EFFECT OF SOIL pH, PHOSPHORUS AND ZINC FERTILIZATION ON CORN AND SUGARCANE AND AN EVALUATION OF EXTRACTANTS FOR AVAILABLE SOIL ZINC

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

AGRONOMY AND SOIL SCIENCE

AUGUST 1978

By

Deo L. Marzola

Thesis Committee:

James A. Silva, Chairman
Wallace G. Sanford
Goro Uehara

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

THESIS COMMITTEE

James A. Silva
Chairman

Wallace G. Sanford

Goro Uehara

TABLE OF CONTENTS

Page

LIST OF TABLES

APPENDIX

APPENDIX

INTRODUCTION

Sugarcane (Saccharum officinarum) is the main crop grown in Hawaii and is an important crop in many other parts of the world. Today there are sixteen sugar plantations and about 550 independent sugarcane growers throughout the State of Hawaii, which supplies roughly one-tenth of the sugar used by the people in the United States.

Hawaiian sugar yields are known to be the highest in the world. This is mainly due to the good management practices that have been developed through research in the industry. Growers must constantly strive for higher sugar yields to keep up with the rapidly increasing costs of labor, fertilizers, etc. and the erratic and often depressed price of sugar.

In the past much effort has been spent to determine the optimum macronutrient (N, P, K, Ca, Mg) requirements of sugarcane. Since this goal has essentially been achieved, deficiencies of other elements are becoming evident. Micronutrients have not received the same research effort as macronutrients, although they are of equal importance in the growth of sugarcane. One reason for this may be that sugarcane can grow successfully under a wide range of climatic and soil conditions, and it is probably somewhat less prone to micronutrient disorders than many other tropical crops (Evans, 1959). The extensive root system of sugarcane may also make it a more efficient extractor of soil nutrients and thus give it tolerance to low soil levels of micronutrients.

Reports of micronutrient deficiencies have increased throughout the world and zinc deficiency, in particular, has recently been reported under a wide range of conditions associated with tropical and sub-tropical crops such as coffee (Coffea arabica), pineapple (Ananas comosus), mango (Mangifera sp), avocado (Persea americana), banana (Musa parasadisiaca) and sugarcane (Saccharum officinarum).

Several reasons for these reports of increasing micronutrient deficiency may be (1) the removal of trace elements by crops in continuously-cropped fields has lowered soil concentrations below those required for normal growth; (2) the rise in crop yields as a result of genetic improvement on crop varieties and macronutrient fertilization has increased the rate of removal of soil micronutrients by plants; (3) the shift to high analysis fertilizers has reduced the quantities of micronutrient impurities formerly added to soil; (4) the improved ability to diagnose micronutrient deficiencies which may have gone unnoticed before and (5) selecting plants less tolerant to Zn stress in plant breeding programs.

Zn fertilizer recommendations have been based mainly on plant tissue analyses. However as this method of measurement can only be made when the crop is being grown, the information is sometimes obtained too late to correct deficiencies in the presently growing crop. To overcome this problem, many studies have been conducted recently to select a rapid and reliable method for assessing Zn levels of soils prior to planting. Uptake of Zn by plants is affected by climatological factors, as well as by the following soil properties: (1) pH; (2) phosphorus status; (3) organic matter content; (4) texture; (5) temperature; and (6) microorganisms (Bauer, 1971). Therefore an extractant should reflect many of these properties if it is to adequately predict Zn uptake by plants.

The objectives of this research were:

1. To measure the effect of pH, P and Zn on sugarcane and corn yields and nutrient uptake.

2. To evaluate extractants for assessing Zn in tropical soils.

3. To determine critical levels of soil Zn for corn and sugarcane.

4. To study Zn distribution in the sugarcane plant.

REVIEW OF LITERATURE

Although Zn deficiency is generally more prevalent on soils that have pH above 7.0, more acute under irrigated than rain fed farming conditions and more striking in soils that have had the top soil removed by operations such as land leveling, Zn deficiency has been reported in Hawaii as well as in other areas under conditions different from these.

Lyman and Dean (1942) reported Zn deficiency in pineapple grown in Hawaii was manifested by blistering and mottling of leaves and the curvature of the "heart" leaves. This was later termed "crook-neck" by Aldrich (1960) who observed this symptom in Australia. This disorder was corrected by foliar application of Zn. Shoji, et al. (1958) reported chlorosis and stunting of coffee in several areas of the island of Hawaii, which was corrected by foliar spray of Zn but not by soil application of Zn. Recently Zn deficiency in cane fields has been reported at Honokaa, Mauna Kea, Paauhau, and Pepeekeo Sugar companies on the island of Hawaii (Juang, 1971). Symptoms were described as a white striping of the leaves in young cane which later developed into chlorosis. Zn is applied regularly in the fertilization program of these companies.

Even though Zn was shown by earlier workers to stimulate growth of various organisms, probably the first evidence that Zn is an essential element was presented in 1914 by Maze, who demonstrated that without added Zn, normal growth of maize (*Zea mays*) was not possible. He considered Zn to be an essential element for growth rather than simply a stimulant. Steinberg (1919) provided proof that

Zn is indispensable for the normal growth of fungi. Since that time a host of reports have presented irrefutable data in support of Zn as an essential element (Chersters and Rolinson, 1951; Gilbert, 1957; Hoch and Vallee, 1958).

The roles attributed to Zn in plants include its being a component of metalloproteins, regulation of enzymatic action, functioning in cellular membranes and its interrelationships with auxins as a coenzyme which appears to be the most important.

The failure of stem elongation in higher plants suffering from Zn deficiency is due to a decrease in auxin as first described by Skoog (1940). Later, Tsui (1948) presented evidence that Zn was related to auxin synthesis by means of tryptophan. Plants deficient in Zn were also low in auxin and showed a decrease in tryptophan content, although the activity of the enzyme system responsible for auxin formation from tryptophan was found to be the same in deficient as in healthy plants. Finally, Nason (1951) provided further information on this phenomenon when he reported that in Neurospora, tryptophan synthetase, the enzyme which catalyzes the formation of tryptophan from indole and serine, is markedly and specifically decreased by Zn deficiency.

Zn Availability to Plants

Deficiency of Zn in plants arises generally from three main causes: (1) low soil Zn, (2) depressed availability to the plant of soil Zn, and (3) genetic differences which may decrease the efficiency of plant uptake of Zn.

Factors that can cause depressed soil Zn availability to plants can be either natural soil factors such as alkalinity, soil organic matter, amount and nature of clays, and low soil temperature; or factors that can be brought about by soil management practices such as phosphate fertilizers, liming (soil pH), land leveling, liberal application of nitrogen fertilizers, and restricted root zones.

Organic Matter and Zn Availability

According to Hodgson (1963) and Manskaya, et al. (1968) micronutrient content of some, but not all, soils is related to organic matter contents. Kanehiro, et al. (1967) also reported that the high rainfall hydrandepts soils (Hilo, Akaka, and Honokaa) have high amounts of extractable Zn in the surface horizons which apparently are associated with the high organic matter content of these soils.

Organic matter can bind Zn to form Zn organic complexes through chelation or sequestration. When micronutrients are bound to humic acids they form very stable complexes. Dubach and Mehta (1963) reported that even after extraction, it is difficult to free humic substances from inorganic (cations, clays) impurities. A variety of forces are involved including H - bonding, ester linkages, Van der Waals forces, and salt linkages (Stenvenson, 1972). Hodgson (1963), Randhawa, et al. (1965a), Schnitzer and Skinner (1966) and other authors suggested that humic fulvic acid fractions of organic matter are very important in adsorption of Zn. The stability constant of the Zn humic acid complexes varies with pH. Randhawa, et al. (1965b) reported stability constants of 4.42 at pH 3.5, 6.18 at pH 5.6 and 6.8 at pH 7.0.

The metals found in soluble complexes are mainly those associated with individual biochemical molecules, such as organic acids. Geering, et al. (1969) reported that micronutrients are largely associated with low-molecular-weight-dialyzable organic constituents. In the case of Zn up to 75% of the Zn in displaced soil solution is reported to occur in organic complexes (Hodgson, et al. 1966; Geering, et al. 1969). However, Tucker and Kurtz (1955) reported that the amounts of Zn released by treatment of soils with peroscide were generally small which indicates that a relatively small portion of soil Zn is in the organic form. Also differences in the susceptibility of plant species to micronutrient deficiencies are often attributed to variation in organic acid production (Hodgson, 1963; Wallace, 1963).

The relationship between Zn and organic matter seems to be very complex and the literature does not agree on the nature of this relationship. However, some cases of Zn deficiency related to the removal of top soil as well as deficiencies in soils with high organic matter content might be explained by it.

Adsorption of Zn on Clays

Zn can be adsorbed by soils to various degrees, depending on the amount and nature of the soil clays. Elgabaly, et al. (1943) observed that not all of the Zn adsorbed by montmorillonite could be removed by extraction with a neutral salt. They concluded that Zn not extractable with neutral salt had entered into the octahedral layer of montmorillonite. Later Elgabaly (1950) reported that Zn may have been fixed in the holes not occupied by Al ions in minerals with Al in octahedral arrangement. However, Hodgson (1963) observed that many of the heavy metals adsorbed could be replaced by acid or even less-destructive means. This suggests that most of the specific adsorption is not by substitution into the octahedral layer (Ellis, et al. 1972). Sharpless, et al. (1969) found that in some soils up to 50% of initially added Zn retained in exchangeable (1N $NH_4C_2H_3O_2$) form reverted to a nonexchangeable acid-extractable form upon standing. Five to 10% of the added Zn was not recovered by extraction with either 1N $NH_4C_2H_3O_2$ or 0.1N HCL. Stanton and Burger (1967, 1970) suggested that Zn was also bound to Fe and Al oxides by two mechanisms. One mechanism involved OH^- and the other HPO_4^{2-} which may be important in soil systems when P is applied as fertilizer. Stanton and Burger (1970) also reported that adsorption of Zn on these oxides is affected by soil pH and generally there is less adsorption at low pH. Shuman (1977) found that adsorption capacities of fresh Fe and Al hydrous oxides (amorphous) were about 10 times those of the aged oxides. This corresponds to a 10-fold difference in their respective surface areas and CEC's. Sharpless, et al. (1969) also observed that the initial retention of Zn in some arid soils seemed to be associated mainly with CEC and to a lesser, but significant, extent with soil pH.

