they observed that potassium and calcium moved out of root cells into the culture medium because of high acidity. Also, Black (1968) attributed the reduction in plant growth at pH 4.0 to the decreased uptake of basic cations due to competition with H ions for absorption sites. Lund (1970) supplied additional evidence of this effect by observing that higher calcium levels were required for normal growth of soybean taproots at pH 4.5 than was required at higher pH levels. He concluded that this was to achieve better competition with H ions.

In other reports, growth and survival of nitrogen fixing bacteria are related to the direct effect of pH. Rhizobium species particularly Rhizobium melilote as reported by Robson (1969), suffered restricted growth at pH 4.5 but completely recovered when pH was raised to 5.0. Moreover, Munns (1968) and Lie (1969) studying nodulation in alfalfa and peas, respectively, demonstrated failure of nodule formation at high acidity. Root hairs did not curl and become infected until pH was raised well above 5. They drew similar conclusions that high H ion concentration has a detrimental effect on Rhizobium growth and on nodulation.

Another direct effect of pH per se was reported recently on the rate of germination of some grasses and alfalfa (Stubbendieck, 1974, Ryan et al., 1975). All test plants showed similar patterns of reduction in germination rates with increasing acidity, but the extent of the reduction varied with plant species. While germination of blue ganicgrass was reduced by 75%, that of alfalfa showed only a 30% reduction (Stubbendieck, 1974, Ryan et al., 1975). It was concluded that low pH affected germination directly. However, the researchers cautioned that such effects would be compounded by toxic levels of other ions whose solubility is controlled largely by soil pH.

Liming of Sugarcane

Sugarcane is grown primarily in the humid tropical and subtropical areas. Intensive weathering processes and extensive leaching of soil profiles in these areas often produce acid soils. Unless a crop is acid tolerant, liming is likely to improve crop yields under these conditions. Numerous recent reports in the literature indicate that sugarcane responded favorably to lime applications (Clements, 1963; Fox et al., 1968; Hurney, 1973; and Haysom and Chapman, 1975).

Response of sugarcane to liming has been attributed to many factors. Ayres (1961) reviewing some lime experiments in Hawaii, concluded that the effect of liming on sugarcane yields was mainly the result of supplying Ca. In a later report, the same author (1966) reasoned that liming also increased nitrogen uptake in sugarcane by enhancing the decomposition of organic matter in soils. Clements (1962) obtained sugarcane yield increases from applying coral stone and stated that such a yield response was beyond that expected from Ca alone. Decreased solubility of Al was reported to be the cause of sugarcane response to liming by Rixon and Sherman (1962), and Plucknett (1972) who concluded that liming increased sugarcane yields by precipitating the free oxides of Fe and Al.

Many workers concerned with liming tropical soils have recently become interested in the use of calcium silicates as liming materials for sugarcane (Hayson and Chapman, 1975; Hurney, 1973; Wong Cheong et al., 1972; and Silva, 1971). Silicate slag, the main economically feasible source of Si for agricultural use, reacts with acids soils and increases soil pH (Pearson, 1975). Normal benefits of liming should thus result from calcium silicate applications. However,there have been persistent reports of sugarcane yield increases realized from silicates beyonds those observed from equivalent treatments with lime. Silva (1971) in a review of possible mechanisms for crop response to silicate applications, pointed out that effects of increased Si content included decreased Al, Fe and Mn activity, P fixation, and increased solubility of sorbed P. Silicate applied to P deficient Latosols in Hawaii, for example, increased extractable P, and increased dry matter yield of sugarcane (Roy et al., 1971). The authors concluded that the increase in yield was associated with improved plant P nutrition.

Williams and Vlamis (1957) reported that in addition to the Si improved yields by depressing uptake of Mn and other ions that exist in excessive amounts. However, Wong Cheong and Halais (1969) showed that sugarcane tolerated high levels of Mn and concluded that sugarcane had a basic need for Si. Later Wong Cheong et al. (1972) investigating the efficiency of sugar production in leaf tissue collected from canes of two varieties growing in nutrient solutions containing different levels of Si, postulated that Si deficiency decreased the rate of photosynthesis. They also observed the inhibition of invertase activity by Si. They suggested that a possible explanation of this Si effect is that silicate formed a chemical linkage with sucrose at the fructose end, thereby rendering the Beta fructosidic bond inaccessible to invertase.

More recently Haysom and Chapman (1975) working with acid Brown Podzolic soils in Queensland observed that lime treatments corrected soil acidity, but did not increase yields significantly, and suggested that basic silicates should be used as alternatives to alleviate the gross limiting factors associated with these soils. They reported that sugarcane responded favorably when cement was used as the source of calcium metasilicate except in ecilt loam soil which contained high amounts of soluble Si. They also noted characteristic dark red freckle (10R 3/4 in the Standard Soil Color Chart) occurring first on the tips of the 3rd and 4th blades and midribs with successively older leaves showing more symptoms. In the older leaves, the freckles were coalesced and later formed grey necrotic spots. These symptoms were completely absent in metasilicate treatments and were only reduced by lime application. The authors also observed that $CaCO_3$ was more efficient in raising soil pH than $CaSiO_3$, but yield increases due to the application of the latter were much greater indicating that silicate had an effect beyond adjusting pH. They further concluded that there may be a critical level of "plant available Si" in the soil below which yields may be limited.

PART I. FIELD EXPERIMENT

Several experiments conducted by the Hawaiian Sugar industry have shown that liming increased both yield of sugar and phosphorus uptake by the sugarcane plant. These results generated considerable interest in evaluating various soil amendments for sugarcane production in the Islands. The current experiment was carried out at the Poamoho Farm of the University of Hawaii Agricultural Experiment Station, on the Island of Oahu. The objectives were to select an optimum pH for sugarcane; compare the effectiveness of $CaCO_3$ and $CaSiO_3$ as liming materials; and evaluate their effect on uptake and movement of P and other nutrients.

Materials and Methods

Description of the Soil

The experimental soil belongs to the Wahiawa Series which is the clayey, kaolnetic, isohyperthermic Family of the Tropeptic Eutrustox subgroup of the Oxisols. This is found at elevations around 200m on Ohau. They are well-drained soils developed in old alluvium derived from basic igneous rock on nearly level to moderately steep slopes. Annual rainfall ranges from 1000 mm to 1500 mm and the annual mean soil temperature is around $22^{0}C$. The surface layer is very dusky-red to about the 30 cm depth, while the subsoil is dark-reddish brown and is about 118 cm deep. This soil is usally used for growing sugarcane and pineapple. The natural vegetation includes Bermuda grass, guava and lantana. Initial soil pH and nutrients are shown below.

pH (H_2O) 1:2.5	Mod. Truog P ppm	NH_4OAc, pH 7.0, extractable cations (ppm)		
		K	Ca	Mg
4.7	98	275	515	130

Experimental Plan

The experimental area which had been devoted to cultivation of macadamia nut trees previously, was plowed, disced and cross disced to effect proper mixing of the soil in an effort to minimize localized tree effects. The experiment was a factorial combination of 7 pH levels (4.7, 5.0, 5.3, 5.6, 6.0, 6.5 & 7.0), two liming materials ($CaCO_3$ and $CaSiO_3$), and 2 P levels (natural soil P(0.006 ppm P) and 0.025 ppm P in solution) installed in an augmented complete block design (Federer, 1956). The P levels were the main plots while the pH levels, which were obtained with either $CaCO_3$ or $CaSiO_3$, constituted the subplots. Only pH levels 5.0, 5.3, and 5.6 were replicated. The main plots had an effective size of 18.39 x 30.58 meters, while the subplots were 6.1 x 9.1 meters. Four plots (6.1 x 9.1 meters each) were included as check plots without lime or P treatments, and were essentially, the same as the pH 4.7, .006 ppm P treatments. The total area including an alley with a diversion terrace, was 0.267 hectares.

The pH of each plot was determined on 1:2.5 soil water suspension with a Beckman digital pH meter. The amounts of liming materials needed to adjust soil pH to the required levels were calculated from titration curves (amounts shown in Table 1). The required P levels were calculated from phosphate sorption isotherms determined for each plot.

Cultural Practices

Soil Cultivation: The liming materials were broadcast manually in August, 1972, mixed with a hand rototiller and left to equilibrate for three months before the planting was done on the 2nd and 3rd of November. A blanket application of N, K, Mg, Zn and B (amounts and forms are shown in Table 2) was made and thoroughly mixed with the soil prior to planting. Six rows 0.914 meters apart (calculated from the center of one row to the center of the next) were constructed with a mold board plow following the contour for surface irrigation. The inversion board of the plow was removed to minimize soil movement.

TABLE 1. AMOUNTS OF LIMING MATERIALS, AND PHOSPHORUS ADDED IN pH x LIMING MATERIALS x P EXPERIMENT

a. Liming Materials

Planned pH Levels	$CaCO_3$ kg/ha	$CaSiO_3$ kg/ha
4.7	-	-
5.0	617	717
5.3	2077	2415
5.6	4210	4895
6.0	4434	5156
6.5	9543	11097
7.0	20770	24151

b. Phosphorus Application

P Treatment ppm in Solution	Nutrient Carrier	Rate of Carrier kg/ha	Rate of P kg/ha
0.006 (natural P conc.)	-	-	-
0.025 (P added)	Treble Superphosphate $Ca(H_2PO_4)_2$	1965	393

TABLE 2. FERTILIZER MATERIALS AND RATES APPLIED TO ALL PLOTS IN pH x LIMING MATERIAL x P EXPERIMENT

Nutrient Carrier	Rate of Carrier kg/ha	Nutrient Element	Rate of Element kg/ha
Urea $CO(NH_2)_2$ (46% N)	624.9	N	287.0*
Potash KCl (50% K)	392.0	K	196.0**
Epsom Salt $MgSO_4 \cdot 7H_2O$ (9.6% Mg)	1170.2	Mg	112.3
Borax $Na_2B_4O_7 \cdot 10H_2O$ (10.6% B)	21.2	B	2.3
Zinc Sulfate $ZnSO_4 \cdot 7H_2O$ (36% Zn)	62.5	Zn	22.5

* Applied at planting, 3 and 6 months after planting, i.e. 115, 86, 86 kg N/ha, respectively.

** Applied at planting, 3 and 6 months after planting, i.e. 84, 56, 56 kg K/ha, respectively.

Weed Control: Many weeds germinated during the lime equilibration period. A rough count of the population and species of weeds was recorded and then a herbicide mixture of lorrox at 3.36 kg/hectare and Treflan at 4.67 liters/hectare was applied, which effectively controlled weeds until the development of the sugarcane canopy. However, weeds that grew later in the open spaces between the plots and in the diversion terrace were controlled by directed spraying with Paraquat.

Planting: Three-eye seed pieces of sugarcane variety (H59-3775) which had been provided by the HSPA Experiment Station were treated with a fungicide, Benlate (0.23 kg/10 gal of water) prior to planting. The seed was planted in the row with an average of 1.5 seed pieces per M^2. There were 6 rows per plot. The seed was covered about 2 to 4 cm deep and immediately irrigated. One month after germination (Dec. 21, 1972), plants were transplanted from guard rows of the plot into harvest rows of the same plot, where necessary, in order to obtain a uniform stand of about 3.2 plants per M^2 (30 plants per plot row).

Soil Sampling

Surface and profile samples were collected from the check plots before lime application and from all plots after harvesting the crop. Profile samples were obtained with an auger at 15 cm intervals to a depth of 90 cm. Surface sample (0-15, 15-30 cm depth) were also collected near the middle of the cropping period (May, 1973).

Plant Sampling

Commencing in March 1973, when the plants were 3 months old, crop log samples were collected every 90 days. Samples were taken by cutting the stalk below internode number 7, counting the spindle as leaf number 1. Four stalks were collected per plot. The weight of the intact top from sheath number 6 to the spindle was recorded then the top was separated into leaves and sheaths 3, 4, 5 & 6 as described by Clements (1962). The sheath samples were weighed; chopped into about 1 cm length and dried in a draft oven at 70°C; then ground in a Wiley mill to pass a 20 mesh stainless sieve; and finally stored for analysis for P, K, Ca, Mg, Mn, Fe, Zn, Al, and Si. The middle 1/3 of blades 3, 4, 5 & 6 were separated, the midrib removed and the samples were then dried, ground and stored for N analysis. Sampling and processing were done as early in the morning as possible to minimize fluctuations in the nutrient status of the plant caused by the metabolic activity associated with photosynthesis later in the day. Samples of the nature stalk and top portion of the stalk were also secured at harvest and mechanically chopped. Samples were weighed fresh when collected and again after drying in a forced draft oven at 70°C for moisture determinations.

Harvesting

Cane was harvested in Oct. 1973 after 12 months of growth. Two rows on either side of the plot and 1.5 meters on either end of the 9.14 meter rows were discarded as border, leaving 2 rows 6.10 meters long as the effective harvested area (1.83 x 6.10 meters per plot). A stalk census which included the number of primary stalks, the number of secondary shoots and a record of any mechanical damage was recorded for each harvested row. The total weight of cane was recorded as a measure of yield per plot.

Soil Analysis

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

Lime Requirement: Liming materials required to raise soil pH to the respective treatment levels were calculated from titration curves constructed by using increments of $CaCO_3$ or $CaSiO_3$.

25 gram soil samples (oven dry basis) were weighed into 100 ml beakers. Distilled eater to form a slurry and various amounts of $CaCO_3$ or $CaSiO_3$ were added. Slurry pH was determined when pH reading was constant i.e. after 14 days. Then titration curves were constructed and the equivalent amounts of liming materials were calculated.

Extractable P: P was extracted using modified truog's reagent (Ayres and Hagihara, 1952). A 2 g soil sample was shaken with 200 ml of the extracting solution (0.02N H_2SO_4 + 3 g per liter of $(NH_4)_2SO_4$ in a 500 ml Erenmeyer flask for 30 minutes, centrifuged and P was determined in the supernatant solution.

P Sorption Isotherms: The method of Fox and Kamprath (1970) was followed to obtain P sorption isotherms for Wahiawa soil. A 3 g sample of soil (oven dry basis) was equilibrated in 30 ml of

0.01 M $CaCl_2$ containing various amounts of $Ca(H_2PO_4)_2$. Three drops toluene were added to suppress onicrobial activity. Suspensions were equilibrated for 6 days at 25°C with shaking for 30 minutes twice a day. Samples were then centrifuged and P determined in the clear supernatant solution.

Extractable Mn: The procedure was a modification of that described by Chapman and Pratt (1961). An 8 g soil sample was shaken for 30 minutes with 40 ml of IN KCl in a 100 ml polyethylene tube, followed by overnight standing. The mixture was again shaken for 30 minutes and the extract filtered through Whatman No. 2 filter paper. Mn was determined in the clear solution with a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

Extractable Al: Ten grams of soil were mixed with 50 ml of IN KCl and allowed to equilibrate overnight. The soil solution was then siltered through a Buchner funnel with suction, and washed several times with 10 ml increments of the extracting solution and the final volume was made to 100 ml.

Aluminum in the clear extracts was determined by the Aluminun method described by McLean (1965).

Cation Exchange Capacity: CEC was determined in selected samples using N NH_4OAc, adjusted to the pH of the soil (Tamimi et al., 1972). A 10 g soil sample (oven dry basis) was introduced into a 500 ml Erlenmeyer flask, 100 ml N NH_4OAc was added and the mixture was shaken for 30 minutes then allowed to stand overnight. The sample was shaken again for 30 minutes and filtered in a Buchner funnel using Whatman No. 42 filter paper. The soil was washed with 4 50 ml increments of N NH_4OAc, adjusted to the pH of the soil. The soil was then washed with 200 ml 95% ethyl alcohol in 50 ml aliquots. The washed soil and filter paper were transferred to a 500 ml Erlenmeyer flask and 200 ml N KCl was added and the mixture shaken for 1 hour. The sample was filtered in a Buchner funnel using Whatman No. 42 filter paper and washed with 200 ml KCl in 50 ml aliquots. The filtrate was transferred to an 800 ml Kjeldahl flask and NH_3 was distilled into 150 ml of boric acid-mixed indicator solution. Standard sulfuric acid (.0142NH_2SO_4) was used to titrate the distillate.

Exchangeable Cations: Exchangeable cations were extracted with neutral, N NH_4OAc. A 10g soil sample (oven dry basis) was introduced into a 500 ml Erlenmeyer flask, 100 ml N NH_4OAc was added and the mixture was shaken for 30 minutes then allowed to stand overnight. The sample was shaken again for 30 minutes and filtered in a Buchner funnel using Whatman No. 42 silter paper. Ca, K, Mg, Mn, Zn and Fe were determined in the filtrate. K was determined with the Beckman DU flame spectrophotometer while Ca, Mg, Mn, Zn and Fe were determined with a Perkin-Elmer model 303 atomic absorption spectrophotometer.

Plant Analysis

Cations and P: Wet digestion with 2:1 nitric:perchloric acid as described by Jackson (1958) was performed and Ca, K, Mg, P, Mn, Al, Zn and Fe were determined in the digest. K was determined with the Beckman DU flame spectrophotometer while Ca, Mg, Mn, Al, Zn and Fe were determined with a Perkin-Elmer model 303 atomic absorption spectrophotometer. For Ca determination a 0.5% lanthanum solution was used to depress P interference. P was determined with the molybdenum blue method of Truog and Meyer as outlined by Chapman and Pratt (1961).

Silicon: Silicon content of the plant tissue was determined by ashing 0.5 gm dry plant material overnight in a muffle furnace at $550^{o}C$. The ash was fused with 0.5 g sodium tetraborate at $950^{o}C$, according to the method of Suhr and Ingamells (1966). The fused material was dissolved in 100 ml 10% nitric acid and a 5 ml aliquot was used for color development. Silicon was determined by the Molybdate blue method of Kilmer (1965).