Effect of Soil pH on Zn Availability

The reduced absorption of Zn as soil pH rises is well-established and can be expressed by the equation $[Zn^{2+}] = 10^6\ (H^+)^2$.

This extremely useful relationship was developed by Norvell and Lindsay (1969). The decreased Zn solubility as pH rises is believed to be caused by low solubility products of Zn soil complexes and carbonates that range from 10^{-16} to 10^{-19} (Udo, et al. 1970). Malavolta and Haag (1962) reported that at high pH zincates such as $HZnO_2^-$ and ZnO_2 possibly are formed and combine with Ca to give insoluble compounds. Jurinak and Thorne (1955) demonstrated that a calcium zincate of low solubility was formed when pH was high from $Ca(OH)_2$ applications.

Thus soil pH seems to influence Zn uptake by plants mainly through its effects on the solubility of Zn compounds. Alben, et al. (1936); Lott, et al. (1939); Gall, et al. (1940); Fudge, (1944) and Rogers, et al. (1948) reported that raising pH reduces Zn availability. Fudge (1944) found that the application of basic materials, increased soil pH above 6.0 and the Zn content of citrus foliage decreased. Rogers, et al. (1948) observed that Zn content of oats decreased with increasing rates of applied lime but increased regularly with increasing Zn applications. Shaw and Dean (1952) reported that decreasing pH of some soils was related to increased dithizone extractable Zn and Zn content of leaves. Wear (1956) obtained a negative correlation between soil pH and plant uptake of Zn. He found that an application of $CaCO_3$ increased soil pH and decreased Zn uptake by sorghum. Equivalent application of $CaSO_4$ decreased pH and increased Zn uptake by plants. He concluded from this that decreased plant uptake of Zn was due to pH rather than Ca. Similar results were also obtained by Gupta, et al. (1971) and John (1972). Massey (1957) also found negative correlation between soil pH and plant uptake of Zn, but obtained a lower correlation coefficient for the relationship between dithizone extractable Zn and soil pH. Lott (1938) demonstrated that the reduction in Zn content was due to pH and not Ca when he found that toxic effects to oats (Avena sativa) caused by application of 800 ppm Zn could be overcome by liming the soil to pH 6.0 or above. Clements (1959) showed that the P-lime interaction significantly decreased Zn content of sugarcane. With high rates of lime absorption of Zn by corn was reduced according to Kanehiro (1964). Melton, et al. (1970) reported that yields on acid soils were generally lower when Zn was applied; however, liming these same soils sometimes induced Zn deficiency on pea beans (Phaseolus vulgaris). According to Meuer, et al. (1971) liming had a much greater effect on Zn uptake than did P applications on four soils of Brasil.

Therefore it may be concluded that Zn deficiency induced by over-liming is due to the effect of pH on Zn availability, since results described above showed that application of $CaCO_3$ increased pH and decreased Zn uptake by plants whereas application of $CaSO_4$ decreased soil pH and increased Zn uptake by plants.

Effect of Phosphorus on Zinc Availability

The P-Zn interaction has been the subject of many studies since 1936 (Barnette, et al. 1936; West, 1938; Boawn, et al. 1954, 1957; Thorne, 1957; Stuckenholtz, et al. 1966). The problem is usually due to P inducing Zn deficiency which is associated with high levels of available soil P. Zn deficiency may also arise from application of P fertilizers to soils in which Zn levels are below or near the critical level for Zn. Although the mechanisms of this interaction are still unknown, Olsen (1972) reported that efforts have been concentrated on four possible causes: (1) a P-Zn interaction in the soil; (2) a reduced rate of Zn translocation from roots to tops; (3) a simple dilution effect on Zn concentration in the tops due to the growth response to P; and (4) a metabolic disorder within plant cells related to an imbalance between P and Zn, or to an excessive concentration of P which interferes with the metabolic function of Zn.

The P-Zn interaction was thought to be due to formation of an insoluble $Zn_3(PO_4)_2$ in the soil. Boawn, et al. (1957), however, indicated that $Zn_3(PO_4)_2$ was a good source of Zn for sorghum. Lindsay (1972) also reported that $Zn_3(PO_4)_2$ is a source of Zn as well as P. Jurinak and Inouye (1962) measured the solubility of $Zn_3(PO_4)_2 4H_2O$ aged 33 days at room temperature and found the lowest concentration of Zn at pH 8.0 was 15.7 μm. Carroll and Loneragan (1968b), 1969) reported that maximum or near maximum yields of legumes were produced with 0.05 μm Zn in a flowing culture solution. This evidence indicates that precipitation of $Zn_3(PO_4)_2$ is not involved in P-induced Zn deficiency in plants (Olsen, 1972). Stuckenholtz, et al. (1966) observed no change in 0.1N HCl soluble Zn in an alkaline soil as rate of P increased from 10 to 1000 ppm.

It seems obvious that formation of $Zn_3(PO_4)_2$ is not the cause of the P-Zn interaction. However, there is some evidence suggesting that the P-Zn interaction occurs in the soil or at the root surface. Boawn and Leggett (1964) found that P fertilization significantly reduced Zn uptake by potatoes and that the antagonistic effect was in the soil once Zn concentration in the roots as well in the tops were reduced. Water-soluble Zn increased in phosphated soil while Zn in roots and tops of corn decreased according to Keefer and Singh (1968). They concluded that an antagonism outside the plant prevented Zn absorption by the roots. Marinho and Igue (1972) also found extractable Zn increased with P application. Shukla (1972) reported that application of $Ca(H_2PO_4)_2H_2O$ (C.P.) at the rate of 560 kg P/ha in the absence of Zn accentuated Zn deficiency symptoms and decreased plant height, dry matter yield, Zn concentration and uptake. However, application of superphosphate under similar conditions improved all the above parameters due to impurities in it including Zn, and to a decrease in soil pH. In laboratory studies he found that availability of Zn was increased with $Ca(H_2PO_4)_2H_2O$, KH_2PO_4, $(NH_4)_2HPO_4$ and superphosphate application, whereas it decreased with $CaHPO_4$ application. Arain (1976) also reported that superphosphate now being used in Hawaii contains 1400 ppm Zn. This emphasizes the importance of possible contaminants in the P fertilizer applied in experiments to study Zn nutrition. Takkar, et al. (1976) suggested that the main effect of P on Zn utilization by corn is to reduce the rate of entry into roots and induce Zn deficiency. Bingham and Garber (1960), Burleson, et al. (1961) and Bingham (1963) suggested also that P reduced uptake of Zn and Cu by some process external to the plant.

Some investigators support the view that the P-Zn interaction occurs within the root. Burleson, et al. (1961) suggested the possibility of a P-Zn antagonism within the root. Stuckenholtz, et al. (1966) found that as rate of P increased on Anselmo silt loam at pH 7.9, Zn concentration and uptake of Zn by roots increased while Zn concentration and uptake in leaves, nodes, and internodes decreased. Similarly, Sharma, et al. (1968b) observed a greater increase in Zn concentration and uptake by roots than by tops of sweet corn. Caroll and Loneragan (1968a) reported that legumes retained 35% of the total absorbed Zn in their roots when growth was limited by Zn deficiency while only 18% was retained under optimum supply of Zn. Dwivedi, et al. (1975) suggested that at high P levels the sites of Zn immobilization are not only the roots, but also at nodes in the stems of corn. Safaya (1976) reported that P applied at relatively low rates induced Zn deficiency by restricting the translocation of Zn to shoots, at high P rates absorption at the root surface itself was slowed to the extent that the total uptake of Zn by the entire plant was reduced. Khan, et al. (1977) also reported that the P-Zn interaction originates in the plant roots, thereby retarding the translocation of both elements to upper plant parts. Youngdahl, et al. (1977) found that the amount of Zn bound to the cell wall of the root tissue is increased with high P applications. This binding of Zn to the cell wall may reduce the amount of Zn available for transport to the upper portions of the plant, resulting in Zn deficiency.

When the rate of plant growth exceeds the rate of uptake of a certain nutrient the tissue concentration of that nutrient decreases or is "diluted" (Olsen, 1972). This explanation applies to many reported cases of P-Zn interactions, but not all. In general, this type of interaction takes place when the soil is P deficient and Zn is at or near deficiency. Loneragan (1951) and Watanabe, et al. (1965) reported that the decrease in Zn concentration in flax caused by P application produced Zn deficiency symptoms. Response to applied Zn was noted only when P was also applied. Therefore the response to applied P caused Zn to be diluted and thus gave rise to the interaction.

Some reports have indicated that P interferes with Zn utilization by the plant, but specific functional mechanisms have not been proposed (Viets, 1966; Boawn and Brown, 1968). Boawn and Leggett (1964) found a P-induced growth disorder in potato that was eliminated by increasing Zn supply. This metabolic disorder was better correlated with the P/Zn ratio than with Zn concentration. They reported that plants were Zn deficient whenever the P/Zn ratio exceeded 400. A P/Zn ratio of 250 or above was proposed by Reddy, et al. (1973) as the critical value above which P induced Zn deficiency in corn. Gattani, et al. (1976) reported that a value of 150 and above may be the critical ratio of P to Zn concentration above which P induced Zn deficiency in wheat may be expected. Takkar, et al. (1976) suggested that critical P/Zn values, above which the P-induced Zn disorder on corn or response to Zn fertilization may be expected were 150 in grain, 90 in stover, and 100 in leaves. These critical values were obtained by the Cate and Nelson procedure (1965). However, highly significant response to Zn application is expected with P:Zn ratio above 245 for grain, 130 for stover, and 150 for leaves.

The P-Zn interaction generally has been found to affect the normal growth of plants in some way. It usually occurs with high P applications to soils with low Zn levels. Whatever the causes are, it is important to measure soil Zn levels before establishing a crop mainly when lime and P fertilizer are to be applied so that possible Zn disorder in plant growth may be avoided.

Evaluation of Soil Zn Extractants

Several chemical extractants have been used to assess Zn content of soils in relation to Zn uptake by plants. The extractants for assessing soil Zn may be grouped in the following classes: complexing agents, dilute acid, chelating agents and neutral salts (Cox, et al. 1972). A brief discussion of each class will be presented with emphasis on 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ which were evaluated in the present study.

Complexing Agents

Shaw and Dean (1952) first used the Dithizone method and tested it on soils from throughout the U.S.A. They found little relationship between soil Zn levels and the occurrence of Zn deficiency because the soils were from such varied conditions. However if soil pH had been considered, a relationship would have been found as shown by Cox, et al. (1972). Massey (1957) found a negative correlation between Zn uptake and soil pH when he measured the uptake of Zn by corn grown in the greenhouse on 34 soils varying from pH 4.3 to 7.5. The correlation coefficient for the relationship between dithizone extractable Zn and Zn uptake was 0.65, but increased to 0.80 when pH was taken into account. Viets, et al. (1953) used the dithizone method to assess Zn on neutral and alkaline soils in central Washington and correlated dithizone-extractable soil Zn with Zn uptake by corn. They found that corn developed Zn deficiency symptoms on soils with less than 0.4 ppm Zn although plants were apparently normal on some soils with less than 0.4 ppm Zn. Brown, et al. (1962) found the distinction between deficient and non-deficient soils was unclear with the dithizone method. However, they proposed a critical level of 0.5 ppm for Zn sensitive crops.

Dilute Acid

Wear and Sommer (1948) used 0.1N HCl to extract Zn from soils and established a critical level of 1 ppm based on the occurrence of deficiency symptoms of corn and Zn extracted by 0.1N HCl.

Tucker and Kurtz (1955) used 0.1N HCl in a 1:10 soil solution ratio and an equilibration time of 45 min. to extract Zn. They compared several methods and found that Zn extracted with 0.1N HCl, dithizone, acetic acid and EDTA were significantly correlated with the bioassay value of *Aspergillus niger*. Nelson, et al. (1959), on the other hand, found little or no relationship between extractable Zn and plant availability of soil Zn for 51 soils which differed in pH, texture and organic matter content. However, the soils could be divided into Zn deficient and Zn sufficient categories on the basis of the content of 0.1N HCl extractable Zn and titratable alkalinity. Titratable alkalinity was defined as the amount of acid necessary to reduce pH to 5. The critical level for calcareous soils was near 1.0 ppm without taking into account titratable alkalinity and 7.5 ppm when titratable alkalinity was 100 meq/100 g. This points out the importance of free lime in the use of acid extractants. Motooka (1962) found no correlation between 0.1N HCl extractable Zn and Zn uptake by soybeans in some Hawaiian soils. However at the Hawaiian Sugar Planters Association Experiment Station, good correlation was found between Zn uptake by sudan grass and Zn extracted with 0.1N HCl (Anon. 1963). Pescador (1963) also found good correlation between 0.1N extractable Zn and Zn uptake by corn on three out of four Hawaiian soils studied. The lack of correlation in one soil was probably due to its high pH. He also reported that moisture content may have influenced Zn extracted with either 0.1N HCl or EDTA.

Martens, et al. (1966) evaluated several extractants for Zn from soils and found the relative amounts of soil Zn extracted were in the order: A. niger > 0.1N HCl > dithizone>0.2M $MgSO_4$. On the basis of correlation data and the greater extractability of Zn by 0.1N HCl over dithizone, they concluded that much of the Zn extracted by 0.1N HCl is not extracted by plants. Kanehiro and Sherman (1967) found a highly significant correlation between total and 0.1N HCl extractable Zn in Hawaiian soils, especially in the relatively young and unweathered soils, but found low correlation in some oxisols and ultisols. Wear and Evans (1968) found that soil Zn extracted by the dilute acid mixture (0.05N HCl + 0.025N H_2SO_4) was better correlated with Zn uptake by corn and sorghum plants than Zn extracted by 0.1N HCl and 0.05 M EDTA. Juang (1971) compared six methods of Zn extraction in Hawaiian sugar cane soils and concluded that 0.1N HCl was the best extractant and that the critical level for sugarcane was around 3 ppm of 0.1N HCl extractable Zn. However, this was a tentative critical level based mainly on the response of corn to Zn fertilization.

It has been shown by simple correlation analyses that either dithizone or 0.1N HCl extractable Zn is a satisfactory predictor of Zn uptake by plants since the soils used in the studies reviewed had a very limited range of characteristics. However if soils have a wide range of characteristics, a satisfactory prediction is possible only when other soil variables are taken into account in a multiple regression analyses.

Chelating Agents

Viro (1955) extracted soils with 0.05M EDTA at pH 9.0 and found very good recovery of added Zn and Cu. Trieweiler and Lindsay (1969) developed an extractant containing 0.01M EDTA and 1M $(NH_4)_2CO_3$ at pH 8.6 and found it to be an excellent extractant for plant available Zn in calcareous soils. They established a critical level of 1.4 ppm Zn based on response of corn to Zn fertilization. Lindsay and Norvell (1969) reported the use of DTPA to extract Zn and Fe from soils. This DTPA extractant solution consists of 0.005M DTPA, 0.01M $CaCl_2$, and 0.1M triethanolamine as a buffer at pH 7.3. This method is now being used in Colorado and the following Zn levels have been suggested for interpretation of Zn values: low-0 to 0.5; marginal-0.5 to 1.0 and adequate-greater than 1.0 ppm. Many authors have reported good correlation between soil Zn extracted by these two methods and Zn uptake by plants.

Brown, et al. (1971) studied four methods for extracting soil Zn using sweet corn as a test crop and reported that the best was DTPA followed in order by dithizone, 0.1N HCl and Na_2EDTA. Stewart and Tahir (1971) compared soil Zn levels measured by four chemical extractants to Zn concentration in cereals (wheat, barley and oat). They found a good correlation between plant Zn concentration and soil Zn extracted with 1N NH4Ac, EDTA-$(NH_4)_2CO_3$ and DTPA, but not with 0.1N HCl extractable Zn. Marinho, et al. (1972) related soil Zn extracted with 0.01M Na_2EDTA and also with 0.1N HCl to Zn uptake by corn on volcanic ash soils. Soil Zn extracted with the EDTA method was more highly correlated with Zn uptake than was that extracted with the HCl method. Alley, et al. 1972 compared the amounts of Zn extracted with 0.1N HCl, dilute HCl-H_2SO_4, EDTA and DTPA and found that the EDTA method most clearly separated soils with adequate or inadequate amounts of Zn for corn grown in the field. EDTA and DTPA were found to be superior to EDDHA and HCl+H_2SO_4 for predicting available soil Zn levels for corn (Hag, et al., 1972). However, Arain (1976) compared DTPA with 0.1N HCl and concluded that 0.1N HCl was a better extractant than DTPA for Hawaiian soils. He also stated that DTPA extracted much less Zn than 0.1N HCl.

Maclean (1974) modified the DTPA method slightly by increasing the DTPA concentration 10-fold over the concentration in the original method (Lindsay and Norvell, 1969). He found that the amounts of Zn extracted with 0.005M DTPA were closely related to those obtained with 0.05M DTPA (r = +0.98), but 0.005M DTPA extracted only 69% as much Zn as 0.05M DTPA. Meyer (1976) found that Zn in T.V.D. (top visible dewlap) leaf samples from several sugarcane fields was more closely correlated with Zn extracted by EDTA$(NH_4)_2CO_3$ than with Zn extracted by 0.1N HCl, 1N KCl, 1N NH_4OAc or 2N $MgCl_2$.

Neutral Salts

Neutral salts have also been used to extract Zn from soils. Mangaroo (1965) used successive extractions with 0.8N KCl and classified soil Zn into soluble Zn, adsorbed Zn, exchangeable Zn and nondisplaced Zn. An apparent relationship between the degree of Zn deficiency exhibited by pineapple plants and soil Zn soluble in N NH_4OAc at pH 4.6 was reported by Syman and Dean (1942). Ravikovitch, et al. (1968) found that NH_4NO_3 and KCl extractable-Zn were correlated with the Zn content of plants. Stewart and Berger (1965) compared Zn extracted by 0.1N HCl, dithizone, and 2N $MgCl_2$ with Zn uptake by millet grass. Correlation coefficients with plant Zn were 0.93 for $MgCl_2$, 0.73 for HCl and 0.63 for dithizone. $MgCl_2$ extraction was better correlated with plant uptake, while HCl extraction was better correlated with total soil Zn. Grewal, et al. (1968) reported that N NH_4OAc (pH 4.6), 2N $MgCl_2$ and 0.2% EDTA extractable Zn were significantly correlated with response of wheat to Zn application while 0.1N HCl extractable Zn was not. Martens (1968) showed that Zn uptake by corn was more closely related to 2N $MgCl_2$- extractable Zn ($r = 0.66$) than to 1.0N HCl- extractable Zn ($r = 0.30$) or to 0.1N HCl- extractable Zn ($r = 0.30$).