Nitrogen: Total nitrogen in sugarcane leaf blades was determined by the Kjeldahl method. One gram ground plant tissue was weighed into an 800 ml Kjeldahl flask and 30 ml conc H_2SO_4, 5 grams Na_2SO_4, 5 drops (0.25 ml) $SeOCl_2$ and a few glass beads were added. The mixture was digested until the solution cleared then digestion was continued for 30 minutes.

The digest was cooled and diluted with 300 ml of distilled water, then 100 ml of 15N sodium hydroxide was added down the side of the falsk without mixing. A few pieces of mossy zinc were added and the digest was distilled into 50 ml 2% Boric Acid-Indicator solution. About 150-200 ml of the distillate was collected and titrated with standard H_2SO_4.

Statistical Analysis

Data analysis was carried out with the facilities of the University of Hawaii computing center. Analysis of variance was done using the

Factorial-Split Plot Program and Duncan's Modified (Bayesian) Least Significant Difference Test (DLSD) was performed where F ratios were significant. Multiple regression analysis was conducted using the BMD O2R, stepwise regression program (Dixon, 1968).

Results and Discussion

Growth of Sugarcane

Growth of sugarcane, as monitored by the growth index described by Clements (1962) and by the weight of cane tops, increased substantially over the control when soil pH was raised above 4.7 with either $CaSiO_3$ or $CaCO_3$ applications. This effect was clearly noticeable as early as March, when the cane was three months old (Fig. 1). This figure also demonstrates that, although growth continued to increase until a maximum was reached around pH 5.9, the highest gain was obtained from the first increments of the two liming materials. A pH 5.9 was the highest attained with $CaSiO_3$ at preplanting, while a pH of 6.4 was reached in the $CaCO_3$ system during this period. An explanation for this is suggested by Rashid (1974), who reported $CaSiO_3$ reacted more slowly than $CaCO_3$. However, after longer equilibration periods the two materials gave comparable soil pH values.

Cane growth significantly increased with soil pH in the August samples, when plants were nine months old. In general, growth was best in the pH range 5.6 to 5.9, with both liming materials as indicated in Figure 2. No further gain in growth of cane occurred as soil pH increased above 5.9. In fact, a significant decline in growth occurred when pH was raised above 6.5 Similarly, Reeve and Sumner (1970) reported a decline in yield of sorghum on some Oxisols when liming increased soil pH to 5.5 Also, Amarasiri and Olsen (1973), working with lime and P observed a significant decline in crop yield

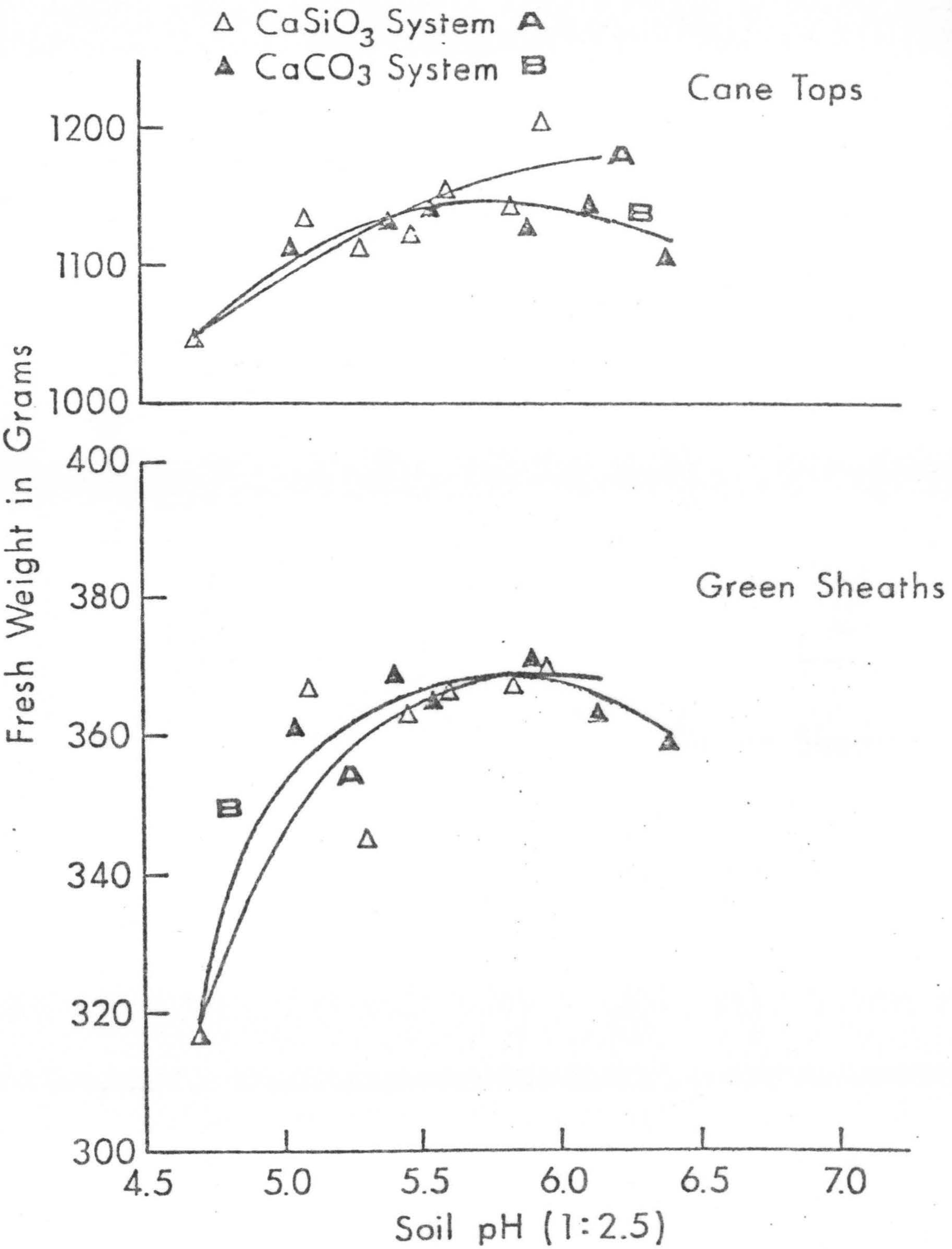


FIGURE 1. EFFECT OF SOIL pH AND LIMING MATERIALS ON CANE TOP AND SHEATH WEIGHTS OF 3 MONTH OLD CANE

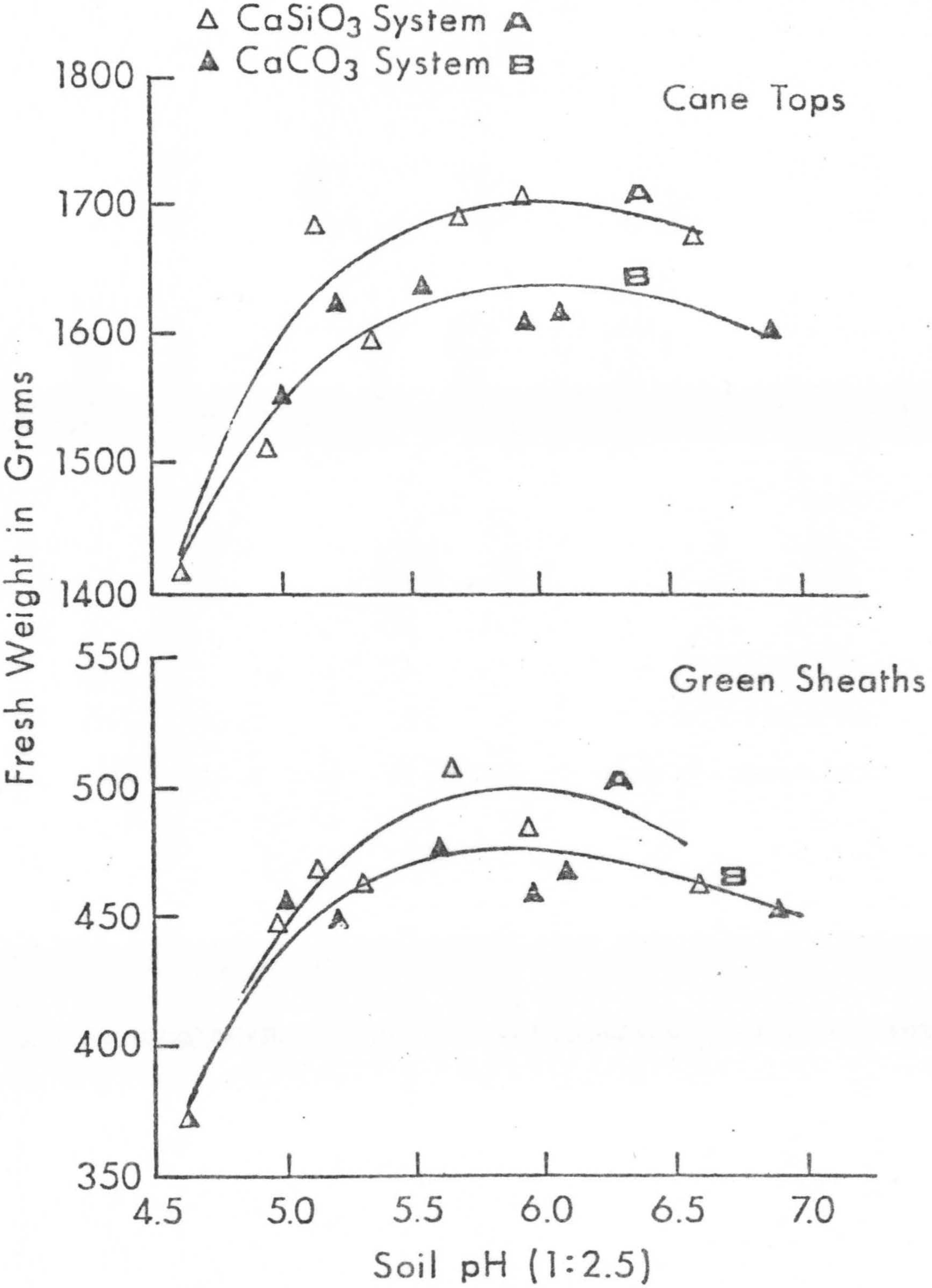


FIGURE 2. EFFECT OF SOIL pH AND LIMING MATERIALS ON CANE TOP AND SHEATH WEIGHTS OF 9 MONTH OLD CANE

with increasing lime application. Both reports suggested a micro-nutrient deficiency that occurred at high pH levels. In view of the high Mn and Fe levels in Wahiawa soil and the application of Zn and B in the current experiment, a micro-nutrient deficiency does not appear likely. However, when a ratoon crop was allowed to grow on the same field some chlorosis similar to Fe deficiency could be observed at the high pH treatments.

Growth patterns observed in March, May and August are shown in Figure 3 and it is apparent that treatment effects became more evident in the later stages of the crop. This corresponds to greater differences in soil pH as equilibration of the liming materials progressed. The boom stage of growth occurred in the March to May period and is reflected in the statistically significant increase in cane top weight in May. The increase in weight was not significantly different between May and August due to a reduced growth rate. Demand of the crop for optimal conditions is generally high during rapid growth, therefore, treatment effects are generally greater.

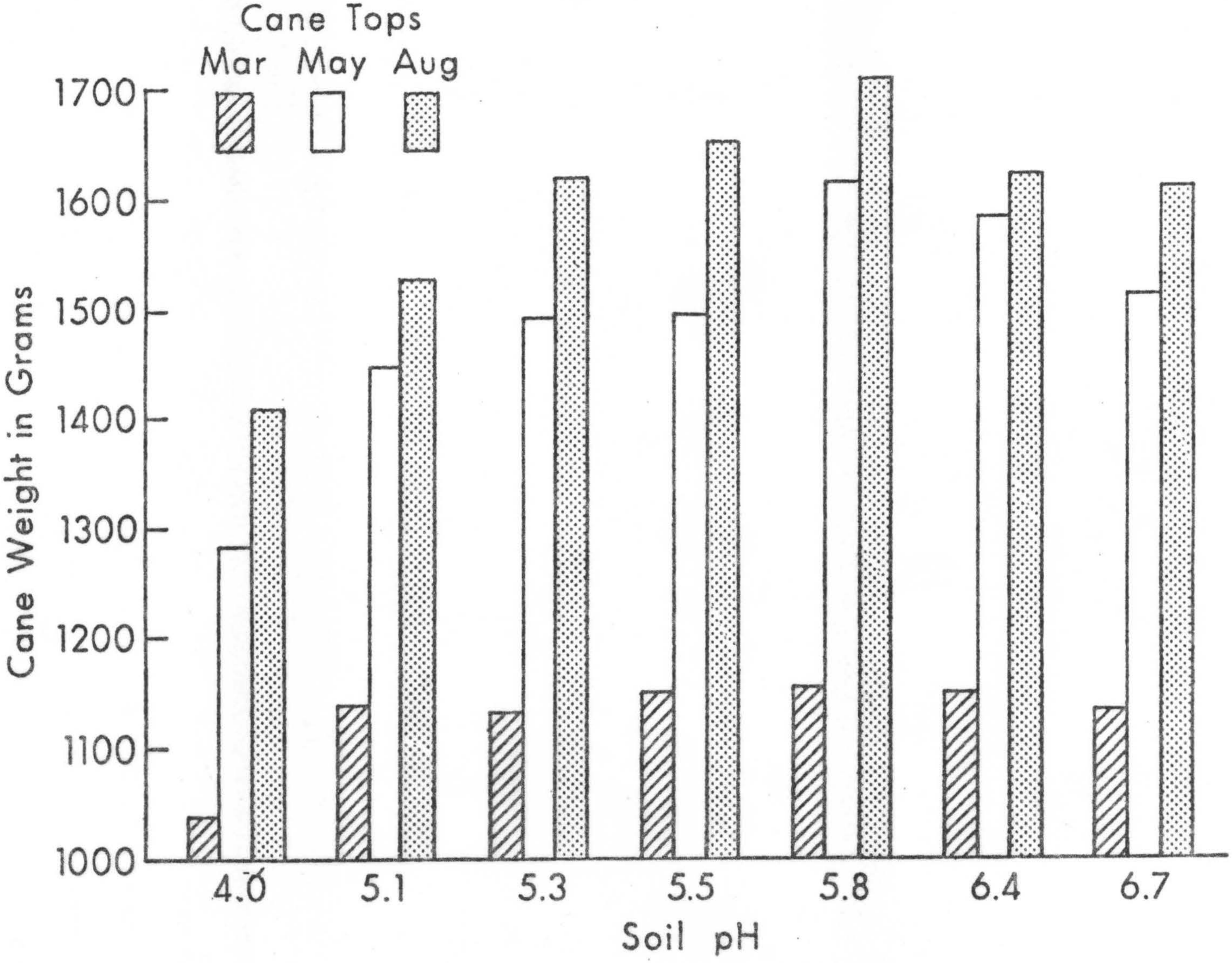


FIGURE 3. EFFECT OF SOIL pH ON YIELD OF SUGARCANE AT 3, 6 AND 9 MONTHS

Yield

Plant species are known to vary in the pH range over which they will grow. Moreover, where attempts were made to establish an optimum pH for a certain crop, complications arose from the fact that crop response to pH depends not only on the plant species, but also on the climatic conditions and soil types. Response of crops to liming are reported to be different in the tropics and in temperate areas (Kamprath, 1970, 1972; and Amarasiri and Olsen, 1973), who suggested limited benefits from liming tropical soils. Favorable response of sugarcane to liming has been reported in Hawaii (Clements, 1965, 1967; and Teranishi, 1968).

In the current experiment, yield of sugarcane was increased substantially over the control when soil pH was raised above 4.7 by either $CaCO_3$ or $CaSiO_3$ (Fig. 4 and Appendix Table 1). In the $CaCO_3$ system maximum yield was obtained at pH 5.8 with no further benefit from higher pH. A considerable yield decline was observed as soil pH approached 7.0. Similar results were reported by Fox et al. (1964) who noted drastically reduced yield and P uptake when plants growing in ash soils were limed to pH 7.0 Hurinburana (1974) also, reported yield of papaya was best at pH 5.7 and decreased significantly when pH was raised to 6.5 and above.