A substantial amount of work has been done to develop and evaluate methods for assessing the availability of soil Zn to plants. The inclusion of titratable alkalinity when using 0.1N HCl in alkaline soils has been helpful. However, the role of pH has not been well defined in acid soils (Cox, 1972). In addition other factors that are known to decrease Zn availability to plants have been ignored or only casually considered in many studies of Zn extractants, e.g. the P-Zn interaction.

MATERIALS AND METHODS

Soil Sampling and Description

Soil samples were collected from areas on the Island of Hawaii, Oahu and Kauai. In each of these areas the sampling was limited to the top soil as much as possible, although some subsoil may have been included with the samples.

Selection of the areas was made through observations nad study of Soil Survey Maps of the Islands of Hawaii, Kauai and Oahu, State of Hawaii, Soil Conservation Service (1973). The soil properties used to select the soils for this study were: soil mineralogy and extractable soil Zn. Sites selected for sample collection were those where Zn deficiency had been reported and/or which had been used for sugarcane cultivation.

Soil samples were stored in tightly-sealed double plastic bags to prevent contamination and dehydration. This was especially important in the case of the Hilo soil from Hawaii which can suffer irreversible dehydration of amorphous material.

Soils for the greenhouse experiments were mixed thoroughly, passed through an 8 mm plastic sieve and stored in plastic bags until treatments were added.

Hilo Soil (Typic Hydrandept)

This soil series consists of well-drained soil formed from volcanic ash. It has low bulk density (0.44) and high moisture content which gives it the characteristic of "smeariness" associated with soils which are thixotropic. It also dries irreversibly to sand

and gravel-size aggregates. A representative soil sample was taken from an uncultivated area between the Pepeekeo Sugar Mill and Pepeekeo Sugarcane field 72-B in Hawaii. This soil is mainly used for sugarcane cultivation and is known to be Zn deficient, therefore Zn fertilizer is commonly applied to the sugarcane grown on it.

Halii Soil (Typic Gibbsiohumox)

This soil series consists of well-drained and moderately-drained soils on uplands on the Island of Kauai. It is highly weathered and developed in material weathered from basic igneous rock. It is rich in iron and aluminum oxides and also contains TiO_2 concretions. A representative sample of this soil series was collected on Kauai at the Kauai Branch Station next to experimental plots A_2 and A_4, 200 feet away from the road. Although the sampling site was an uncultivated area, this soil occupies extensive areas of sugarcane cultivation. This soil is suspected to be Zn deficient based on 0.1N HCl extractable Zn according to Kanehiro, et al. (1967).

Molokai Soil (Typic Torrox)

This series consists of well-drained upland soils formed in material weathered from basic igneous rock. It contains large amounts of iron and manganese oxides. A sample of this soil series was collected from the H.S.P.A. Kunia sub-station, on the island of Oahu, from plots of a former irrigation experiment. It is also an important sugarcane soil and is not known to be Zn deficient.

Lualualei Soil (Typic Chromustert)

This series consists of imperfectly-drained soils, developed in alluvium and colluvium from basic igneous rocks. The very sticky and very plastic nature of the clay makes cultivation practical only within a narrow range of moisture content. When dry it has deep cracks due to high shrink-swell potential because of the high content of a 2:1 type expanding clay. A representative sample of this soil series was collected from an area next to Kuanale St. and Homestead Rd. intersection at Lualualei Valley.

Table 1 shows some characteristics of the soils used in this study. More detailed descriptions may be found in Soil Surveys of the Islands of Hawaii, Kauai and Oahu, State of Hawaii, Soil Conservation Service (1973).

Greenhouse Experiments

Greenhouse experiments were set up with the following objectives:

1. To study the effect of pH, P and Zn on the growth and nutrient uptake of corn (*Zea mays*) and sugarcane.

2. To correlate soil Zn extracted by different methods with yields, Zn concentration and Zn uptake by corn and sugarcane.

3. To determine critical levels of soil Zn for corn and sugarcane.

4. To study Zn distribution in the sugarcane plant.

Experiment No. 1

This experiment, designed as a randomized complete block, was used to study the effects of pH, P and Zn on corn growth. Two soils, i.e. Hilo series (Typic Hydrandept) and Halii series (Typic Gibbsihumox which were suspected of being Zn deficient were used in this experiment. The factor levels are shown in Table 2.

Table 1. Some general characteristics of soils used in this study

Property	Soil Series: Hilo	Halii	Molokai	Lualualei
Soil Group	Typic Hydrandept	Typic Gibbsihumox	Typic Torrox	Typic Chromustert
Family	Thixotropic, Isohyperthermic	Clayey, Ferritic Isothermic	Clayey Kaolinitic Isohyperthermic	Very fine, Montmorillonitic Isohyperthermic
Parent Material	Volcanic ash	Basic Igneous Rock	Basic Igneous rock	Alluvium and Colluvium
Initial pH (1:1 H_2O)	5.60	5.16	6.55	6.70
O. M. %	3.31	4.31	1.40	0.74
Truog Ext. P. (ppm)	8.0	1.2	34.9	251.1
0.1N HCl Ext. Zn (ppm)	3.89	8.20	10.19	11.07
Total Zn (ppm)	141	73	215	150
CEC (meq/100 g)	90.7	25.2	24.7	61.2
Exch. Cations (me/100 g)				
Na	.3	.6	.4	8.2
Ca	1.1	.3	10.2	36.7
Mg	1.3	1.4	6.3	14.3
K	.1	.2	1.2	2.4

Table 2. P, pH and Zn levels used in the experiments

Factor	No. of Levels	Levels
Zn	pH 5.0 - 5	0 2 4 8 16 (ppm)
	pH 6.0 - 6	0 2 4 8 16 32 (ppm)
P	2	.05 .1 (ppm P in solution)
pH	2	5.0 6.0

The final average soil pH was: 5.1 and 5.7 for the Hilo soil and 3.8 and 4.8 for the Halii soil. The large difference between the theoretical (5.0 and 6.0) and actual pH in the Halii soil is probably due to non-uniformity in mixing of the soil when samples for the acidulation curve were collected.

These factors were combined factorially to give a total of 44 treatments for each soil which were replicated 2 times due to the internal replication within each replicate and the total size of the experiment. Either $CaCO_3$ or H_2SO_4 (reagent grade) was added to adjust soil pH according to titration or acidulation curves constructed for each soil (see Figures B.1 and B.2). P was added in solid form as reagent grade $Ca(H_2PO_4)_2\ H_2O$ (monobasic calcium phosphate) and the amounts were based on P adsorption curves according to the method of Fox and Krampth (1970) of the respective soils (see Figures B.3 and B.4).

The oven-dry weight of soil in a 1-gal pot (3.7 l), and the amounts of $CaCO_3$, H_2SO_4, and $Ca(H_2PO_4)_2$ added are shown below:

	Soil Series	
	Hilo	Halii
Oven-dry wt of soil in a 1 gal pot (g)	800	1600
$CaCO_3$ added (g/pot) - pH 6.0	1.6	5.6
1N H_2SO_4 added (ml/pot) - pH 5.0	32	2
Ca $(H_2PO_4)_2$ added (g/pot)		
.05 ppm in solution	7.8	2.2
.1 ppm in solution	10.7	3.2

Zn was added as a solution of Zn $SO_4 . 7H_2O$ together with 100 ppm N (as urea, reagent grade), 100 ppm K (as potassium chloride, reagent grade) and 100 ppm Mg (as magnesium sulfate, reagent grade). B at the rate of 2 ppm B (as sodium borate, reagent grade) was applied in a separate solution to prevent precipitation of Zn B_4O_7 that can occur at the pH of this nutrient solution. All concentrations were calculated on the oven-dry soil basis.

The soil was spread on a plastic sheet and the nutrients added in the following order:

1. either $CaCO_3$ or H_2SO_4
2. P
3. Zn + N + K + Mg
4. B

The soil was thoroughly mixed on the sheet after each addition to assure uniform distribution of nutrients. After treatments were added the soil mixtures were placed in 1 gal pots and allowed to equilibrate for 7 days. Additional N as urea (reagent grade) and K as potassium chloride (reagent grade) were supplied to the plants. The first application (50 ppm N and K on the soil volume basis) was made two weeks after emergence. Thereafter 100 ppm (N and K) were applied weekly, totaling 450 ppm each of N and K per pot during the growth cycle.

Corn (*Zea mays*) variety (AA-25) was used as the test crop. Six seeds were planted per pot and plants were thinned to three per pot seven days after germination. Watering was done with distilled water and nutrient losses due to leaching were prevented by placing a plastic basin under each pot. The leachate was recycled every other day.

Plants were harvested 40 days after germination and weighed at harvest. Roots were separated from the soil and washed according to the following technique:

Roots were washed with tap water to remove all visible soil particles and then dipped in 0.01N HCl for 30 seconds. Next the roots were rinsed in three consecutive basins filled with distilled water for a total of 30 seconds. Finally, they were wrapped in nylon netting and washed in distilled water for 30 seconds in a waring blender.