The increase in yield in the carbonate treatments was more consistent when P was added until a miximum of 315 T of cane/ha was attained at pH 5.8. In the low phosphorus (0.006 ppm P) treatment the maximum yield obtained was only 282 T/ha at the same pH. This could

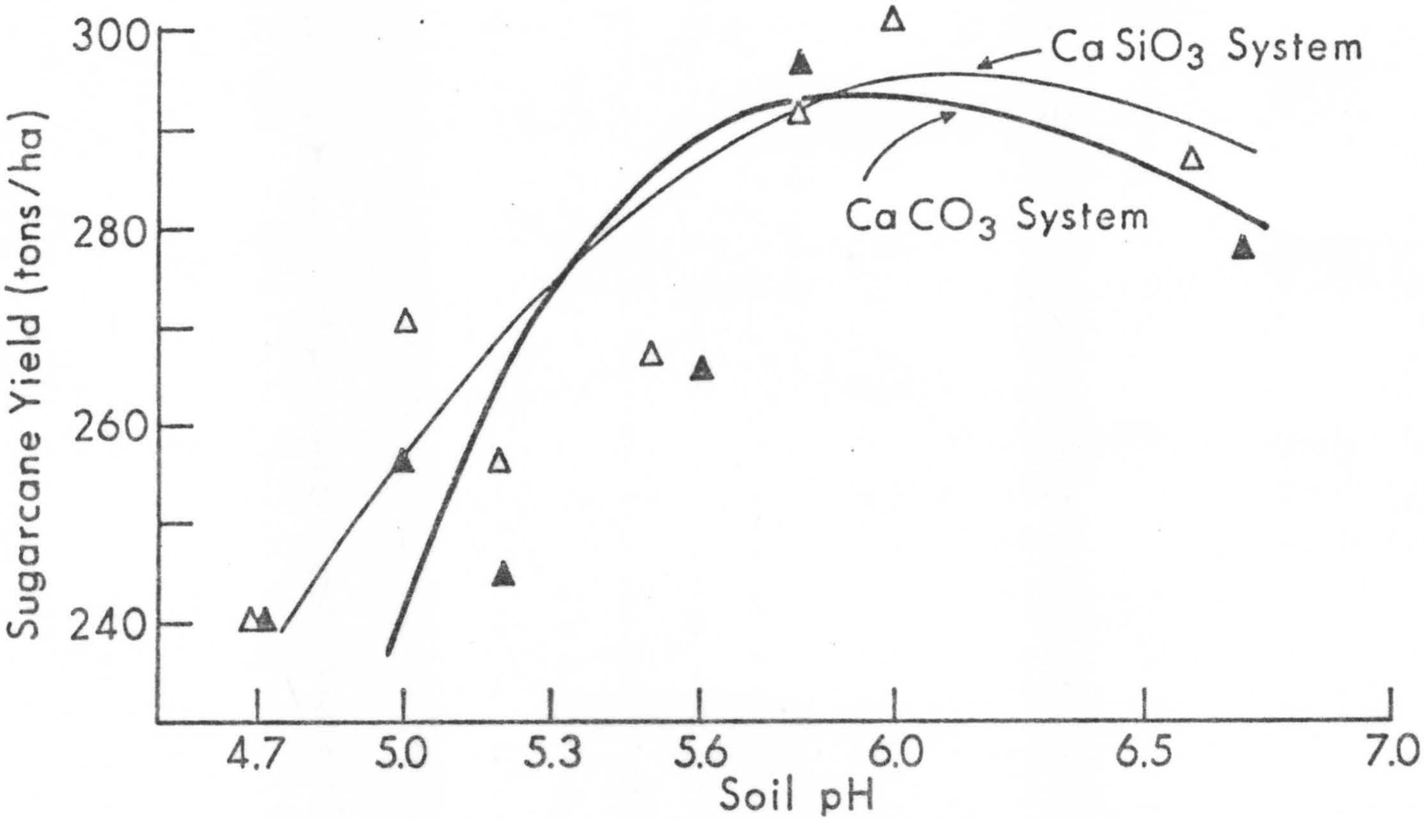


FIGURE 4. EFFECT OF SOIL pH ON YIELD OF SUGARCANE AT 12 MONTHS

be due to reduced P availability when no P was applied at the relatively high Ca saturation. Clements (1961) reported limited response of cane to crushed coral stone applications up to 11 T/ha in a Hydrol Humic Latosol when no phosphorus was added.

When considering the $CaSiO_3$ system, a similar trend of yield increase was evident. The increase was substantial with the first increments of $CaSiO_3$ with diminishing increases as pH was raised. The beneficial response continued up to pH 6.0 where a maximum yield of 301 T/ha of cane was obtained. Since the silicate ion is also a variable, there is the possibility of a silicate effect which may have offset overliming problems encountered when pH was raised with $CaCO_3$. This probably resulted in extending the response of sugarcane to higher pH levels with $CaSiO_3$. This could be due to chemical effects in the soil and/or physiological effects in the plant as reported by some workers. The increase in yield of $CaSiO_3$ over $CaCO_3$ was more pronounced when no P was applied,but it was not statistically significant. It has been established that silicate enhances P solubility in the soil and P uptake by plants which may account for this response. When phosphorus was applied this benefit of silicate over carbonate diminished.

Beside the apparent interaction between phosphorus and the liming materials, P had a distinct direct effect on yield. Cane yield increased as much as 38 T/ha from P application to the unlimed soil. Sugarcane responed to P in the limed plots especially in the carbonate system. At the apparent optimal pH level (5.8) with carbonate, applied P increased yield of cane by 32 T/ha over the low P treatment while the corresponding increase in the silicate system was only 8 T/ha.

Plant Nutrient Composition

Calcium: Raising soil pH with either $CaCO_3$ or $CaSiO_3$ consistently increased percent sheath Ca in the early stages of plant growth, i.e. in 3-month-old cane (Table 3). These data indicate that the highest increase in percent Ca occurred with the first increments of the liming materials followed by a progressively smaller increase at the middle rate of lime and then a larger increase at the higher rates of lime. It is also apparent that $CaCO_3$ supplied slightly more Ca to plants than $CaSiO_3$ at this stage. This corresponds to the higher soil pH in the carbonate system than in the silicate system during the early stages of equilibration which is probably due to the greater solubility and reactivity of $CaCO_3$. Another possible reason for lower Ca value in $CaSiO_3$ treatments in teh higher yield in these treatments which would cause a dilution of plant Ca. At the later stages of equilibration, however, $CaSiO_3$ was equally effective in raising soil pH and in supplying Ca. No significant difference in Ca concentration could be attributed to P application.

When the cane was 9 months old, sheath Ca levels were generally above the 0.20 percent level established by Clements (1962) as being adequate for sugarcane (Table 4). At harvest (12 months) there was little difference in Ca levels within the limed treatments. Comparable results were reported by Teranishi (1968) from an experiment in Kapaa (Halii) soil. The discrepancy in trends of sheath calcium content between the early stages of plant growth, where statistically significant

TABLE 3. EFFECT OF pH, LIMING MATERIALS AND P ON % SHEATH Ca OF 3 MONTH OLD CANE

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	0.21	0.28	0.25	0.27	0.35	-	-	0.21	0.20	0.32	0.36	0.39	-	0.36
	P 0.025	0.18	0.26	0.22	0.25	-	0.40	0.41	0.18	0.19	0.33	0.30	-	0.40	-
Rep II	P 0.006	0.24	0.25	0.29	0.35	-	0.36	0.39	0.24	0.31	0.28	0.41	-	0.51	-
	P 0.025	0.30	0.27	0.35	0.37	0.33	-	-	0.30	0.25	0.28	0.38	0.34	-	0.46
pH Ave		0.23	0.26	0.28	0.30	0.34	0.38	0.40	0.23	0.25	0.30	0.34	0.36	0.45	0.41

Check plot 0.23

pH x Liming Materials$^+$

LM pH	5.0	5.2	5.6
$CaSiO_3$	0.26	0.28	0.30
$CaCO_3$	0.25	0.30	0.34

pH x P$^+$

P pH	5.0	5.2	5.6
P 0.006	0.27	0.29	0.34
P 0.025	0.25	0.30	0.31

Liming Materials x P$^+$

LM P	P 0.006	P 0.025
$CaSiO_3$	0.29	0.27
$CaCO_3$	0.30	0.26

+ Means of replicated treatments

TABLE 4. EFFECT OF pH, LIMING MATERIALS AND P ON % SHEATH Ca OF 9 MONTH OLD CANE

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	0.19	0.22	0.21	0.26	0.31	-	-	0.19	0.23	0.25	0.26	0.29	-	0.32
	P 0.025	0.21	0.23	0.23	0.28	-	0.29	0.36	0.21	0.24	0.23	0.27	-	0.28	-
Rep I	P 0.006	0.20	0.20	0.26	0.28	-	0.28	0.33	0.20	0.23	0.24	0.25	-	0.29	-
	P 0.025	0.20	0.23	0.27	0.26	0.28	-	-	0.20	0.25	0.25	0.26	0.26	-	0.34
pH Ave		0.20	0.22	0.25	0.27	0.30	0.29	0.35	0.20	0.24	0.26	0.26	0.28	0.29	0.33

Check plot 0.24

pH x Liming Materials+

LM \ pH	5.0	5.2	5.6
$CaSiO_3$	0.22	0.25	0.27
$CaCO_3$	0.24	0.26	0.26

pH x P+

P \ pH	5.0	5.2	5.6
P 0.006	0.22	0.24	0.26
P 0.025	0.24	0.25	0.26

Liming Materials x P+

LM \ P	P 0.006	P 0.025
$CaSiO_3$	0.25	0.26
$CaCO_3$	0.25	0.25

+ Means of replicated treatments

differences were observed due to applied calcium, and the later stages where no such response occurred, are probably due to the fact that plant roots when small are limited to Ca supplied by the liming materials. When plant roots were able to tap more soil at the later stages of growth, the effect of supplied calcium probably decreased. A similar explanation was suggested Tisdale and Nelson (1969) for lack of response of corn to applied P. Further comparison of these data also show that calcium concentration was generally higher at 3 months than at 9 months. This could be due to a dilution effect after the boom stage of growth. Similar results were obtained by Clements (1961). Sheath Ca values were generally adequate above pH 5.0 with $CaSiO_3$ and above pH 5.3 with $CaCO_3$. Wahiawa soil had a fairly high level of exchangeable Ca which accounts for the relatively high Ca levels in the unlimed plots.

Calcium content in cane tops increased with increasing soil pH and/or applied Ca (Table 5). When no lime was applied, added P increased percent Ca slightly, but when lime was applied, added P did not affect plant Ca. Within the plant, calcium content was considerably lower in the stalk than in the sheaths or cane tops (Appendix Tables 3 and 4). A higher percent Ca was obtained in the silicate system in this tissue than in the carbonate system. Stalk Ca was not significantly affected by soil pH, however, the lowest Ca values were consistently found at the low pH levels (4.7 and 5.0).

Although soil calcium before application of liming materials was 489 ppm which was considered adequate for sugarcane by HSPA

TABLE 5. EFFECT OF pH, LIMING MATERIALS AND P ON % Ca IN PLANT TOPS AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	0.20	0.20	0.22	0.22	0.21
5.0*	0.24	0.22	0.22	0.22	0.23
5.2*	0.22	0.23	0.24	0.23	0.23
5.6*	0.26	0.22	0.23	0.23	0.24
5.8	0.24	0.28	0.26	0.26	0.26
6.0	0.27	0.30	0.28	0.24	0.27
6.7	0.29	0.25	0.27	0.28	0.27
Ave	0.25	0.24	0.25	0.24	

* Replicated treatments

specialists (M. Doi, personal communication), much of the yield response was correlated with Ca saturation. However, under the conditions of this experiment, the calcium effect could not be separated from other pH effects.

Nitrogen: Nitrogen concentration in leaf blades was significantly enhanced by lime application. While both leaf blade and plant top N followed similar trends with pH, only the former trend was statistically significant. The leaf blade nitrogen level at pH 5.6 was considerably higher than that at either 5.2 or 5.0, but the N levels at 5.2 and 5.0 were not significantly different (Table 6).

Liming is known to affect soil microbial populations to a great extent. The activity of soil microorganisms that cause N transformations are reported to be enhanced by adequate amounts of calcium and appropriate soil pH. Ayres (1961) reported that organic matter decomposition was greatly increased by liming Low Humic and Hydrol, humic Latosols in Hawaii.

Other than the pH effect, no difference in nitrogen was observed between the two liming materials. In an earlier report, Tamimi and Matsuyama (1972) noted that percent tissue N decrease slightly with increasing $CaSiO_3$ while it increased with $CaCO_3$. They attributed this to a dilution effect due to increased yield of sorghum with addition of calcium silicate.

Potassium: Sheath potassium values observed in this experiment were high in all treatments probably due to the high levels of native K in the soil at planting coupled with the K applied to the crop (196.0 kg/ha).

TABLE 6. EFFECT OS SOIL pH, LIMING MATERIALS AND P ON % SUGARCANE LEAF BLADE N AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	2.05	2.05	2.06	2.06	2.06
5.0*	2.06	2.09	2.08	2.04	2.06
5.2*	2.06	2.07	2.09	2.08	2.07
5.6*	2.29	2.38	2.28	2.36	2.33
5.8	2.14	2.15	2.28	2.26	2.21
6.0	2.33	2.17	2.23	2.21	2.24
6.7	2.18	2.21	2.19	2.21	2.20
Ave	2.16	2.16	2.17	2.17	

* Replicated treatments

Sheath potassium did not show any specific trend with pH or phosphate treatments in the earlier stages of plant growth (Table 7). However, when the crop was nine months old and at harvest, K decreased generally with increasing pH and phosphorus (Table 8 and Appendix Table 5). The K value at pH 5.6 was significantly lower than the K value at pH 5.0 according to the Bayesian Least Significant Difference Test. Similarly, the average K level was markedly lower in the high P treatments than in the P treatments. Since exchangeable soil potassium increased significantly with pH as discussed later in the soil analysis section, the above observation may be due to a yield-induced dilution effect, i.e. higher yields were obtained both with increasing pH and P. Also, it was observed that the decrease in K was associated with an increase in calcium in the plant tissue which might suggest competative absorption of the two elements. This is in agreement with the finding of Misra (1970) who concluded that high levels of readily available calcium suppress potassium uptake by plants. However, even in the highest lime treatments (pH 6.7) sheath K remained well above the critical level (2.25%) for sugarcane reported by Humbert (1968).

<u>Magnesium</u>: A significant increase in plant sheath magnesium occurred with lime application (Table 9). Although the increase in Mg at pH 5.0, 5.2 and 5.6 was not statistically significant, consistently higher magnesium concentrations were observed in the limed than in the unlimed plots. Retention of basic cations on the exchange complex against leaching is improved by raising pH of soils containing appreciable amounts of pH dependent charge (Fox et al., 1970, Uehara et al., 1972).

TABLE 7. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % SHEATH K OF 3 MONTH OLD CANE

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	3.3	3.3	3.1	3.1	3.20
5.0*	3.1	2.9	3.4	3.2	3.15
5.2*	3.1	3.2	3.0	3.1	3.10
5.6*	3.2	3.0	3.1	3.2	3.15
5.8	3.3	3.1	3.3	2.9	3.15
6.0	3.0	3.0	3.2	3.1	3.10
6.7	3.3	2.9	2.8	3.1	3.03
Ave	3.19	3.06	3.13	3.10	

TABLE 8. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % SHEATH K OF 9 MONTH OLD CANE

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	3.4	3.4	3.1	3.1	3.25
5.0*	3.2	3.3	3.0	3.1	3.15
5.2*	3.0	3.1	2.6	2.9	2.90
5.6*	2.9	2.6	2.6	2.8	2.73
5.8	3.0	2.8	2.9	2.8	2.88
6.0	2.7	2.8	2.8	2.7	2.75
6.7	2.8	2.6	2.6	2.7	2.68
Ave	3.00	2.94	2.80	2.87	

* Replicated treatments

TABLE 9. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % SHEATH Mg AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	0.078	0.078	0.089	0.089	0.084
5.0*	0.087	0.092	0.097	0.094	0.093
5.2*	0.093	0.096	0.098	0.107	0.099
5.6*	0.093	0.101	0.112	0.107	0.103
5.8	0.095	0.111	0.114	0.102	0.106
6.0	0.113	0.118	0.113	0.099	0.111
6.7	0.105	0.117	0.117	0.122	0.115
Ave	0.096	0.102	0.106	0.103	

* Replicated treatments

Also, the two liming materials used in this investigation contained Mg as an impurity ($CaSiO_3$ 0.48%, $CaCO_3$ 0.88% as MgO). Therefore, the limed plots received additional amounts of magnesium. This impurity might also account for the slightly higher Mg values observed in the low P -- silicate system.

Phosphorus treatments had a minor effect on Mg concentration in plant tissues, and Mg increased slightly in the P-treated plots. Application of P improved plant growth and yield as mentioned earlier, and probably increased the plant's ability to take up more nutrients.

Phosphorus: Phosphorus concentration in sugarcane sheath and stalks increased noticeably when soil pH was raised above 4.7 (Tables 10 and 11). A 20% increase in stalk P over the control occurred due to liming when no P was applied, while the gain in sheath P was relatively smaller. This increase resulting from the first increments of lime parallels a rapid decrease in extractable soil Al (Fig. 10). Much evidence exists of the depressing effect of Al on P availability to plants; either by sorption of phosphates on the surfaces of hydrous oxides of Al, (Rajan, 1975), by precipitation of added fertilizer P as the sparingly soluble Al phosphates (Amarasiri and Olsen, 1973), or by restricting plant root growth, thus limiting the volume of soil tapped for P. The latter workers reported a very low level of P uptake by plants grown in strongly acidic aluminous soils in Hawaii. Using calcium monphosphate labelled with P^{32}, the authors found that small applications of $Ca(OH)_2$ enhanced P uptake which reached a maximum at pH 5.0, and greatly reduced Al uptake. Another possibility

TABLE 10. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % SHEATH P AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	0.102	0.102	0.106	0.106	0.104
5.0*	0.104	0.105	0.108	0.106	0.106
5.2*	0.103	0.093	0.107	0.105	0.102
5.6*	0.104	0.103	0.107	0.108	0.106
5.8	0.109	0.105	0.106	0.104	0.106
6.0	0.106	0.096	0.109	0.104	0.104
6.7	0.108	0.102	0.111	0.107	0.107
Ave	0.105	0.101	0.108	0.106	

TABLE 11. EFFECT SOIL pH, LIMING MATERIALS AND P ON % STALK P AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	0.04	0.04	0.06	0.06	0.05
5.2*	0.05	0.05	0.07	0.06	0.06
5.6*	0.05	0.06	0.08	0.07	0.07
5.8	0.06	0.06	0.06	0.07	0.06
6.0	0.06	0.05	0.08	0.06	0.06
6.7	0.09	0.05	0.11	0.06	0.08
Ave	0.05	0.05	0.07	0.06	

* Replicated treatments

for the increased P concentration is the improved plant growth observed in the limed treatments which allowed greater root development and thus greater P uptake. Since no consistent difference was obtained in plant tissue phosphorus within the limed treatments, P uptake was probably not closely related to soil pH.

A comparison of the two liming materials in Tables 10 and 11 reveals a strong relationship between plant P and the high rates of calcium silicate applications. Adding silicates increased stalk and cane top phosphorus with or without fertilizer P added. The increased solubility of phosphate by anion exchange with silicate has been documented by many workers. Furthermore, anion exchange is pH dependent, and silicate displacement of phosphate was very small at low soil pH, but the displacement was highly significant as pH approached neutrality (Reifenberg and Buckwold, 1954). This is substantiated by the finding of Kafkafi (1972) who stated that more silicate than phosphate is absorbed by soils as pH approached the pH of monosilicic acid, 8.6.