Tops and roots were dried at 70°C in a forced-draft oven. After taking dry weights, plant samples were ground in a stainless-steel Wiley mill and stored in plastic vials. Analysis was carried out by x-ray fluorescent technique with a x-ray quantometer model 72 000 supplied by Applied Research Laboratories.

Soils from the pots were collected for laboratory analysis. The Hilo soil was passed through a 4mm sieve because it cannot be air-dried and stored in double plastic bags to prevent dehydration. The Halii soil was air dried, crushed with a wooden rolling pin, passed through a 2mm sieve and stored in plastic bags.

Experiment No. 2

This experiment was conducted to study the effects of pH, P, and Zn on sugarcane growth. The soils, design and treatments were the same as in experiment No. 1 (Table 2). There were also 44 treatments for each soil, replicated 2 times.

All nutrients were added following the same principles and procedures as in experiment No. 2. However, as the pot size was 2.5 gal (9.25 l), the oven-dry soil weight and amounts of $CaCO_3$, H_2SO_4 and $Ca(H_2PO_4)_2\ H_2O$ added were the following:

	Soil Series	
	Hilo	Halii
Oven-dry wt of a 2½ gal pot (g)	2,300	4,700
$CaCO_3$ added (g/pot) - pH 6.0	3	16.5
1N H_2SO_4 added (ml/pot) - pH 5.0	92	7.5
$Ca(H_2PO_4)_2$ added (ml/pot)		
.05 ppm P in solution	24.31	6.88
.1 ppm P in solution	31.79	9.55

Note: For acidulation and titration curve see Figures B.1 and B.2.

For P isotherm see Figures B.3 and B.4.

The soil mixtures were placed in 2.5 gal pots and allowed to equilibrate for 7 days after being treated. Additional N and K were supplied to the plants. The first dose (100 ppm N and K) was given 1 month after the plants were transplanted to the pots and the second dose one month later, totaling 300 ppm N and K per pot during the growth cycle.

The final average soil pH after the ratoon crop was 4.8 and 5.2 for the Hilo soil, 3.8 and 4.8 for the Halii soil. As mentioned in experiment No. 1 the large difference between the theoretical (5.0 and 6.0) and actual pH in the Halii soil is probably due to non-uniformity in mixing the soil at the time when samples for the acidulation and titration curves were collected.

Sugarcane, (*Saccharum officinarum*) variety H59-3775, one of the top varieties grown in Hawaii at the present time and known to be a Zn-sensitive variety, was used as the test crop.

Germination of Sugarcane Seed Pieces

Seed pieces measuring 1.5 inches (3.8 cm) on either side of the node were weighed and classified into 3 classes according to the range of weights as shown below:

Classes	Avg. F. Wt (g/seed)	Avg. Dry Wt (g/seed)
1	36.86	9.60
2	47.67	12.58
3	64.80	15.72

Seed pieces were dipped for 1 minute in a solution of Benlate (Benomyl (methyl -1- butylcarbomoyl) -2- benzimidazolecarbamate) having 1 g of active product per 1600 g of H_2O. The seed pieces were then placed in trays containing perlite and watered daily with distilled water.

Samples from each seed piece class were taken, chopped, dried at 70°C in a forced-draft oven, ground and sent to the Service Center to be analyzed with the quantometer to determine the initial Zn content in the seed pieces. The Zn concentration of the seed piece classes as well as the concentration of other nutrients are shown in Table A.1.

Two plants were transplanted into each pot when they were 40 days old. Plants of uniform length from only one seed piece class were selected for a replicate.

Watering was also done with distilled water and leaching losses were prevented by placing a plastic basin under each pot and recycling the leachate weekly.

Plants were harvested when they were 100 days old because of spray damage that occurred three weeks before harvesting which killed the spindles of some plants. The top of each plant was cut off, weighed and kept separate because the death of plants was not uniform among and within the pots.

Tops were chopped into 1-3 cmm pieces and dried at 70° in a forced-draft oven. Dry weights were obtained then plant samples were ground in a stainless steel Wiley mill, stored in plastic vials and analyzed with the quantometer.

Ratoon Crop

A ratoon crop of sugarcane was allowed to grow after harvesting the first crop and tillers (shoots) were not thinned.

Only N and K were applied to all pots every 2-3 weeks to give a total application of 300 ppm each during the ratoon crop. Watering and recycling of leachate followed the same pattern as in the plant crop.

Plants were harvested 100 days after the tillers emerged. Fresh weights were taken then plants were subdivided into the following parts:

Sheaths 3, 4, 5 and 6: This is the standard tissue sampled in Hawaii for nutrient analysis of sugarcane grown for about 24 months (Clements, et al. 1945).

T.V.D. leaf (top visible dewlap leaf): This is the standard tissue sampled for nutrient analysis in many parts of the world where sugarcane is grown for about 12 months (Evans, 1959).

Meristem (top 5 mm of growing point): This is reported to be a very sensitive tissue for determining Zn (Bowen, 1972).

Remaining top materials: This was collected to permit calculation of total Zn uptake.

All parts were dried in a draft oven at 70°C, weighed and ground in a stainless steel Wiley mill. All samples except the meristem were analyzed with the quantometer. The meristem because of its small size was digested using the Wet Ashing method according to the procedure described elsewhere (laboratory analyses section) and analyzed for Zn using a Perkin Elmer model 303 Atomic Absorption Spectrophotometer.

Soil Sampling

Soils from the pots were collected for laboratory analysis. All procedures for sample preparation were identical to those described in experiment No. 1.

Experiment No. 3

This experiment, designed as a randomized complete block, provided a range of soil mineralogy for evaluation of soil extractants for Zn with Zn uptake by corn. Four soils were used and each soil was replicated 3 times.

The soils used were:

a. Halii series (Typic Gibbsihumox)

b. Hilo series (Typic Hydrandept)

c. Molokai series (Typic Torrox)

d. Lualualei series (Typic Chromusterst)

More detailed information on these soils is presented in Table 1.

The kinds and amounts of materials added to the soils to make up the treatments and the weight of soil in a 1 gal-pot are shown below:

	Soil Series			
	Hilo	Halii	Molokai	Lualualei
Oven dry wt of soil in a 1 gal-pot (g)	800	1,600	2,800	2,200
Ca $(H_2PO_4)_2$(g/pot) (.05 ppm P in solution)	7.8	2.2	.5	.0
N, K, Mg (ppm)	100	100	100	100
B (ppm)	2	2	2	2

All procedures regarding corn variety, planting, harvesting, sampling soils, watering and addition of N and K were as described for experiment No. 1 except that the corn roots were not harvested.

Molokai and Lualualei soils were prepared for laboratory analysis as described for Halii soil in experiment No. 1.

Experiment No. 4

This experiment provided a range of soil mineralogy for evaluation of soil extractants for soil Zn. In addition it was used to study Zn distribution in the sugarcane plant.

Experimental design and soils used were the same as in experiment No. 3. The test crop was sugarcane variety H 59-3775, the same used in experiment No. 2. To obtain uniform-sized plants, the technique described in experiment No. 2 was followed.

The kinds and amounts of materials added to the soil to make up the treatments and the weights of soil in a 2.5 gal-pot are presented below:

	Soil Series			
	Hilo	Halii	Molokai	Lualualei
Oven dry wt of soil in a 2.5 gal-pot (g)	2,300	4,700	8,500	4,900
$Ca(H_2PO_4)_2$ (g/pot)	1.47	2.0	0.00	0.00
N, K, Mg (ppm)	100	100	100	100
B (ppm)	2	2	2	2

The amount of P added was based on Modified Truog extractable P and the chart used by HSPA (Hawaiian Sugar Planters Association) to recommend P rates for sugarcane.

The Modified Truog Method is described in the laboratory analysis section and the HSPA chart is shown in Figure B.5. An additional 100 ppm of N and K was supplied to the cane monthly to give a total application of 400 ppm of each during the plant crop. Thereafter all procedures up to harvest were the same as in experiment No. 2.

Plant tops were harvested 120 days after planting and subdivided into the parts listed below to study the Zn distribution in sugarcane.

Sheaths 3, 4, 5, 6: (as previously described)

Middle third of blades 3, 4, 5, 6: This is the standard tissue sampled in Hawaii for nitrogen analysis of sugarcane grown for about 24 months.

Middle third of midribs 3, 4, 5, 6: midribs removed from middle third of leaf blades 3, 4, 5, 6.

Meristems: (as previously described)

Immature Stalk: Internodes 3, 4, 5

Spindle: All parts above and 3rd internode, less meristem.

Lower sheaths: All green sheaths below sheath No. 6.

Lower blades: All blades attached to the lower sheaths.

Dry leaves: All dry leaves below the lower leaves (lower sheaths and blades) at harvest.

Mature stalk: All internodes below the 6th internode.

Tillers: All shoots arising after the primary stalk.

Remaining material: Plant parts not included in the above samples which were collected to permit estimation of total Zn uptake.

Processing of plant samples was the same as described in experiment No. 2. All tissue samples were analyzed with the quantometer except the meristems which because of their small size were digested using the wet ashing method as described elsewhere and analyzed for Zn using a Perkin Elmer model 303 Atomic Absorption Spectrophotometer.

A ratoon crop was also allowed to grow and procedures followed were similar to those described for the ratoon crop in experiment No. 2. Molokai and Lualualei soils were prepared for laboratory analysis as described for the Halii soil in experiment No. 2.