In the current investigation high silicate applications (pH 6.6) decreased soil P sorption markedly and increased P concentration in sugarcane stalks and tops. In the lower silicate applications, however, no difference in plant P due to the two liming materials was observed.

Stalk P concentration was most affected by fertilizer P applications. When P was added to attain 0.025 ppm P in the supernatant solution, stalk phosphorus concentration increased more than 30% in the unlimed plots. This was reflected in the increased sugarcane yield in the phosphate-treated unlimed plots c~~a~~ompared to plots where no P was applied

Microelements

Manganese: Most microelements such as Mn, Fe, Cu and Zn are readily available in acid soils. Since plants require small amounts of these nutrients for normal growth, an abundant supply of any of these elements can have a detrimental effect. Excess manganese is frequently reported to cause crop injury. Williams and Vlamis (1957) and Vlamis and Williams (1967) reported significant decreases in yield of barley and rice when Mn concentration was gradually increased in standard Hoagland's solution to 0.5 ppm Mn. They observed severe Mn toxicity symptoms in barley at a leaf Mn content of 1200 ppm while rice was relatively tolerant and showed severe symptoms only at 7000 ppm Mn in the leaf.

Wahiawa soil is known to have a high amount of available Mn that can become toxic to plants grown under acid conditions. Freckling of sugarcane leaves, a symptom frequently associated with Mn toxicity, has been observed in plants grown in acid Wahiawa soil (Clements, 1965).

Lime applications significantly reduced plant tissue Mn. The greatest reductions occurring at the lowest rates of both $CaCO_3$ and $CaSiO_3$ (Table 12). The average decrease due to the first increment of the two liming materials is 30 ppm compared to a reduction of less than 10 ppm with each subsequent addition.

The data in Table 12 and Figure 5 show that $CaSiO_3$ was consistently more effective in reducing Mn concentration in sheaths and plant tops. For example compared to the control, 1 30% decrease of Mn in

TABLE 12. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON SHEATH Mn (ppm) AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	146	146	147	147	147
5.0*	125	121	108	119	118
5.2*	109	111	107	117	111
5.6*	97	90	100	116	101
5.8	78	89	86	88	85
6.0	72	82	92	82	82
6.7	77	83	79	77	79
Ave	101	103	103	107	

* Replicated treatments

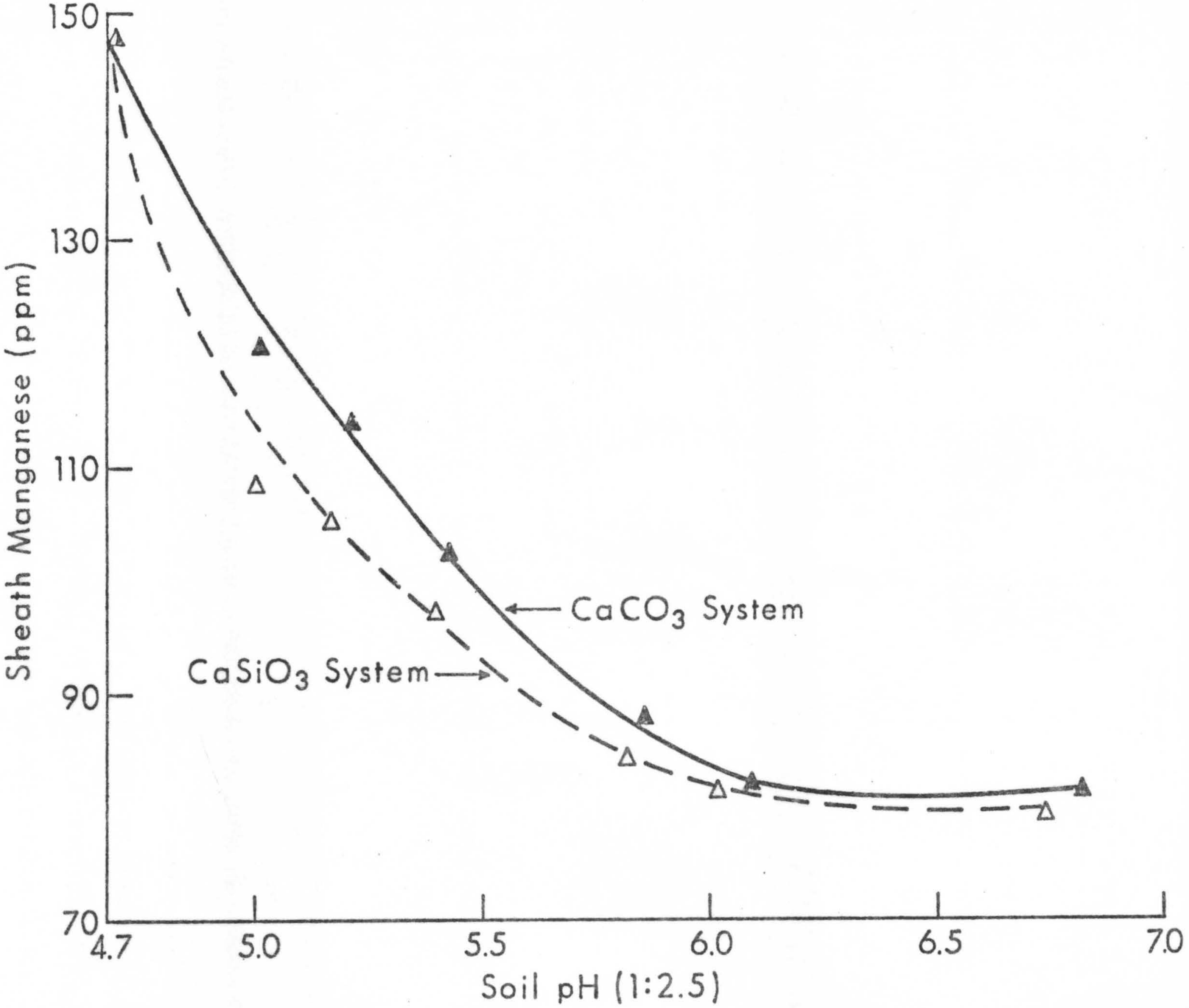


FIGURE 5. EFFECT OF SOIL pH AND LIMING MATERIALS ON SHEATH Mn (ppm) AT 12 MONTHS

plant tissue was observed at the highest rate of $CaCO_3$, while $CaSiO_3$ caused a reduction of more than 40% at the same level of application. Similar reports Clements (1961) observed Mn reduction in sugarcane leaf sheaths from 111 ppm in the control to 74 when 11T/ha crushed coral stone were applied to a Hydrol Humic Latosol. These data also indicate that phosphate fertilization also reduced Mn concentration somewhat in sugarcane tops. However, the effect of liming on Mn reduction was much greater than the effect of P.

Since sugarcane yield increased with lime and phosphorus applications as discussed earlier, Mn is inversely related to yield. However, no symptoms of Mn toxicity, leaf freckling, were observed at low pH. From surveys of sugarcane fields in which soil silicon was related to sugarcane growth, Fox et al. (1967) proposed a range for % sheath silicon below which freckling symptoms may occur in sugarcane leaves. They observed that severe freckling occurred at 0.61% sheath silicon which they suggested was probable deficiency level for Si. Clements (1965) stated that sugarcane growth response to liming was affected by the Mn (ppm)/SiO_2 (%) ratio and that Mn toxicity occurred when this ratio was over 50. In the current investigation the silica content of sugarcane sheaths was above the 0.61% silicon level in plants supplied with $CaSiO_3$, but was only slightly above this level in the control plots or when pH was raised with $CaCO_3$. Plant Si may be reduced by $CaCO_3$ applications which increase soil pH, but decrease solubility of soil Si (Teranishi, 1968). This could be important in leached soils where soluble silicon is low.

The soil used in the current experiment had 2 ppm water soluble silicon, which was considered marginal for sugarcane by Silva (1971).

It may be reduced from the foregoing discussion that in acid, leached soils where Mn toxicity can be a problem, $CaSiO_3$ is a more effective liming materials than $CaCO_3$ and can maintain a higher Si:Mn ratio and improve plant growth.

Other Micronutrients: A consistant reduction in sheath and plant top Zn followed increasing liming rates. Sheath Zn concentration decreased from 80 ppm in the unlimed treatments to less than 40 ppm when soil pH was raised to 6.7 (Table 13). The corresponding reduction in the cane tops was smaller (20 ppm). In some earlier reports Zn was reduced to the deficiency level in corn and cucumbers by liming, and severe deficiency symptoms were induced in desmodium by liming some Hawaiian soils to around pH 7.0 (Fox and Plucknett, 1964). No Zn deficiency was observed in sugarcane in the current study even at the highest liming rates, probably due to a reasonable application of $ZnSO_4$ (62.5 kg/ha). Juang (1971) reported that Zn uptake was greatly influenced by Fe/Mn ratio. Zn uptake was depressed with high Fe concentration, but was not affected by Mn concentration. Zn concentrations of less than 20 ppm in young cane sheath was considered deficient, while 30 to 40 ppm was considered adequate. The Zn values observed in this experiment were generally at or above the adequate levels reported by Juang. Phosphorus did not show any consistant effect on plant Zn.

Iron availability like that of most other micronutrients is closely

TABLE 13. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON SHEATH Zn (ppm) AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	81	81	76	76	79
5.0*	48	55	32	53	47
5.2*	51	52	49	61	53
5.6*	40	52	48	55	49
5.8	43	47	40	42	43
6.0	38	45	33	39	39
6.7	34	42	36	31	36
Ave	48	53	45	51	

* Replicated treatments

related to soil pH. The more soluble ferrous Fe^{++} is reported to be more abundant at pH 5 and below, while ferric Fe^{+++} dominates at pH 6 and above (Tisdale and Nelson, 1969). High levels of Fe were observed in sheaths and plant tops especially at low pH (Table 14). Raising soil pH reduced sheath Fe markedly. It may be noted that the decrease in Mn in the sheath was greater than the decrease in Fe. Iron deficiency was reportedly observed in soybeans when the Fe:Mn ratio was low. Clements (1962) also reported that high Mn can induce Fe deficiency. In our experiment Fe:Mn was around 2 with no Fe deficiency symptoms. However, when a ratoon crop was allowed to grow in the same field, a chlorosis resembling iron deficiency symptoms developed in the high lime plots.

TABLE 14. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON SHEATH Fe (ppm) AT HARVEST

pH	P 0.006		P 0.025		Ave
	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	$CaCO_3$	
4.7	131	131	147	147	139
5.0*	120	129	111	131	123
5.2*	112	111	116	111	113
5.6*	105	113	104	113	109
5.8	105	101	102	107	104
6.0	98	103	85	109	99
6.7	82	78	91	85	84
Ave	108	109	108	115	

* Replicated treatments

Soil Analysis

CEC: Loss of basic cations by leaching is a major factor in developing soil acidity. Under the intensive leaching conditions prevailing in the humid tropics, this phenomenon can be of important practical concern. Results from this investigation (Table 15) indicated that increasing applications of $CaCO_3$ and $CaSiO_3$ steadily increased cation exchange capacity while phosphorus applications did not have any consistent effect.

The first increments of liming did not raise CEC significantly, which is in agreement with Kamprath (1970) who reported very slight increases in CEC when Ultisols and Oxisols were limed to pH 5.2, but marked increases in CEC when the soils were limed to pH 5.4 and above. Kaolinite predominates in Wahiawa soil and therefore, lime applications cause an increase in pH dependent charge. It is also believed that additional exchange sites are released when adsorbed Al and weak organic acids are precipitated when liming materials are added. The lack of a definite P effect on CEC does not agree with the result of Mekaru and Uehara (1972) who stated that phosphate and other specifically absorbed anions can increase CEC in soils with constant charge colloids. However, their observation was made at much higher P applications.

Soil Ca: Lime application to Wahiawa soil (Tropeptic Eutrustox) significantly increased extractable Ca in the surface soil. Calcium increased from 3.8 me/100g in the control to 10.9 me/100g in the highest liming rate, a nearly two-fold increase. Although calcium was considered sufficient for sugarcane even at the lowest pH, plants probably benefited

TABLE 15. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON CEC (me/100g) OF SURFACE WAHIAWA SOIL

pH	P 0.006		P 0.025		Ave
	$CaCO_3$	$CaSiO_3$	$CaCO_3$	$CaSiO_3$	
4.7	11.2	11.2	10.9	10.9	11.1
5.2*	11.4	11.7	11.0	10.8	11.2
5.6*	11.9	11.5	11.0	12.7	11.8
6.0	13.4	14.8	15.4	14.9	14.6
6.7	15.3	15.9	15.7	16.1	15.8
Ave	12.6	13.0	12.8	13.1	

* Replicated treatments

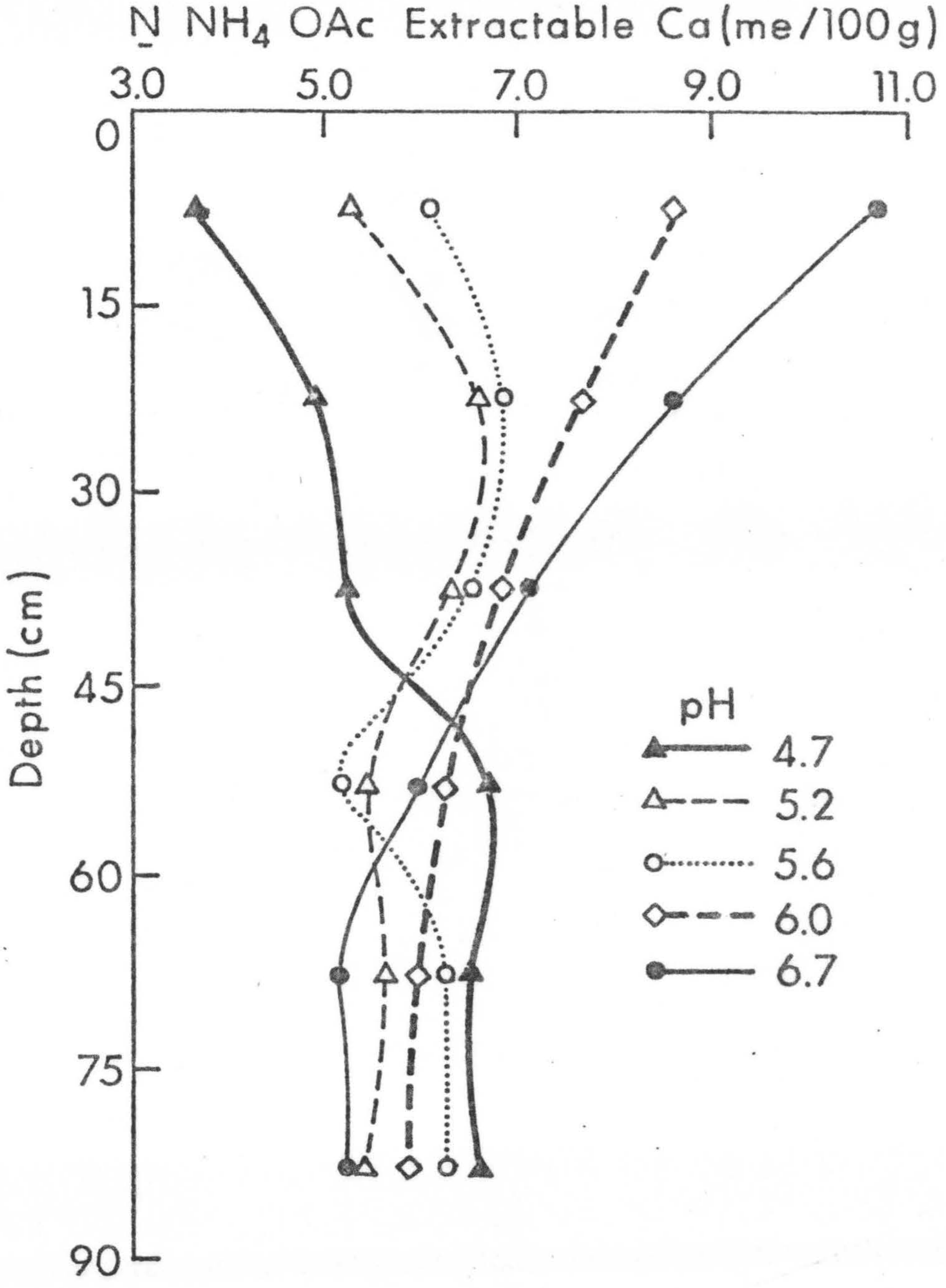


FIGURE 6. EFFECT OF SOIL pH ON N NH_4OAc - EXTRACTABLE Ca IN THE SOIL PROFILE

served for extractable Ca. This gain in extractable K parallels the increase in CEC at the high liming rates.

The profile analysis revealed that a considerable amount of K moved from the surface in the low pH treatment to a depth of 45 cm (Fig. 7). The order of treatments at 45 cm was the reverse of that at the surface. The highest K level in this depth was found in the unlimed treatment. This probably indicates greater K leaching in this treatment with low CEC coupled with the good internal drainage which is characteristic of Wahiawa soil. The high liming rates increased CEC and improved retention of K in the surface soil. This is in agreement with Bartlett and McIntosh (1969) who reported pH dependent K adsorption in a Typic Haplorthod. Similarly Ayres (1961) noted slower K leaching from limed Hawaiian Latosols than from unlimed Latosols. Liming also improves K retention when Ca replaces Al, H, Mn and Fe as the complementary ion on the exchange complex.

Soil Mn: Increasing soil pH by addition of $CaCO_3$ and $CaSiO_3$ decreased extractable Mn in the surface soil (Fig. 8). However, unlike Al, the reduction of Mn solubility was rather gradual. With the first increment of lime Al decreased by 50% (Fig. 10) while the reduction in Mn was only about 14% from the same increment (Figs. 8 and 9). These figures also show that a considerable amount of Mn could still be extracted at the highest pH (6.7) whereas no Al could be detected at this pH. Figure 8 also indicates that $CaSiO_3$ was slightly more effective than $CaCO_3$ in reducing Mn solubility.