Laboratory Analysis

Plant Analysis

Analysis of Meristem

Meristem samples were placed in 75 ml micro-Kjeldahl flasks and pre-digested overnight with 5 ml of 2:1 nitric: perchloric digestion and mixture (prepared by mixing two volumes of concentrated HNO_3 with one volume of concentrated $HClO_4$). Digestion was continued on a micro-Kjeldahl digestion block for 2 hours at 180°C. Temperature was then raised to 230°C and when the white-fuming stage was reached (about 2 hours after raising the temperature), digestion was continued for 30 minutes more. The digest was cooled and made to 75 ml volume. Zn in the digest was determined with a Perkin Elmer Model 303 Atomic Absorption Spectrophotometer.

Soil Analysis

Soil pH

Soil pH readings were made on a 1:1 soil: water paste after 1 hour equilibration using a Beckman phasar I pH meter with a glass electrode.

Soil Moisture

Soil moisture was determined by drying 20 g of soil for at least 24 hours at 105°C.

Zn Extraction Methods

0.1N HCl: The procedure is similar to that described by Wear and Sommer (1948) and Tucker and Kurtz (1955). A 20 g soil sample (oven-dry basis) was shaken with 200 ml 0.1N HCl for 45 minutes. The suspension was filtered immediately with Whatman No. 42 filter paper and the filtrate analyzed for Zn with the Atomic Absorption Spectrophotometer.

EDTA - $(NH_4)_2CO_3$: The procedure is similar to that described by Trieweler and Lindsay (1969). A 10 g soil sample (oven-dry basis) was shaken with 20 ml of extractant (pH 8.6) containing 0.01M EDTA (ethylenediaminetetraacetic acid) and 1M $(NH_4)_2CO_3$. After a 30 minute-shaking period the suspension was entrifuged at 12,000 rpm for 15 minutes. The supernatant solution was analyzed for Zn by means of an Atomic Absorption Spectrophotometer.

0.05M DTPA: The procedure is similar to that described by Lindsay and Norvell (1969) with the modification suggested by Maclean (1974). This modification consists of using a DTPA (diethylenetriaminepentaacetic acid) concentration of 0.05M instead of 0.005M as specified in the original method. A 10 g soil sample (oven-dry basis) was shaken with 20 ml of solution containing 0.05M DTPA in 0.01M $CaCl_2$ buffered with 0.1M TEA (triethanolamine) at pH 7.3 for 2 hours. The suspension was centrifuged for 15 minutes at 12,000 rpm and the supernatant solution was decanted and analyzed for Zn with an Atomic Absorption Spectrophotometer.

2N $MgCl_2$: The procedure is similar to that described by Maclean (1974). A 20 g soil sample (oven-dry basis) was shaken with 100 ml of 2N $MgCl_2$ for 2 hours. The suspension was filtered with Whatman No. 42 filter paper and the filtrate analyzed for Zn with an Atomic Absorption Spectrophotometer.

Soil P

P was extracted with the Modified Troug Method. A 2 g soil sample (oven-dry basis) was shaken for 30 minutes with 200 ml of 0.02N H_2SO_4 containing 3 g of $(NH_4)_2$ SO_4 per liter. The suspension was filtered and P in the filtrate determined by the Ascorbic Acid Method (Watanabe et al. 1965) using a Bausch & Lomb Model Spectronic 20 colorimeter with wavelength set at 882 mμ.

Total Soil Zn

Total Zn was determined by the procedure of Suhr and Ingamells (1966), whereby the soil was mixed with lithium metaborate, transferred to a preignited high-purity graphite crucible and placed in a muffle furnace at 950°C for 10 to 15 minutes. The fused sample was transferred into 200 ml of dissolving solution composed of 100 ml of concentrated nitric acid made up to 1 liter volume that contains 50.0 ml of dilute cobalt nitrate (113 g of Co $(NO_3)_2$ $6H_2O$/liter of H_2O). The sample was stirred and cooled, then Zn in the solution was analyzed with an Atomic Absorption Spectrophotometer.

Organic Carbon

The procedure is similar to that described in Soil Survey Investigations Report No. 1 (U.S.D.A. - 1972). A 1 g soil sample ground to pass an 80-mesh sieve was transferred to a 500 ml Erlenmeyer flask and 10 ml N K_2Cr_2O7 was added followed by rapid addition of 20 ml concentrated H_2SO_4. The mixture was shaken for

1 hour then 200 ml water, 10 ml concentrated H_3PO_4, and 0.5 ml barium diphenylaminesulfonate indicator were added. Titration was carried out by adding N $FeSO_4$ until the light green end point was attained.

CORN EXPERIMENT

Effects of pH, P and Zn on Yield and on Zn and P Content of Corn

Dry Matter Production

Plant yields differed significantly with added Zn on the Hilo soil (Table 4). The amounts of added Zn required for optimum yield varied with applied P and soil pH, indicating that the Zn requirement of corn may increase at higher rates of P and higher pH values (Tables 3 and 3-A). Generally, no further yield increase was obtained after 8 ppm added Zn (Figure 1). On the other hand, plant yields on the Halii soil did not show any significant increase with increasing amounts of added Zn (Table 6). This soil probably had sufficient available Zn at the pH attained. The average soil pH values for this soil were 3.8 and 4.8 as indicated in Table 5. At this pH soil Zn is highly available to plants.

The amounts of P added to both soils were based on the P adsorption curve method of Fox and Kamprath (1970) and the amount of P required to give .05 and .1 ppm P in solution was 7.8 and 10.8 g $Ca(H_2PO_4)_2$/pot for the Hilo and 2.2 and 3.2 g $Ca(H_2PO_4)_2$/pot for the Halii soil. This is comparable to 1195 and 1654 kg P/ha and 337 and 490 kg P/ha for the Hilo and Halii soils, respectively. These levels are reported to be adequate and excessive, respectively, for corn growth (Fox, et al. 1970). These P levels were selected to minimize yield response to P so that a better understanding of the P-Zn interaction could be obtained. Also these levels (.05 and .1 ppm P in solution) were established for mature corn and it is known

Table 3. Effect of Zn, P and soil pH on yields, Zn concentration, and Zn uptake in corn grown on the Hilo soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	Yield (g/pot)	Zn Conc (ppm)	Zn Uptake (µg/pot)
7.8	4.9	0	13.72	26	353.7
10.8	5.0	0	9.03	28	256.2
7.8	5.1	2	22.83	23	513.4
10.8	5.1	2	18.83	22	414.8
7.8	5.1	4	22.40	22	518.1
10.8	5.1	4	24.24	21	544.1
7.8	5.1	8	22.96	22	488.8
10.8	5.1	8	22.56	25	553.0
7.8	5.1	16	24.82	24	580.8
10.8	5.1	16	25.14	28	691.3
7.8	5.4	0	3.34	29	95.5
10.8	5.4	0	1.30	34	44.3
7.8	5.7	2	12.55	27	338.9
10.8	5.7	2	9.30	25	227.8
7.8	5.7	4	21.48	20	428.2
10.8	5.7	4	21.34	22	470.5
7.8	5.7	8	19.89	22	448.2
10.8	5.7	8	25.07	23	575.9
7.8	5.7	16	20.00	25	499.9
10.8	5.7	16	26.72	23	614.4
7.8	5.7	32+	22.09	26	574.2
10.8	5.7	32+	20.32	27	549.8

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 3-A. Average corn yields for pH-Zn interactions in the Hilo soil

I - Average Corn Yields for P-Zn Treatment Combinations in the Hilo Soil

Applied $Ca(H_2PO_4)_2$	Applied Zn (ppm)					P Average
	0	2	4	8	16	
7.8	8.53	17.69	21.94	22.62	24.17	18.4
10.8	5.17	14.07	22.79	23.82	25.93	18.4
Zn+ Average	6.85c	15.88b	22.37a	22.62a	24.17a	

+Means in the same row or the same column not followed by the same letters are significantly different at the 5% level.

II - Average Corn Yields for pH-Zn Treatment Combinations in the Hilo Soil

Soil pH	Applied Zn (ppm)					pH Average
	0	2	4	8	16	
5.0	11.38	20.83	23.32	22.76	24.98	20.65
5.7	2.32	10.93	21.41	22.48	23.36	16.10
Zn+ Average	6.85c	15.88b	22.37a	22.62a	24.17a	

+Means in the same row or the same column not followed by the same letters are significantly different at the 5% level.

Table 4. Summary of statistical analyses of the effects of Zn, P and soil pH on yields, Zn concentration and Zn uptake in corn grown on the Hilo soil

Treatment	F Values		
	Dry Weight	Zn Concentration	Zn Uptake
Applied P	.01	5.03*	.62
Soil pH	69.74****	4.23*	52.69****
Applied Zn	138.92****	25.18****	77.49****
Interactions			
P x pH	6.04*	.56	.53
P x Zn	7.26***	2.56	7.45***
pH x Zn	13.91****	4.68**	6.22**
P x pH x Zn	2.01	2.59	.19

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table 5. Effect of Zn, P and soil pH on yields, Zn concentration, and Zn uptake in corn on the Halii soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	Yield (g/pot)	Zn Conc (ppm)	Zn Uptake (µg/pot)
2.2	3.7	0	13.23	21	272.2
3.2	3.8	0	18.93	21	397.5
2.2	3.8	2	15.99	24	391.5
3.2	3.8	2	22.01	24	527.8
2.2	3.9	4	12.67	33	400.0
3.2	3.8	4	20.22	28	578.4
2.2	3.8	8	13.16	35	453.3
3.2	3.8	8	29.41	29	830.6
2.2	3.8	16	16.75	51	854.3
3.2	3.8	16	24.30	43	1034.2
2.2	4.8	0	22.44	20	460.0
3.2	4.8	0	19.46	24	428.0
2.2	4.8	2	21.81	23	500.0
3.2	4.8	2	24.11	24	566.6
2.2	4.8	4	23.49	24	617.6
3.2	4.8	4	30.24	27	740.1
2.2	4.8	8	24.76	25	608.6
3.2	4.8	8	25.88	25	654.3
2.2	4.8	16	22.75	33	750.0
3.2	4.8	16	27.62	34	939.1
2.2	4.8	32+	25.22	43	1071.3
3.2	4.8	32+	27.17	38	1032.2