The effect of liming on Mn was observed in the soil profile down to the 30 cm depth. The lowest extractable Mn was still associated

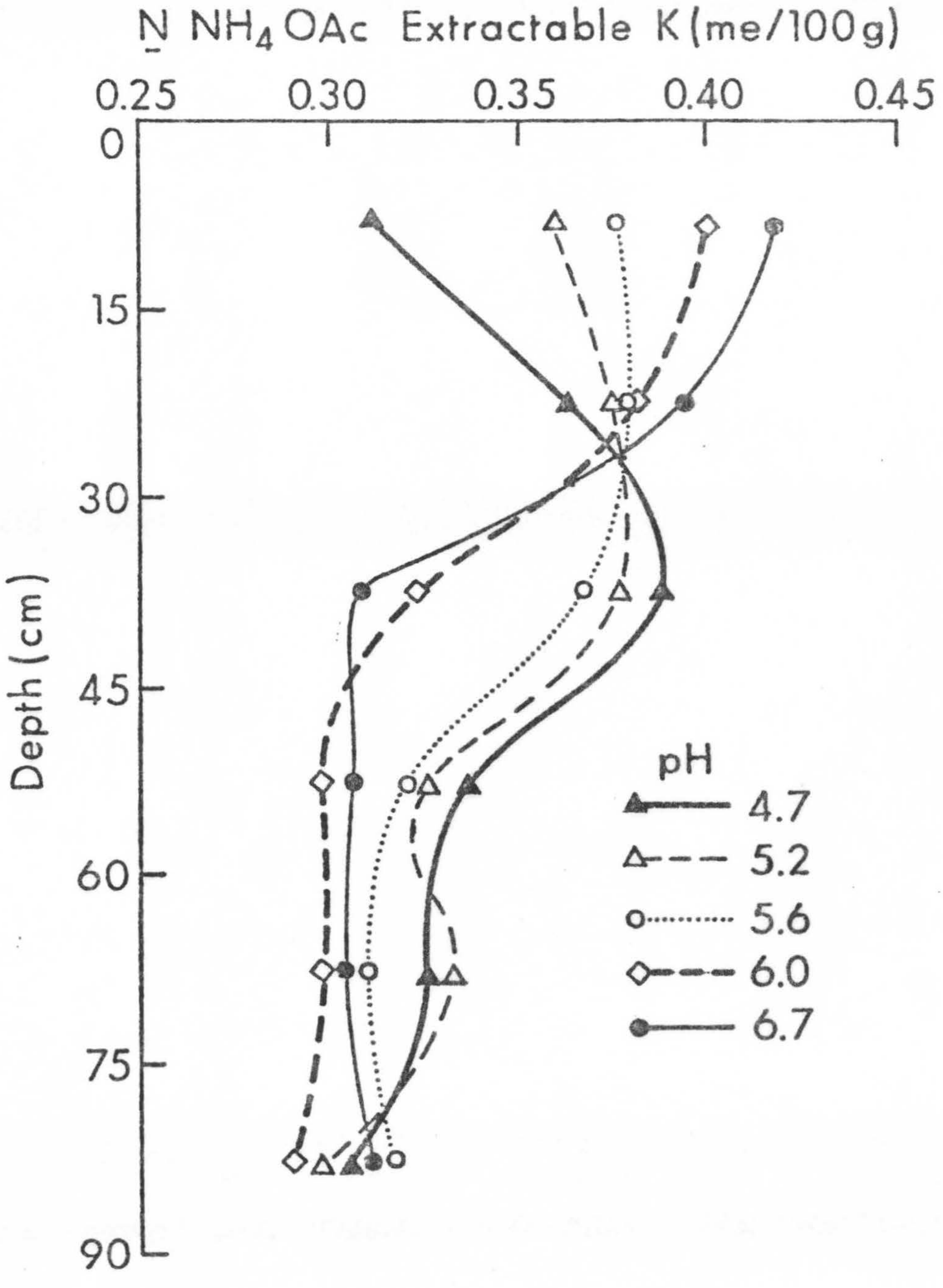


FIGURE 7. EFFECT OF SOIL pH ON N NH$_4$OAc - EXTRACTABLE K IN THE SOIL PROFILE

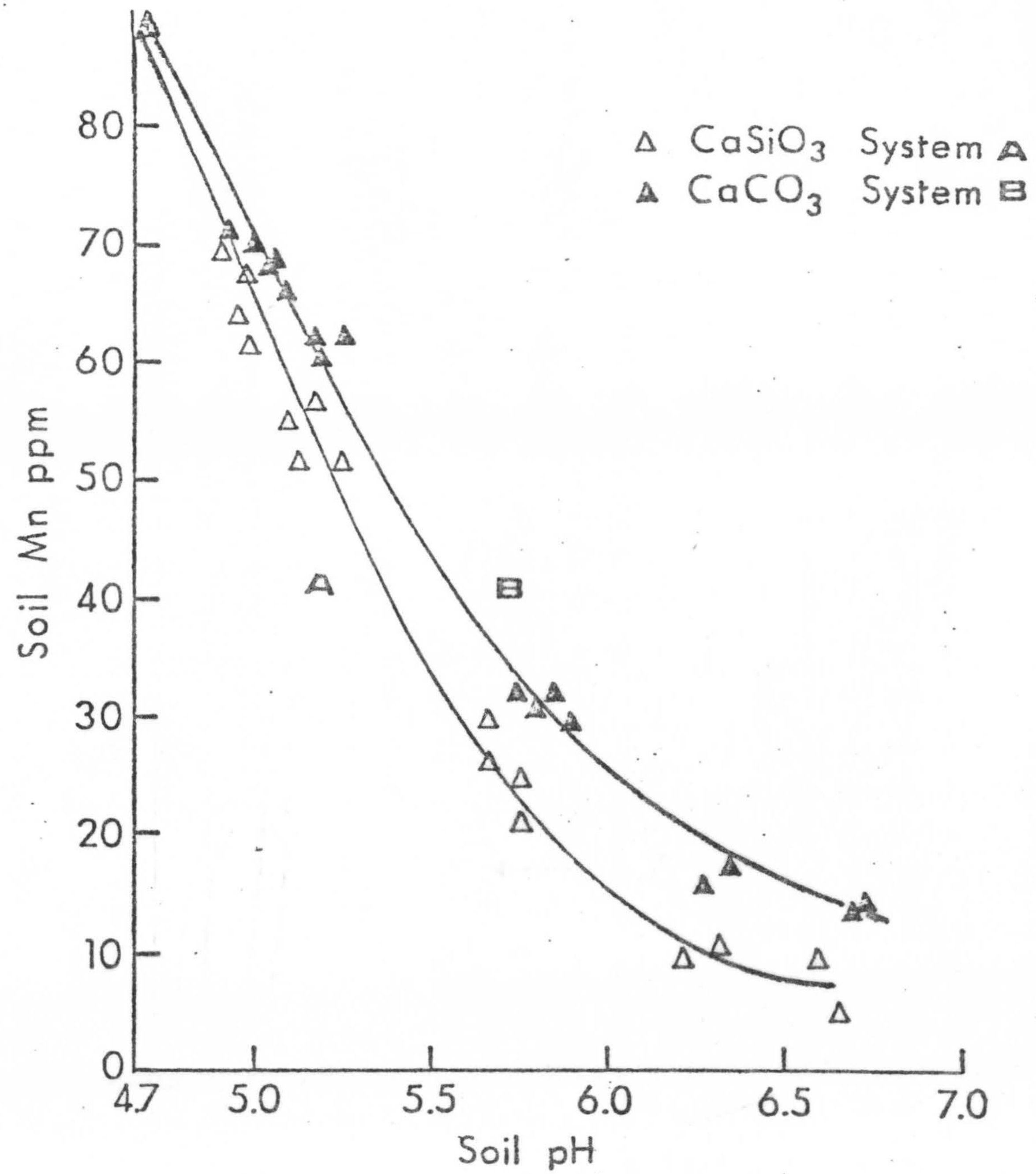


FIGURE 8. EFFECT OF SOIL pH AND LIMING MATERIALS ON N KCl - EXTRACTABLE Mn IN THE SOIL SURFACE

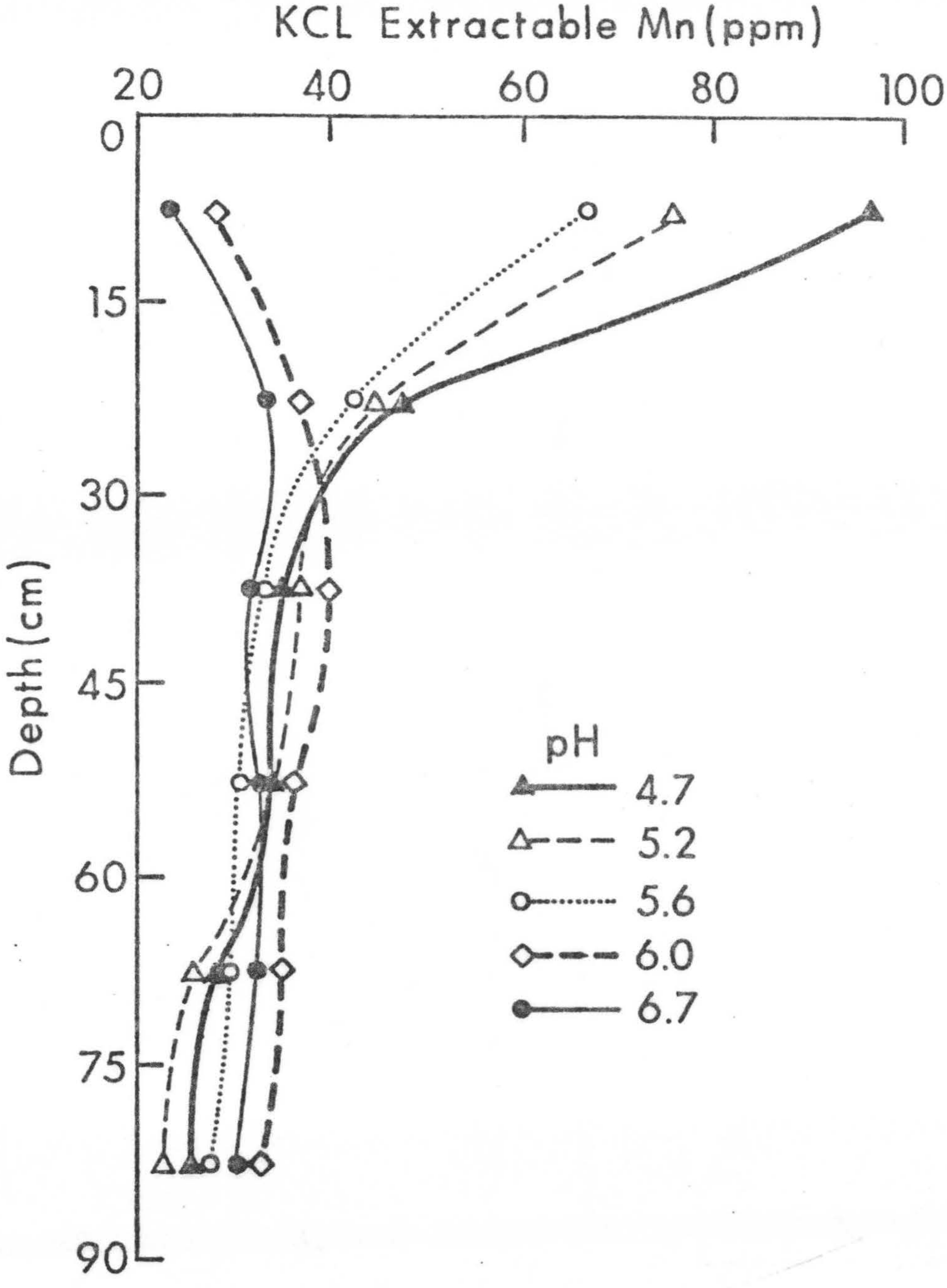


FIGURE 9. EFFECT OF SOIL pH ON KCl - EXTRACTABLE Mn IN THE SOIL PROFILE

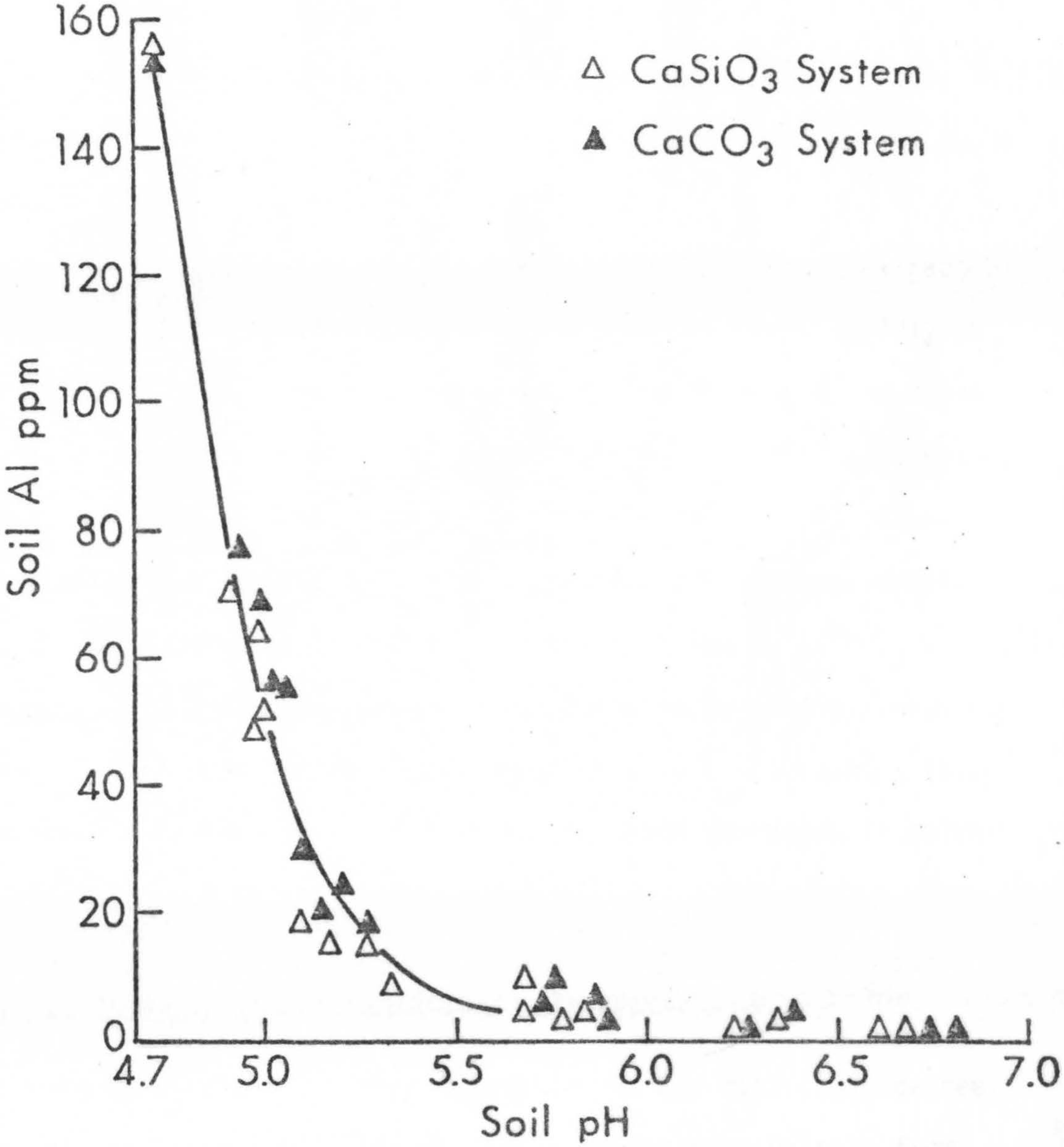


FIGURE 10. EFFECT OF SOIL pH AND LIMING MATERIALS ON KCl- EXTRACTABLE Al

with high liming treatment at the 30 and 45 cm depths. High liming rates effectively decreased Mn in these depths. These Mn values were negatively correlated with the Ca levels discussed previously which is in agreement with the finding of Hirunburana (1974) who demonstrated marked reduction in Mn solubility when Ca was applied as gypsum.

The relatively lower levels of extractable Mn in the deeper profile layers parallels the comparatively higher pH levels observed in these layers.

<u>Soil Al</u>: Both liming materials effectively decreased extractable soil Al (Fig. 10). Aluminum solubility was reduced very rapidly as pH was increased and eventually approached zero at pH 5.6 and above. This strong negative relationship between Al and soil pH has been observed frequently by many workers, (Reeve and Sumner, 1970; Kamprath, 1972; and Pearson, 1975). Al ions adsorbed on the exchange complex of acid colloidal surfaces are said to be precipitated as $Al(OH)_3$ when OH^- concentration in the soil solution is raised by liming. Aluminum saturation decreased steadily as liming rates were increased. This is expected from the dual effect of liming which depresses Al solubility and increases Ca concentration.

<u>P sorption</u>: Traditionally lime has been thought to improve P availability. However, several recent reports indicate that liming soils with $CaCO_3$ did not reduce P sorption to any noticeable degree. Amarasiri and Olsen (1973) reported that liming some Oxisols from Columbia failed to reduce the high P absorption capacity of the test soils. Similarly, Reeve and Sumner (1970) working with several Oxisols from Natal, South Africa found that although lime eliminated exchangeable

Al, it did not affect P fixation.

The P sorption isotherms constructed for the different treatments in the present investigation demonstrate a reduction in P sorption due to the first increment of liming materials as pH was raised from 4.7 to 5.2, but no consistant effect was noticed for the subsequent increments of $CaCO_3$, therefore only curves for pH 4.7 and 6.7 are shown in Figure 11.

Phosphorus sorption increased slightly with application of the highest rate of $CaCO_3$ (pH 6.7). This probably resulted from the increased concentration of Ca^{2+} ions. This is in agreement with reports of Rajan and Fox (1972) who observed marked influence of the ionic environment on phosphate adsorption. Their results indicated that equilibration in solutions containing calcium instead of potassium and increasing ionic strength always decreased phosphorus concentration of equilibrated solutions. Stoop (1974) also observed a decrease in extractable phosphorus in Wahiawa soil as calcium was increased to 2.6 me/100g soil.

Application of P at pH 4.7 decreased P sorption markedly, while application of high rates of $CaSiO_3$ (pH 6.6) without added P resulted in a larger decrease in P sorption. However, the largest decrease occurred with the combined application of P with $CaSiO_3$ to raise the pH to 6.6.

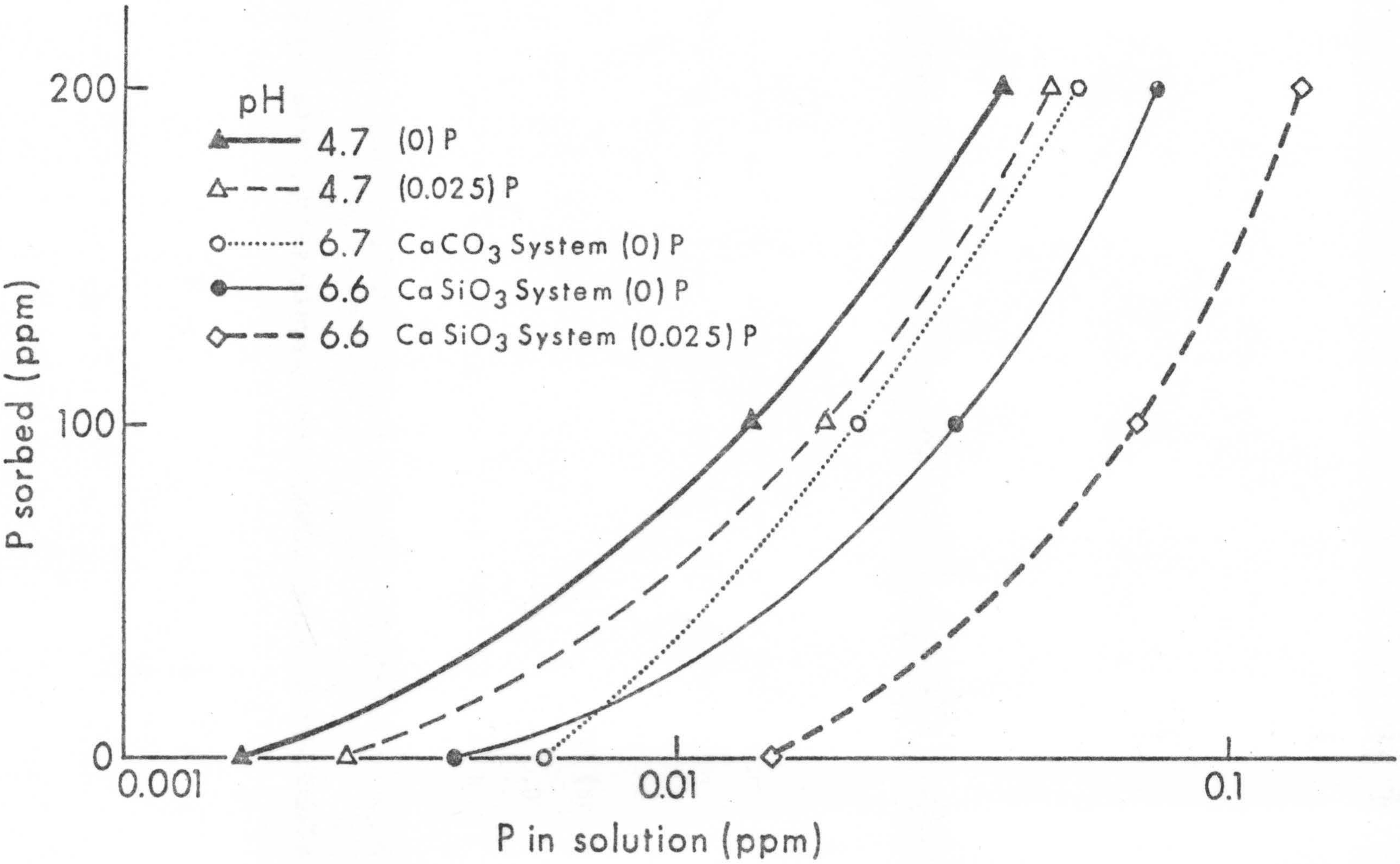


FIGURE 11. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON P SORPTION

Summary and Conclusions

Sugarcane (<u>Saccharum</u> <u>officinarum</u>) yield and nutrient composition were studied in relation to soil pH, liming with $CaCO_3$ and $CaSiO_3$, and P fertilization. The pH levels investigated were 4.7, 5.0, 5.2, 5.6, 5.8, 6.0, and 6.7 obtained by either $CaCO_3$ or $CaSiO_3$. Two P levels; 0.006 and 0.025 ppm P in solution were also included in the study as the main plots. The liming materials were broadcast, thoroughly mixed and equilibrated for three months. P and a blanket application of N, K, Mg, Zn and B were made prior to planting sugarcane (variety H59-3775). Plant samples were collected and analyzed periodically following the crop log system. Surface and profile soil samples were secured and analyzed for pH, CEC, Al and various plant nutrients.

Sugarcane growth and yield were improved by liming the soil to pH levels above 4.7. Miximum yield was obtained at pH 5.8 in the $CaCO_3$ system and at pH 6.0 in the $CaSiO_3$ system. In general, growth (green sheath weight and top weight) was best in the pH range 5.6 to 6.0. Cane yield also responded to P application and increased as much as 38T/ha when P was applied to the unlimed soil.

Plant nutrient composition indicated a significant increase in Ca, Mg and N in various plant tissues with liming. Liming materials supplied Ca and some Mg and improved retention of these elements within the reach of plant roots. The increase in N is probably due to increased microbial activity for organic matter breakdown and non-symbiotic fixation of N when liming supplied Ca and raised soil pH to a favorable level. P in the stalk increased only slightly with the first liming rates and increased significantly with applied P. Sheath K decreased slightly with pH probably due to competition for absorption sites with Ca. K in cane tops was not effected by liming. Mn and Fe concentrations in leaf sheaths and cane tops decreased markedly with liming. This was reasoned to be due to the depressing effect of increasing soil pH on the availability of these elements.

As soil pH was raised by liming, the cation exchange capacity of the surface (0-15 cm) increased substantially. On the average, CEC was 11.1 me/100g at pH 4.7 and 15.8 me/100g at pH 6.7. The increase in CEC resulted in increased retention of Ca and K in the surface against leaching in the soil profile. At pH 4.7 K leached down to the 45-60 cm depth during the crop period. Soil Mn decreased rapidly as pH was increased with both materials, but levels of Mn were lower with $CaSiO_3$ than with $CaCO_3$. Soil Al decreased to nearly zero levels as pH was increased with both liming materials.

Phosphate sorption isotherms suggested that the first increment of liming decreased P sorption probably by reducing Al activity which otherwise could immobilize P by precipitation as Al-phosphate or absorption on the surface of hydrous Al oxide. At the highest pH (6.7) $CaSiO_3$ decreased P sorption possibly by anion exchange. However, the most significant reduction in P sorption was obtained with P application.

Results of this study generally indicated that liming resulted in a favorable nutrient balance for sugarcane growth by enhancing the supply of certain essential elements and depressing the solubility of other elements which otherwise could impede plant growth.

PART II. NUTRIENT CULTURE EXPERIMENT

Much has been done on the effect of soil pH on plant growth, but little work has been done on the direct effect of hydrogen ion concentration on plant growth. This might be due to the difficulties involved in determining direct pH effects in soils. Kamprath and Foy (1971) stated that at pH levels where H ion is expected to be harmful, Al, Mn and perhaps other leements are present in toxic concentrations. Such indirect effects associated with pH make the interpretation of plant responses to soil reaction difficult.

In our field experiments, growth and yield data indicated a response of sugarcane to soil reaction. Therefore, a nutrient culture experiment was initiated to allow closer study of the effect of pH of the root environment on plant growth and nutrient uptake,and to try to secure some evidence on the direct effect of hydrogen ion concentration.

Materials and Methods

Experimental Procedure and the Split Root Technique

A range of solution pH was established at 3 calcium levels, 15, 45, and 90 ppm in solution. Five pH levels, 3.0, 4.0, 5.5, 6.5, and 8.5, were established in the medium (45 ppm) calcium level and 3 pH levels, 4.0, 5.5, 6.5, were maintained in the low (15 ppm) and the high (90 ppm) calcium treatments. $Ca(NO_3)_2$ was used to establish the Ca levels and equivalent amounts of HNO_3 were used to equalize the NO_3 ion. The treatments were completely randomized in the greenhouse with 3 replications. Containers used were 10 liter crocks covered with wooden lids 12" in diameter. A 3" hole was made in the lid through which the plant grew. The container was filled with 1/8 strength Hoagland's solution containing macro-nutrients, Ca, Mg, K and N, with pH adjusted to the appropriate treatment level with either 1N H_2SO_4 or 1N NaOH. A one-quart plastic container which was suspended inside the crock with monofilament line (Fig. 12) was filled with a solution containing nutrients sensitive to pH, i.e., P, Zn, Mn, Fe and B. The pH in the plastic containers was kept at about 5.2. This was done to minimize the effect of pH on availability of P and micronutrients. A sugarcane plant was supported on the lid over the container and a few roots were led into the one-quart container while the main mass of roots was allowed to grow in the larger container.

Establishment of cane plants

Sugarcane stalks (var H59-3775) of similar size were selected for seed material from the check plots of the field experiment. One-eye seed pieces were cut from the middle section of the stalk so that there was 1½" of internode tissue on either side of each node. Several seed pieces were kept for analysis to estimate nutrients in the seedpiece which may be translocated to the cane plant. Seed pieces were tied horizontally on a wax-coated screen and placed in distilled water so that the buds were partially above the surface. Three weeks after germination, the distilled water was replaced with ¼ strength Hoagland's solution which was continuously aerated. Plants were allowed to grow

FIGURE 12. SUGARCANE ROOTS SPLIT INTO 2 CONTAINERS

until shoot roots had developed, then the seed pieces and attached seedpiece roots were removed. After the plants had recovered, uniform plants were selected for use in the experiment.

pH Control

Reasonable control of solution pH was maintained with the use of large volumes of dilute solutions which were changed frequently (generally twice a week). Air was continuously bubbled into both containers. pH was checked frequently and adjusted with either 1N H_2SO_4 or 1N NaOH, throughout most of the experiment.

Harvesting

Sugarcane was allowed to grow for 10 weeks then harvested, after plant height and number of tillers were recorded. Plants were then separated into shoots and roots and the fresh weight of each section was obtained. Shoots were separated into primary (P) and secondary (S). Then each plant was further divided into spindle cluster (leaves and sheaths No. 2 and younger), sheaths and blades 3-6, green leaf (GL) blades and sheaths (blades and sheaths No. 7 and older) and stalks. The roots were wrapped in nylon netting and dipped repeatedly in 0.5N HCl for 5 seconds and rinsed 3 times with distilled water. Portions of all tissues were kept for moisture determination and chemical analysis. Plant samples were prepared and analysed as described under chemical analysis in Part I.

Results and Discussion

Results of this investigation revealed that growth of sugarcane plants was severely restricted in the pH 3.0 treatment (Fig. 13). As shown in Fig. 14, little root growth occurred at this pH. Plant roots when immersed into the solution turned dark after a few days and finally died. The extreme acidity at this pH may have caused hydrolysis of plant cell membranes. Roots remaining above the solution escaped direct acid injury and kept some plants alive until just before the termination of this experiment, although there was no increase in root growth. Some absorption of moisture possibly occurred in the humid area above the solution.

Figure 13 shows a statistically significant ($P < 0.5$) increase in growth as solution pH was raised to 4.0. However, plant growth at this pH was still significantly less than that at pH 5.5 and 6.5. Similar observations were also reported by Arnon (1942) and Black (1968); these authors attributed the reduction in growth, at high H ion concentration, to decreased uptake of the basic cations due to competition with H ions for absorption sites. The greatest growth of plant shoots and roots occurred at pH 5.5, 6.5, and 8.5 with no significant differences between these treatments. Increasing Ca concentration increased plant growth noticeably at pH 4.0, but had little effect on growth at pH 5.5 and 6.5 (Fig. 15).

On the alkaline end of the treatment range, pH 8.5, some reduction in growth was observed, but unlike pH 3.0, all plants remained healthy,