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 6. Summary of statistical analyses of the effects of Zn, P and soil pH on yields, Zn concentration and Zn uptake, in corn grown on the Halii soil

Treatment	F Values		
	Dry Weight	Zn Concentration	Zn Uptake
Applied P	26.60****	2.80	28.68****
Soil pH	27.31****	19.93***	4.54*
Applied Zn	2.50	34.50****	43.92****
Interactions			
P x pH	8.42**	4.98*	5.22*
P x Zn	1.42	1.12	1.32
pH x Zn	1.30	5.43**	4.01*
P x pH x Zn	1.46	.50	1.39

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

that the requirement for young corn is higher. P did not increase dry weight significantly in the Hilo soil, but it did in the Halii soil (Tables 4 and 6, respectively). In the Halii soil at pH 3.8 the mean increase in yield due to P was about 59% compared to 10% at pH 4.8 (Table 5). This larger response at low pH may be due to high solubility of heavy metals such as Mn, Al, Fe, etc. which may have complexed P, making it unavailable to plants. Another possibility is the benefit of Ca added with P. This soil had low Ca status, and Ca was added only as $Ca(H_2PO_4)_2$ to the pH 3.8 treatment which may not have supplied adequate Ca for corn in this soil.

As soil pH increased the overall yield for all Zn levels decreased by an average of 24% on the Hilo soil. However, the yield decrease with increasing pH was more striking at 0 and 2 ppm added Zn (Table 3 and Figure 1). On the other hand, with the Halii soil the overall yield for all Zn levels increased by an average of 37% as soil pH increased (Table 5 and Figure 2). The benefits from increasing soil pH were probably due to decreased solubility of heavy metals and/or the increased supply of Ca, especially in the low P treatments which received small amounts of Ca with the low rates of P.

Added Zn generally had no effect on soil pH in both soils. However, in the Hilo soil, pH of the control treatments was somewhat lower than pH of treatments that received Zn, especially at the higher pH (Table 3). The reason for this drop in pH might be that the urea added as the N source produced H ions which accumulated in the control pots because there was little N uptake by the very

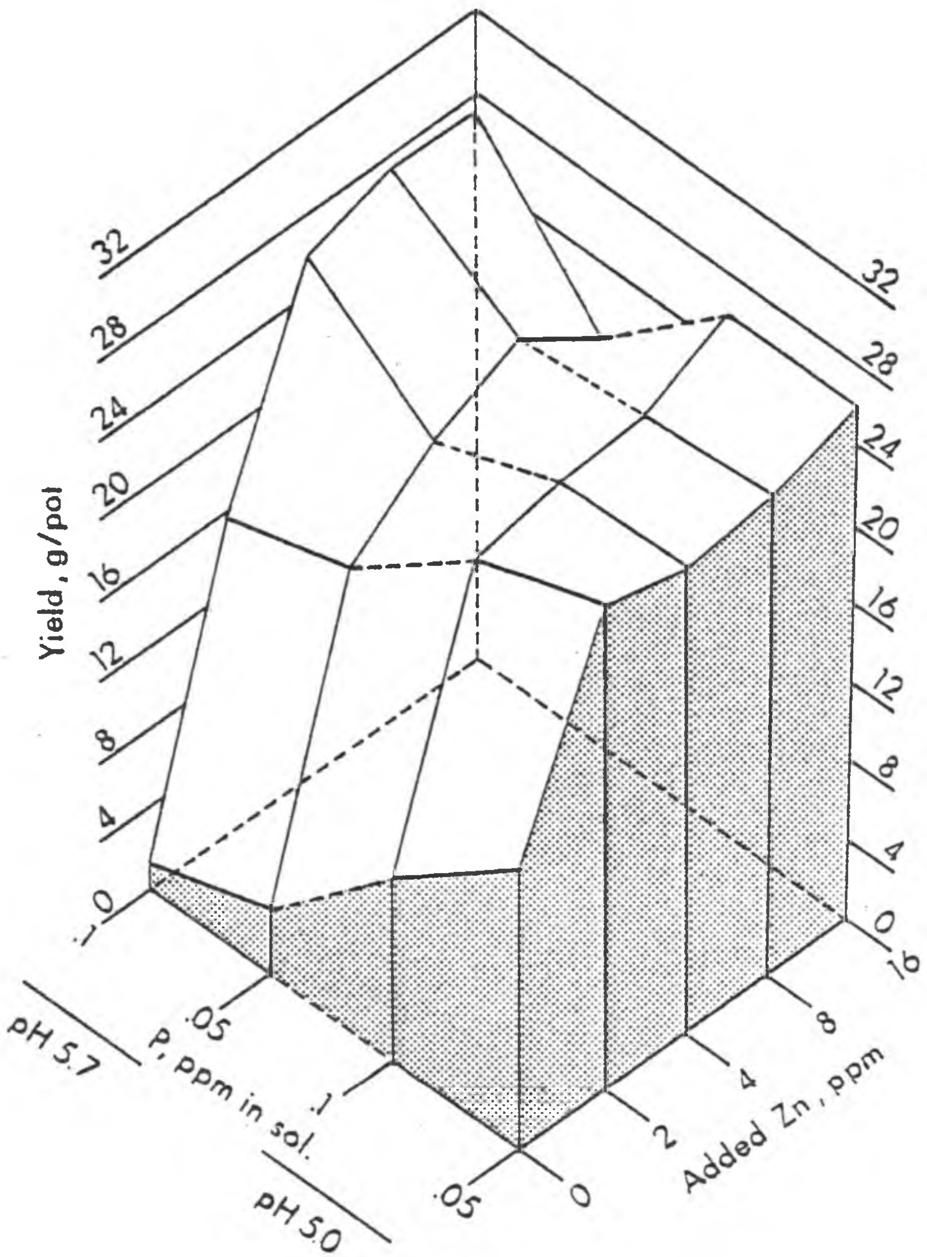


Figure 1. Effects of P and Zn fertilization and soil pH on yield of corn grown in the Hilo soil

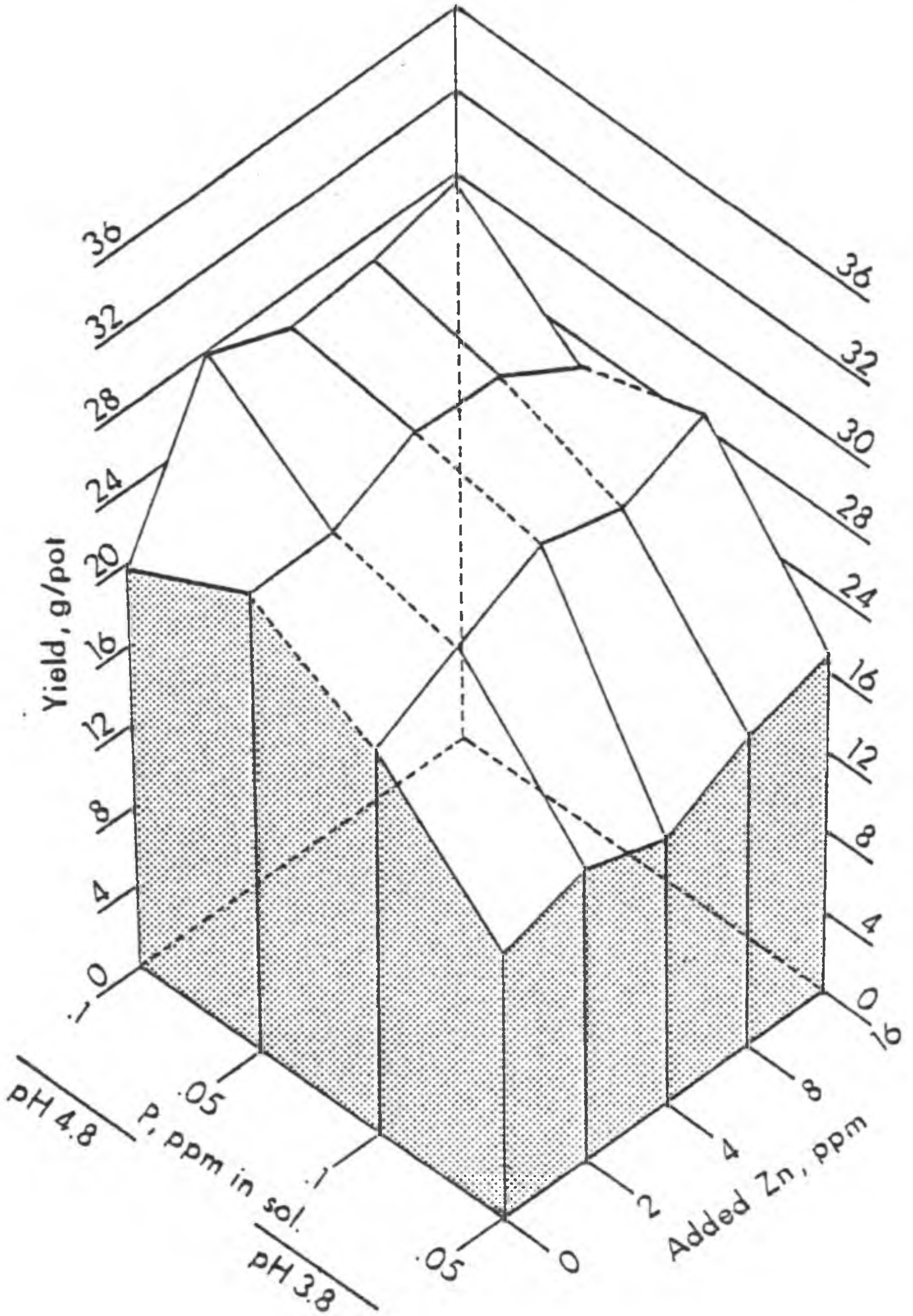


Figure 2. Effects of P and Zn fertilization and soil pH on yield of corn grown in the Halii soil

small plants in these pots. Leachate from the pots was reapplied so that there was no net movement of ions out of the pot. The drop in pH was greater at the higher pH and the amount of growth made was smaller than in the low pH. This larger pH drop associated with less growth supports the hypothesis that accumulation of H ions from urea may have caused the decrease in pH.