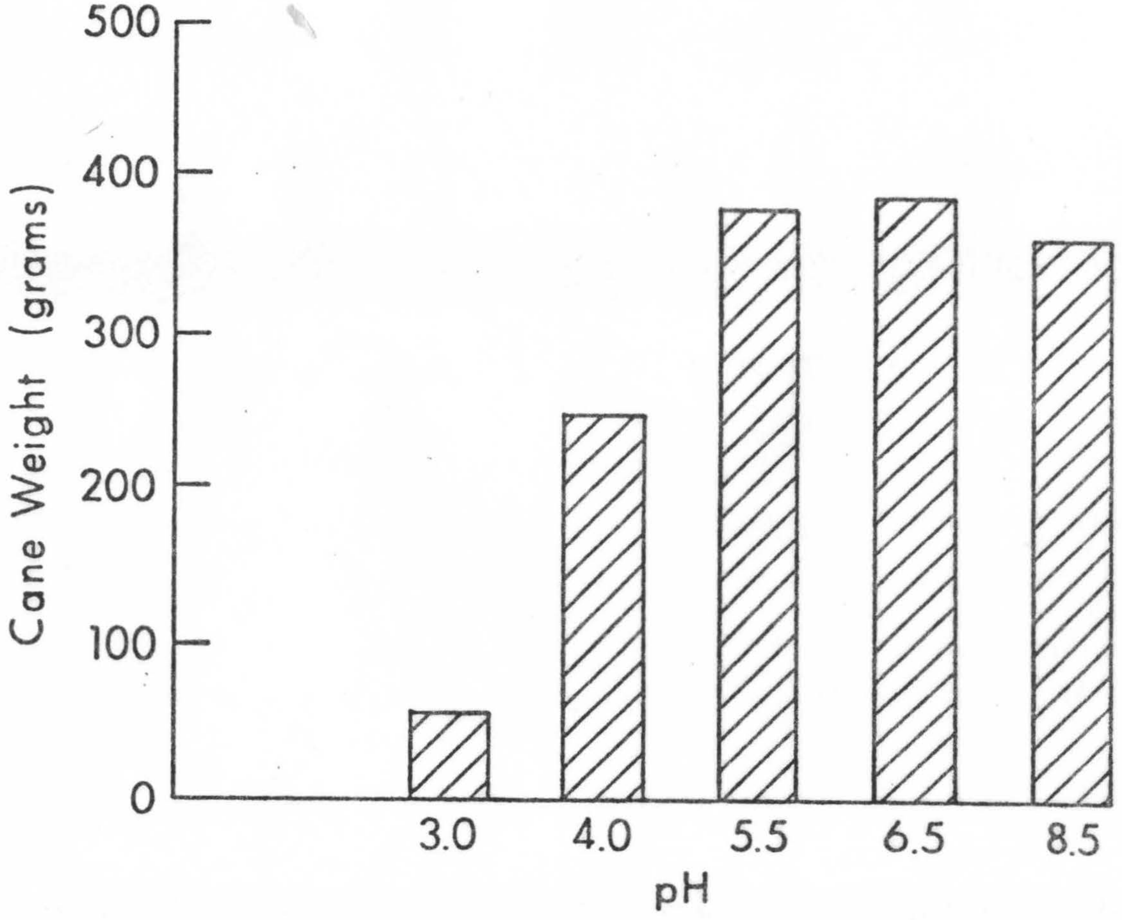


FIGURE 13. EFFECT OF SOLUTION pH ON YIELD OF SUGARCANE

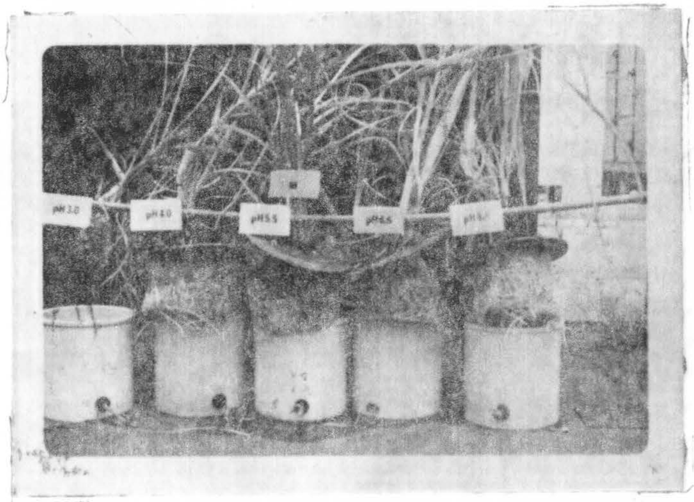


FIGURE 14. EFFECT OF SOLUTION pH ON SUGARCANE ROOT GROWTH

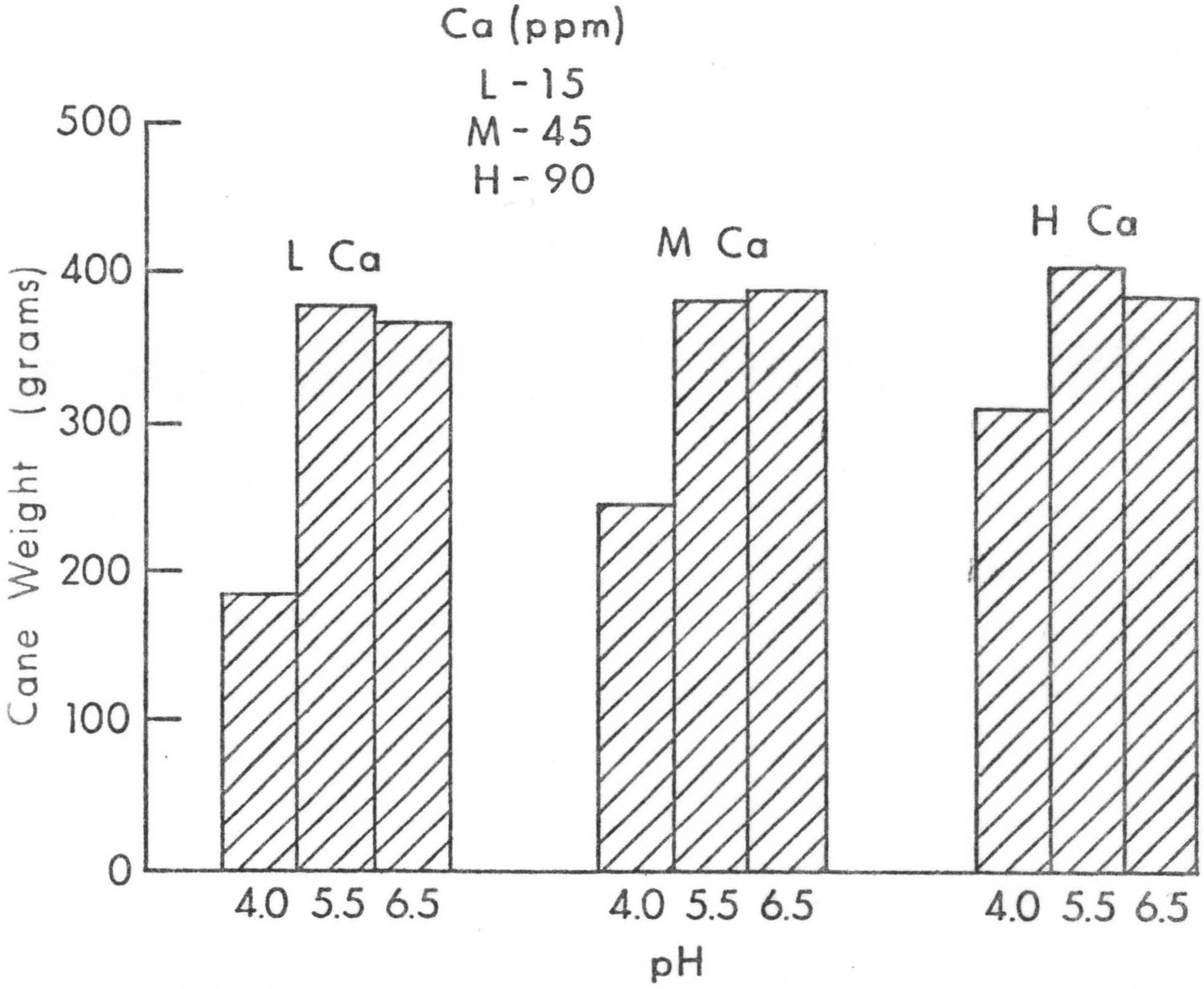


FIGURE 15. EFFECT OF SOLUTION pH AND Ca SUPPLY ON GROWTH OF SUGARCANE

with viable roots and noticeable increase in growth. Interveinal yellowing of leaves, believed to be Fe deficiency, was observed in this treatment. Plant tissue analysis confirmed this as low Fe concentrations were found in plant tops at pH 8.5 (Table 16). Since Fe was supplied in a separate container kept at pH 5.2, deficiency was not expected. However, it may be possible that Fe absorbed at pH 5.2 precipetated in the stalks due to ion imbalance. The fact that Fe concentration increased markedly in the stalks at pH 8.5, but decreased in the leaf and sheath tissues suggest Fe accummulation in the stalks. Calcium levels also increased in the stalks at pH 8.5.

Plant nutrient analysis showed a strong relationship between calcium absorption and solution pH. Absorption as reflected in percent tissue Ca increased as pH was raised above 4.0 at all 3 calcium levels (Fig. 16 and Appendix Table 9). Absorption was minimal in the low calcium treatment at pH 4.0 and in the medium calcium treatment at pH 3.0. Possibly, high H ion concentration reduced Ca absorption by competition when Ca supply was low. Absorption in the low calcium treatment increased steadily at pH 5.5 and 6.5. In the medium calcium treatment, a marked increase in absorption occurred as solution pH was raised to 4.0 This was followed by a smaller increase at pH 5.5 and then Ca absorption remained unchanged with further increases in pH. The high calcium treatment partially offset the harmful effects of the high concentration of H ions on Ca absorption. This is shown by the slightly higher tissue Ca levels in the high Ca treatment.

TABLE 16: INFLUENCE OF pH AND Ca CONCENTRATION ON THE IRON CONTENT (ppm) OF SUGARCANE TISSUES+

pH	MEDIUM Ca					LOW Ca			HIGH Ca		
CANE TISSUE	3.0	4.0	5.5	6.5	8.5	4.0	5.5	6.5	4.0	5.5	6.5
SPINDLE CLUSTER		80	67	53	23	38	47	43	59	45	46
SHEATHS 3-6		55	57	52	22	62	50	54	60	63	56
BLADES 3-6	11	40	39	42	19	45	49	43	46	57	52
GL SHEATHS		79	49	49	21	53	52	48	50	42	37
GL BLADES		64	51	48	27	40	39	51	38	47	40
P STALKS	6	52	40	50	63	42	37	49	51	41	48
S LEAVES		42	26	47	39	41	45	52	37	53	45
S STALKS		37	41	32	51	-	36	41	39	46	36
ROOTS		24	19	17	21	20	17	19	23	15	26

+ Average of 3 replications

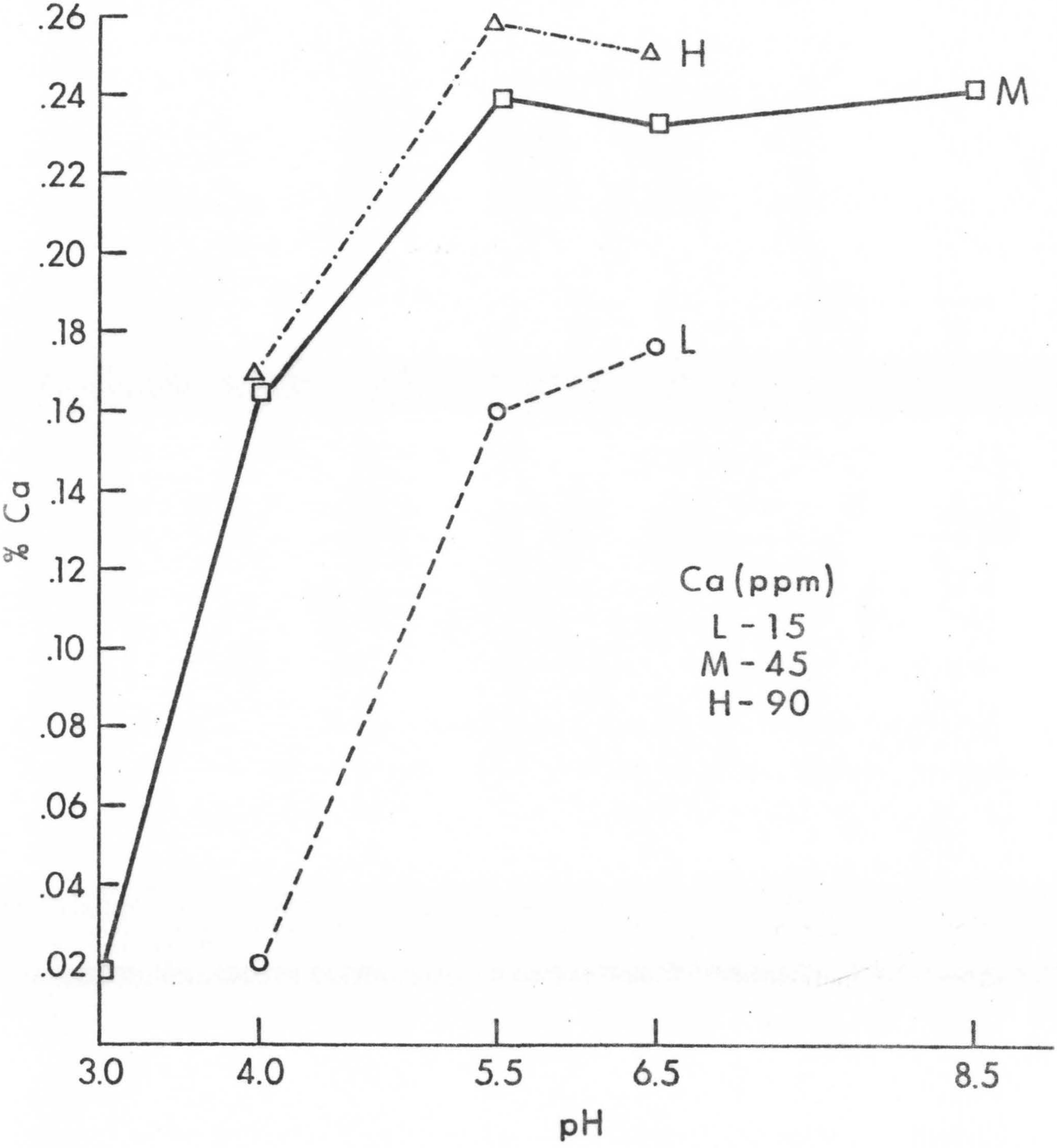


FIGURE 16. EFFECT OF SOLUTION pH AND Ca SUPPLY ON Ca CONTENT OF SUGARCANE LEAF SHEATHS

Nevertheless, the pH effect was still evident as tissue Ca increased from pH 4.0 to pH 5.5 Calcium levels were highest in blades and sheaths 3-6 and were lowest in roots and stalks. All tissues reflected the Ca differently.

Sheath K increased significantly from 0.9% at pH 3.0 to approximately 2.0% at pH 4.0 (Fig. 17). There was a smaller increase as solution pH was raised to 5.5 and 6.5. The highest concentration of sheath K (2.8%) was observed at pH 8.5. Since plants were somewhat smaller in this treatment than in the pH 5.5 and 6.5 treatments, this apparently high K may partially be due to a concentration effect. K concentration increased rapidly in the spindle cluster and the primary stalk as solution pH was raised above 3.0, and in all plant tissues when pH was raised above 4.0. Stalks contained the highest % K and showed the most pronounced increase in K concentration with pH, while roots contained the lowest % K and showed only slight increases in K concentration with pH. Comparatively low plant K concentrations were obtained in the high Ca treatment, probably indicating competition with Ca ions.

Phosphorus concentration was generally lower at pH 4.0 than at higher pH levels (Table 17). Leaf and stalk P increased consistently as solution pH was raised to 5.5 and above in the medium and high Ca treatments. The low Ca treatment did not show a definite trend. No decrease in P absorption was observed at pH 8.5, in fact, higher P values in leaf sheaths and blades were observed at pH 8.5. This is probably the result of the split-root technique in whic P was supplied

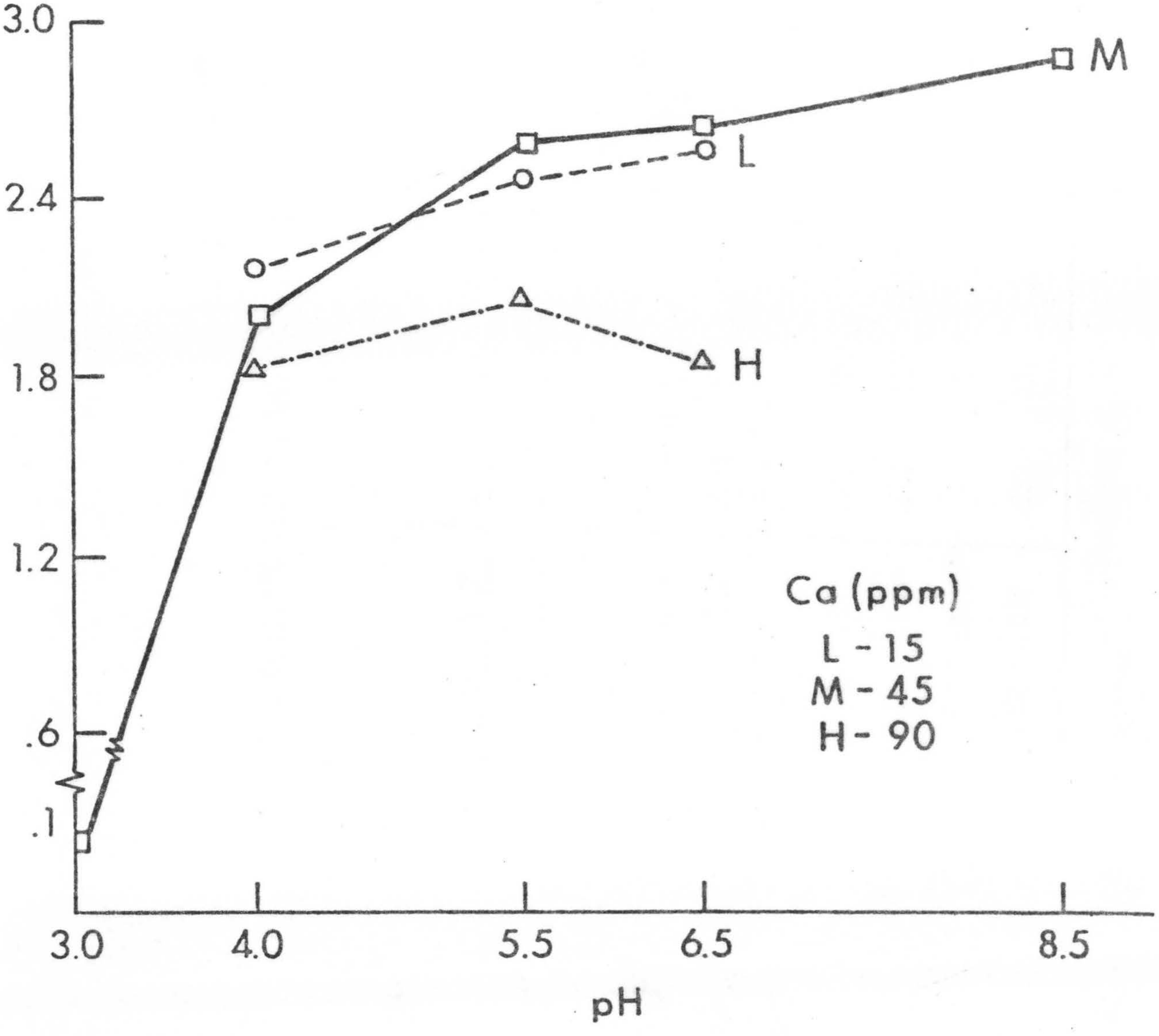


FIGURE 17. EFFECT OF SOLUTION pH AND Ca SUPPLY ON K CONTENT OF SUGARCANE LEAF SHEATHS

TABLE 17: INFLUENCE OF pH AND Ca CONCENTRATION ON THE PHOSPHORUS CONTENT (%) OF SUGARCANE TISSUES +

pH	MEDIUM Ca					LOW Ca			HIGH Ca		
CANE TISSUE	3.0	4.0	5.5	6.5	8.5	4.0	5.5	6.5	4.0	5.5	6.5
SPINDLE CLUSTER		.101	.120	.143	.141	.107	.114	.120	.110	.105	.126
SHEATHS 3-6	.001	.08	.113	.114	.131	.112	.109	.118	.090	.101	.106
BLADES 3-6		.107	.152	.136	.203	.123	.119	.134	.063	.111	.113
GL SHEATHS		.100	.114	.113	.180	.098	.121	.127	.110	.108	.120
GL BLADES		.09	.108	.111	.116	.104	.117	.106	.114	.125	.115
P STALKS	.003	.112	.135	.142	.121	.063	.102	.113	.112	.167	.129
S LEAVES		.115	.125	.114	.133	.087	.113	.124	.118	.142	.133
S STALKS		-	.121	.107	.119	-	.099	.114	.108	.130	.116
ROOTS		.031	.071	.052	.050	.032	.037	.056	.073	.080	.069

\+ Average of 3 replications

in a separate container with pH maintained at 5.2.

Fe and Mn concentrations in the leaf and sheath tissues were generally lower in the pH 8.5 treatment (Tables 16 and 18). Fe showed a tendency to accumulate in the primary and secondary stalk tissues in this treatment, while Mn accumulated only in the primary stalks. There were generally lower Mn concentrations in the blades and sheath tissues of the high Ca treatment than in the medium Ca treatment, while stalk Mn levels were highest in the high Ca treatment. This may indicate that although Mn was taken up readily at pH 5.2 in the micronutrient container, it precipitated in the stalks due to the high Ca uptake in the high Ca treatment. A similar trend was not found between the medium and the low Ca treatments.

TABLE 18: INFLUENCE OF pH AND Ca CONCENTRATION ON THE MANAGANESE CONTENT (ppm) OF SUGARCANE TISSUES+

pH	MEDIUM Ca					LOW Ca			HIGH Ca		
CANE TISSUE	3.0	4.0	5.5	6.5	8.5	4.0	5.5	6.5	4.0	5.5	6.5
SPINDLE CLUSTER		38.5	30.8	32.5	24.0	31.0	30.7	28.8	30.1	27.1	31.0
SHEATHS 3-6		34.0	32.2	36.0	18.5	29.6	30.2	31.3	29.4	28.5	27.6
BLADES 3-6	17.0	30.5	29.9	31.0	22.0	27.5	25.4	19.6	24.0	25.6	25.7
GL SHEATHS		26.6	28.7	28.5	29.0	30.5	25.6	26.0	19.8	20.1	23.4
GL BLADES		29.9	26.0	19.5	20.7	27.8	27.0	29.2	31.7	29.2	24.9
P STALKS		25.0	24.0	25.6	36.6	40.2	26.7	29.6	30.5	28.3	31.4
S LEAVES		27.9	28.3	24.0	23.5	28.0	28.4	28.9	25.6	23.1	23.9
S STALKS		-	26.2	27.1	17.5	-	24.0	26.1	26.1	18.6	22.3
ROOTS		23.0	25.5	24.4	28.1	24.7	21.1	19.3	25.0	17.0	20.1

+ Average of 3 replications

Summary and Conclusions

Results of this investigation indicated that the H ion concentration at pH 3.0 drastically curtailed nutrient absorption and resulted in complete failure of plant growth. Plants benefitted markedly from increasing Ca concentration in the nutrient solution at pH 4.0 and only slightly at higher pH levels. However, high H ion concentration reduced growth and adversely affected nutrient uptake even at the highest Ca level (90 ppm). As solution pH was raised above 4.0, the increase in plant growth was statistically significant, but there were no significant differences in growth between the higher pH treatments. This was due to the split-root technique which was used to minimize the effect of pH on availability of P and micronutrients. Normally, at the alkaline end of the pH range, a decrease in growth would be expected due to unavailability of micronutrients and P as reported by Arnon (1942) and Arnon and Johnson (1942). Symptoms of Fe deficiency occurred at pH 8.5, in spite of the split-root technique, and it appears that the Fe absorbed was precipitated in the stalks. Concentrations of nutrients varied in the different plant parts in response to the pH and Ca treatments.

It is apparent from this study that H ion concentration (pH) per se can affect plant growth and nutrient uptake. However, this effect is greatest at low pH, i.e., pH $\leq$ 4.0, with no apparent effect in the pH range of 5.5 - 6.5 which is generally considered optimum for sugarcane.

General Summary and Conclusions

Sugarcane yield and nutrient composition were studied in a field and a nutrient culture experiment. The field experiment was conducted to determine the optimum pH for sugarcane and to evaluate the effectiveness of $CaSiO_3$ and $CaCO_3$ as liming materials and also, to determine the P x pH interaction with the two liming materials.

The pH levels investigated in the field experiment were 4.7, 5.0, 5.2, 5.6, 5.8, 6.0 and 6.7 obtained with either $CaSiO_3$ or $CaCO_3$. Sugarcane growth and yield in the field were significantly improved by liming the soil to pH levels above 4.7. Maximum yield was obtained at pH 5.8 in the $CaCO_3$ system and at 6.0 in the $CaSiO_3$ system.

Plant Ca, Mg, and N increased significantly with lime application as did CEC in the surface soil. Leaching of K and Ca was reduced by lime applications due to the increased retention of cations. Plant Al, Mn and Fe were markedly decreased by lime applications. Soil Al and Mn also dropped to very low levels with application of liming materials and $CaSiO_3$ was more effective than $CaCO_3$ in reducing soil Mn levels. Phosphorus sorption was reduced by P application, and increasing soil pH above 4.7. The greatest decrease in P sorption was obtained with the application of P and the highest rate of $CaSiO_3$ (pH 6.6).

The nutrient culture experiment compared three Ca levels, 15, 45, and 90 ppm, in solution and five pH levels 3.0, 4.0, 5.5, 6.5 and 8.5. A split-root technique was used to separate nutrient whose solubility was affected by pH from the pH differential and then nutrients were maintained at pH 5.2 in a separate container.

The hydrogen-ion concentration at pH 3.0 was toxic to sugarcane roots and plants eventually died. Although sugarcane grew at pH 4.0, growth increased significantly as pH was raised above 4.0. No significant difference in growth were found among the higher pH treatments. Plants benefitted markedly from increasing Ca concentration in the nutrient solution at pH 4.0 and only slightly at higher pH levels.

It is apparent from this study that H ion concentration (pH) per se can affect plant growth and nutrient uptake. However, this effect is greatest at low pH, i.e., pH $\leq$ 4.0, with no apparent effect in the pH range of 5.5 - 6.5 which is generally considered optimum for sugarcane.

APPENDIX

TABLE 1. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON SUGARCANE YIELD (T/ha)

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P \ pH		4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	269.5	282.9	247.3	282.9	287.8	-	-	269.5	272.4	236.5	256.9	281.8	-	274.5
	P 0.025	262.5	269.5	234.3	263.6	-	319.9	302.4	262.5	261.4	227.4	262.5	-	279.3	-
Rep II	P 0.006	174.2	266.1	241.9	268.6	-	281.3	271.9	174.2	249.8	260.7	274.6	-	236.1	-
	P 0.025	257.4	267.7	290.1	258.5	295.9	-	-	257.4	248.9	247.1	279.6	314.7	-	254.9
pH Ave		240.9	271.6	253.4	268.4	291.9	300.6	287.2	240.9	258.1	242.9	268.4	298.3	257.7	264.7

Check plot 240.5

pH x Liming Materials+

LM \ pH	5.0	5.2	5.6
$CaSiO_3$	271.6	253.4	268.4
$CaCO_3$	258.1	242.9	268.4

pH x P+

P \ pH	5.0	5.2	5.6
P 0.006	267.8	246.6	270.8
P 0.025	261.9	249.7	266.1

LM \ P	P 0.006	P 0.025
$CaSiO_3$	261.3 95.1	274.7 100
$CaCO_3$	96.2% 253.4	100% 263.2

+ Means of replicated treatments

TABLE 2. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON STALK CENSUS (STALKS/m^2)

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P \ pH		4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.5	5.8	6.0	6.7
Rep I	P 0.006	10.8	10.1	8.1	9.5	8.7	-	-	10.8	8.5	7.9	7.9	8.6	-	9.2
	P 0.025	9.4	9.4	7.2	8.7	-	10.5	10.1	9.4	7.7	8.4	8.2	-	9.3	-
Rep II	P 0.006	6.0	9.7	6.5	7.2	-	9.3	8.6	6.0	7.9	8.3	7.7	-	8.2	-
	P 0.025	8.7	7.3	10.6	7.6	9.9	-	-	8.7	7.2	7.7	9.7	8.8	-	9.9
pH Ave		8.7	9.1	8.1	8.3	9.3	9.9	9.3	8.7	7.8	8.1	8.4	8.7	8.7	9.6

Check plot 8.2

pH x Liming Materials+

LM \ pH	5.0	5.2	5.6
$CaSiO_3$	9.1	8.1	8.3
$CaCO_3$	7.8	8.1	8.4

pH x P+

P \ pH	5.0	5.2	5.6
P 0.006	9.1	7.7	8.1
P 0.025	7.9	8.5	8.6

LM \ P	P 0.006	P 0.025
$CaSiO_3$	8.6	9.0
$CaCO_3$	7.5	8.6

+ Menas of replicated treatments

TABLE 3. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % STALK Ca AT HARVEST

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	0.04	0.06	0.05	0.07	0.07	-	-	0.04	0.04	0.06	0.06	0.07	-	0.09
	P 0.025	0.05	0.05	0.06	0.10	-	0.08	0.11	0.05	0.05	0.07	0.08	-	0.10	-
Rep II	P 0.006	0.05	0.04	0.06	0.06	-	0.10	0.12	0.05	0.06	0.06	0.08	-	0.09	-
	P 0.025	0.05	0.07	0.07	0.08	0.11	-	-	0.05	0.05	0.06	0.09	0.07	-	0.11
pH Ave		0.05	0.06	0.06	0.08	0.09	0.09	0.12	0.05	0.05	0.06	0.08	0.07	0.10	0.10

Check plot 0.05

pH x Liming Materials+

LM \ pH	5.0	5.2	5.6
$CaSiO_3$	0.06	0.06	0.08
$CaCO_3$	0.05	0.06	0.08

pH x P+

P \ pH	5.0	5.2	5.6
P 0.006	0.05	0.06	0.06
P 0.025	0.05	0.06	0.09

Liming Materials x P+

LM \ pH	P 0.006	P 0.025
$CaSiO_3$	0.07	0.08
$CaCO_3$	0.07	0.07

+ Means replicated treatments

TABLE 4. EFFECT OF pH, LIMING MATERIALS AND P ON % SHEATH Ca AT HARVEST

Liming Materials (LM)		CaSiO$_3$ System							CaCO$_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	0.17	0.21	0.24	0.23	0.24	-	-	0.17	0.20	0.22	0.22	0.24	-	0.26
	P 0.025	0.19	0.21	0.23	0.24	-	0.23	0.30	0.19	0.22	0.20	0.23	-	0.24	-
Rep II	P 0.006	0.21	0.20	0.22	0.23	-	0.25	0.29	0.21	0.21	0.23	0.23	-	0.25	-
	P 0.025	0.22	0.23	0.24	0.25	0.25	-	-	0.22	0.23	0.24	0.24	0.21	-	0.26
pH Ave		0.20	0.22	0.23	0.24	0.23	0.24	0.30	0.20	0.22	0.22	0.23	0.23	0.25	0.26

Check plot 0.21

pH x Liming Materials$^+$

LM / pH	5.0	5.2	5.6
CaSiO$_3$	0.22	0.23	0.24
CaCO$_3$	0.22	0.22	0.23

pH x P$^+$

P / pH	5.0	5.2	5.6
P 0.006	0.20	0.23	0.23
P 0.025	0.22	0.23	0.24

Liming Materials x P$^+$

LM / P	P 0.006	P 0.025
CaSiO$_3$	0.23	0.24
CaCO$_3$	0.22	0.23

+ Means of replicated treatments

TABLE 5. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON % SHEATH K AT HARVEST

Liming Materials (LM)		CaSiO$_3$ System							CaCO$_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.1	5.3	5.6	5.8	6.0	6.7
Rep I	P 0.006	2.7	3.1	3.4	2.5	3.1	-	-	2.7	3.4	3.3	2.9	3.0	-	2.8
	P 0.025	3.2	2.9	3.8	3.0	-	2.7	2.6	3.2	3.6	3.7	3.1	-	2.9	-
Rep II	P 0.006	3.4	3.5	3.0	3.1	-	2.9	2.5	3.4	3.1	3.4	2.8	-	3.1	-
	P 0.025	3.7	2.7	3.3	3.1	2.9	-	-	3.7	3.4	3.6	2.9	2.8	-	2.9
pH Ave		3.3	3.1	3.3	3.0	3.0	2.8	2.6	3.3	3.4	3.5	2.9	2.9	3.0	2.9

Check plot 3.1

pH x Liming Materials+

LM	pH	5.0	5.2	5.6
CaSiO$_3$		3.1	3.3	2.9
CaCO$_3$		3.4	3.5	2.6

pH x P+

P	pH	5.0	5.2	5.6
P 0.006		3.4	3.4	2.8
P 0.025		3.1	3.5	2.7

Liming Materials x P+

LM	pH	P 0.006	P 0.025
CaSiO$_3$		3.1	3.1
CaCO$_3$		3.3	3.0

+ Means replicated treatments

TABLE 6. EFFECT OF SOIL pH, LIMING MATERIALS AND P ON SHEATH Al (ppm) AT HARVEST

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	200	120	129	109	114	-	-	122	128	100	108	105	-	75
	P 0.025	122	109	131	100	-	72	89	200	130	101	113	-	107	-
Rep II	P 0.006	140	119	95	101	-	98	100	140	121	123	118	-	106	-
	P 0.025	132	96	111	106	105	-	-	132	119	119	115	110	-	105
pH Ave		147	111	116	104	109	85	95	147	131	111	103	117	106	90

Check plot 135

pH x Liming Materials+

LM / pH	5.0	5.2	5.6
$CaSiO_3$	111	116	104
$CaCO_3$	131	113	111

pH x P+

P / pH	5.0	5.2	5.6
P 0.006	120	112	105
P 0.025	102	121	103

Liming Materials x P+

LM / pH	P 0.006	P 0.025
$CaSiO_3$	112	111
$CaCO_3$	118	119

+ Means replicated treatments

TABLE 7. EFFECT OF SOIL pH, LIMING MATERIALS, AND P ON SHEATH Mn (ppm) AT HARVEST

Liming Materials (LM)		$CaSiO_3$ System							$CaCO_3$ System						
P	pH	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
Rep I	P 0.006	166	121	114	106	78	-	-	166	133	119	89	89	-	83
	P 0.025	142	111	118	98	-	92	79	142	130	121	114	-	82	-
Rep II	P 0.006	126	129	104	87	-	72	77	126	110	106	90	-	81	-
	P 0.025	152	105	96	101	86	-	-	152	107	113	118	88	-	77
pH Ave		147	117	108	98	82	82	78	147	120	115	103	89	82	80

Check plot 148

pH x Liming Materials+

LM \ pH	5.0	5.2	5.6
$CaSiO_3$	117	108	98
$CaCO_3$	120	115	103

pH x P+

P \ pH	5.0	5.2	5.6
P 0.006	123	111	93
P 0.025	113	112	108

Liming Materials x P+

LM \ P	P 0.006	P 0.025
$CaSiO_3$	107	93
$CaCO_3$	108	113

+ Means of replicated treatments

TABLE 8 . EFFECT OF LIMING MATERIALS ON SOIL FURFACE AND PROFILE pH AFTER HARVEST

	CaSiO$_3$ System							CaCO$_3$ System						
Applied lime t/ha	-	0.7	2.4	4.9	5.2	11.1	24.2	-	0.6	2.1	4.2	4.4	9.5	20.8
Depth (cm)														
0-15	4.7	5.0	5.2	5.5	5.8	6.0	6.6	4.7	5.0	5.2	5.6	5.8	6.0	6.7
15-30	5.2	5.3	5.3	5.2	5.6	5.9	6.1	5.0	5.2	5.5	5.6	5.6	6.0	6.3
30-45	6.1	6.0	6.3	6.0	5.9	6.2	6.0	6.1	5.8	5.9	6.1	6.0	6.1	6.2
45-60	5.9	6.1	6.2	5.9	6.1	5.9	6.0	5.9	6.1	6.0	6.1	6.2	6.2	6.0
60-75	6.2	6.3	6.1	6.3	6.2	6.2	6.1	6.3	6.2	6.2	6.3	6.1	6.1	6.2
75-90	6.2	6.2	6.1	6.3	6.1	6.3	6.2	6.2	6.3	6.1	6.2	6.0	6.2	6.2

TABLE 9 : INFLUENCE OF pH AND Ca CONCENTRATION ON THE CALCIUM CONTENT (%) OF SUGARCANE TISSUES +

pH / CANE TISSUE	MEDIUM Ca					LOW Ca			HIGH Ca		
	3.0	4.0	5.5	6.5	8.5	4.0	5.5	6.5	4.0	5.5	6.5
SPINDLE CLUSTER	.010	.152	.227	.244	.230	.037	.140	.136	.155	.211	.217
SHEATHS 3-6	.019	.165	.240	.231	.241	.021	.161	.167	.169	.260	.256
BLADES 3-6		.172	.270	.310	.281	.011	.132	.172	.200	.313	.291
GL SHEATHS		.162	.180	.201	.196	.06	.119	.132	.183	.231	.240
GL BLADES		.147	.176	.159	.203	.090	.132	.151	.172	.186	.195
P STALKS	.009	.061	.040	.051	.092	.071	.044	.059	.089	.073	.065
S LEAVES		.143	.311	.270	.221	.131	.129	.198	.240	.246	.236
S STALKS		.011	.032	.054	.062	.04	.039	.067	.077	.069	.089
ROOTS	.005	.009	.032	.027	.016	.006	.008	.011	.021	.037	.040

+ Average of 3 replications

TABLE 10. INFLUENCE OF pH AND Ca CONCENTRATION ON THE POTASSIUM CONTENT (%) OF SUGARCANE TISSUES +

pH	MEDIUM Ca					LOW Ca			HIGH C		
CANE TISSUE	3.0	4.0	5.5	6.5	8.5	4.0	5.5	6.5	4.0	5.5	6.5
SPINDLE CLUSTER	.07	2.76	2.63	2.93	2.78	2.42	2.19	2.61	2.01	2.69	2.88
SHEATHS 3-6		2.01	2.58	2.67	2.85	2.17	2.41	2.56	1.97	2.14	2.06
BLADES 3-6		1.12	1.83	1.90	1.87	1.30	1.40	1.61	1.45	1.09	1.22
GL SHEATHS		2.10	2.49	2.59	2.81	2.11	2.20	1.99	1.93	2.14	1.87
GL BLADES		2.30	2.45	2.27	2.61	1.90	1.86	1.47	1.04	2.18	1.56
P STALKS	.04	3.06	3.99	3.22	3.87	2.14	2.40	1.96	3.90	3.47	3.66
S LEAVES		1.86	2.15	2.64	2.22	1.19	1.70	1.69	2.10	1.99	2.07
S STALKS		2.00	2.79	2.83	3.01	1.88	1.40	2.04	3.60	2.45	2.56
ROOTS		.35	.52	.46	.49	.33	.42	.49	.21	.54	.39

\+ Average of 3 replications

GLOSSARY

Common and Scientific Names of Plants Referred to in this Monograph

Common name	Scientific name
Alfalfa	*Medicago sativa L*.
barley	*Hordeum vulgare L*.
bermuda grass	*Cynodon dactylon L*.
bluegrass	*Poa parathensis L*.
cauliflower	*Bassica oleracea L*.
corn	*Zea mays L*.
cotton	*Gossypium hirsutum L*.
cucumber	*Cucumis sativus L*.
cowpeas	*Vigna sinensis Endl*.
desmodium	*Desmodium aparines L*.
guava	*Psidium guajava L*.
lantana	*Lantana camara L*.
macadamia	*Macadamia integrifolia F. Muell*
papaya	*Carica papaya L*.
peas	*Pisum sativum L*.
pineapple	*Ananas comosus L*. Merr.
potato	*Solanum tuberosum L*.
rice	*Oryza sativa L*.
saltbush	*Atriplex portulacoides L*.
snapbeans	*Phaseolus vulgaris L*.
sudangrass	*Sorghum vulgare var. Sudanense Hitchc*
spinach	*Spinacia oleracea L*.
soybean	*Glycine max L*.
sugarcane	*Saccharum officinarum L*.
sweetclover	*Melilotus indica L*.

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