The control treatments on the Hilo soil made poor growth which is illustrated in Figures 1 and 3. It was observed that fifteen days after germination the terminal shoots died. This was followed by growth of tillers which made better growth than the terminal shoots (Figure 4). Kanehiro (pers. comm.) also observed the death of terminal shoots of pineapple growing in soils extremely deficient in Zn. The better growth of tillers may have resulted from the above mentioned drop in pH which increased Zn availability and/or enhanced Zn uptake by the root system of the tillers, which was probably more extensive than that of the initial shoots.

In the Hilo soil increasing pH and P decreased yields particularly on those treatments (zero and 2 ppm added Zn) where Zn was limiting for growth (Figure 1). However, when Zn was adequate there was a yield response to P, especially at high pH. In the Halii soil, response to P was greater at low pH, irrespective of Zn levels (Figure 2). These findings were reflected in the significant pH x P interaction in both soils. Figures 1 and 2 show the relationship between pH, P, Zn and corn growth for Hilo and Halii soils, respectively. The pH x Zn and P interactions were significant only in the Hilo soil.[1] An increase in pH decreased yield to a greater

[1]Increased P application decreased yields on the treatments that received 0 and 2 ppm Zn but at higher Zn levels yields increased with increased P (Table 3-A).

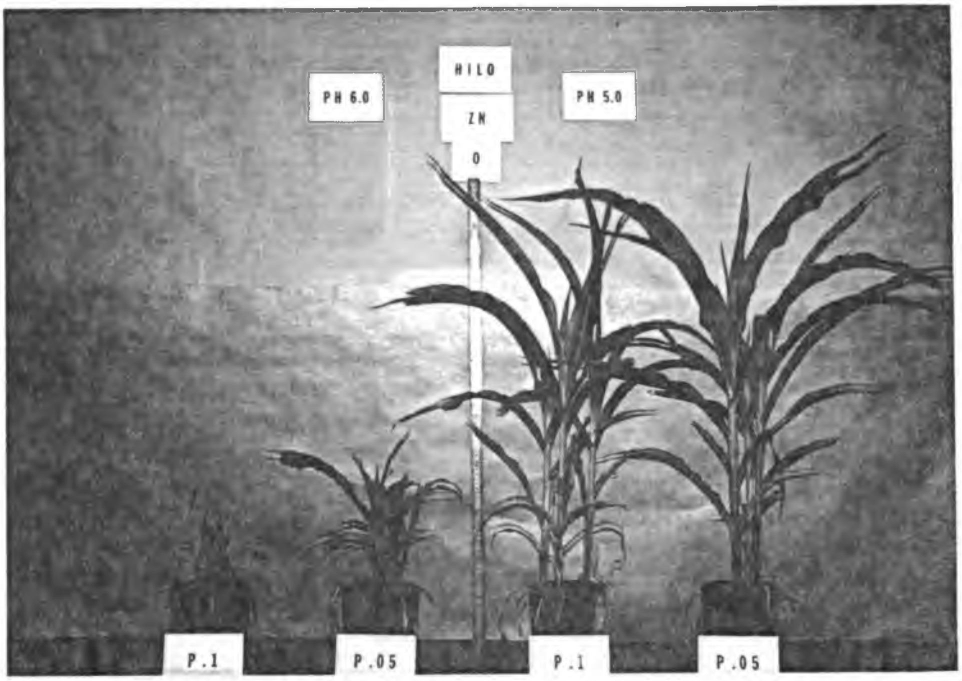


Figure 3. Corn growing in Hilo soil at two pH levels (5.0 and 5.7), two P levels (.05 and .1 ppm P in sol.) and zero ppm Zn

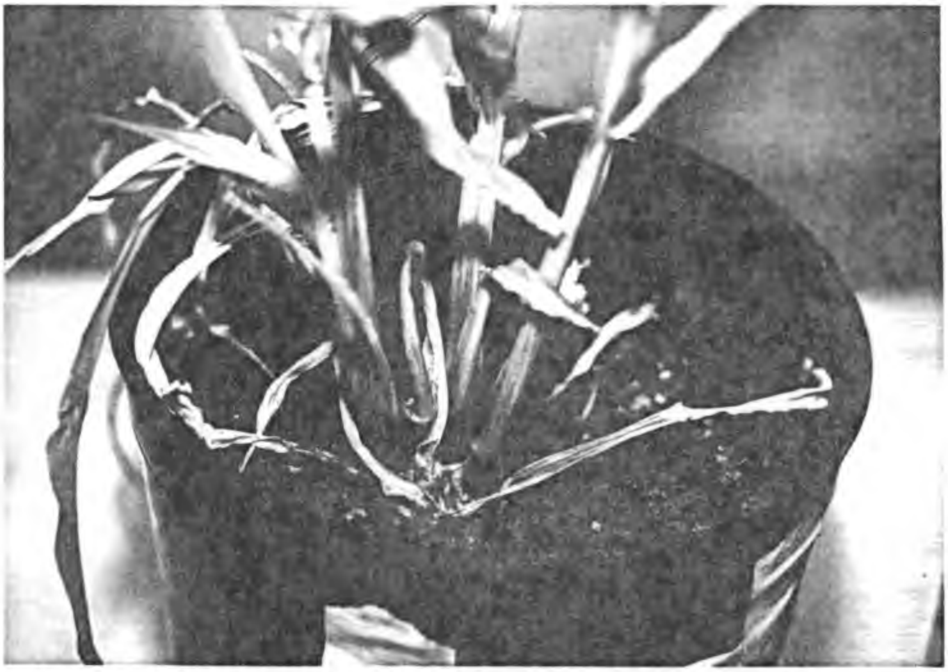


Figure 4. Control treatment (zero ppm Zn) at pH 5.7 and .1 ppm P for the corn experiment in the Hilo soil showing the first shoot which died and the secondary shoots that emerged later

extent than an increase in P (Tables 3 and 3-A) especially on those treatments where Zn was limiting plant growth (zero and 2 ppm added Zn).[2] Although these interactions are not significant in the Halii soil, careful examination of Figure 2 and Table 5 reveals a similar but smaller response. Yields also decreased slightly with added P in the zero Zn plots at the high pH level. These results suggest that if the Halii soil is limed to pH 5.0 or above Zn may become limiting. In addition, Zn may become even more limiting if high rates of P are applied together with lime. Melton, et al. (1972) reported that yields on acid soils generally decreased when Zn was applied. However, he also found that liming these same soils could induce Zn deficiency.

Zn Concentration

The pattern of response of tissue Zn to applied Zn differed in the two soils. On the Hilo soil Zn concentration decreased with the initial increments of Zn then tended to increase gradually at the highest levels of added Zn (Table 3). The high Zn concentration with the zero Zn treatments may have been caused by a concentration of plant Zn due to severely limited growth which was probably caused by extremely low amounts of available soil Zn that severely limited growth. This resulted in a small amount of dry matter production (growth) which caused high plant Zn concentrations even though the plants were Zn deficient. As Zn applications were increased, dry matter production (growth) increased, generally up to 4 ppm added Zn. This probably resulted in dilution of plant Zn and caused Zn concentrations to decrease. On the Halii soil, however, plant Zn

[2]Increased soil pH decreased yields up to 4 ppm Zn.

concentration increased with added Zn (Table 5).

On the Hilo soil, it appears that P decreases Zn concentration at 2 ppm Zn while at zero and higher Zn levels P had either no effect or increased Zn concentration. On the Halii soil, P decreased plant Zn concentration at the 4, 8 and 16 ppm Zn rates at low pH (3.8). The dilution of plant Zn by increased dry matter associated with P fertilization is a factor that should be considered when evaluating plant Zn concentration. This dilution of Zn concentration related to P fertilization has been suggested by Langin, et al. (1962), Stuckenholtz, et al. (1966) and Sharma, et al. (1968a,b). There was little evidence of an effect of P on Zn concentration at high pH (4.8) which supports the concept of a dilution effect resulting from a yield response to applied P since at this pH there was a relatively small yield increase from P compared to that at low pH (3.8).

On the Hilo soil, increasing pH increased Zn concentration at 0 and 2 ppm added Zn while at higher Zn levels soil pH either had no effect or decreased Zn concentration. There was a significant interaction between soil pH and Zn concentration (Table 4). The Zn concentration at high pH with 0 and 2 ppm Zn was higher than at low pH for these same Zn levels. These results agree with the observation that Zn availability decreases with increasing pH. These high plant Zn concentrations, therefore, are associated with Zn deficient plants in which plant growth is limited by Zn since at high pH and zero Zn plants made the smallest growth and had the highest Zn concentrations.

The low correlation between added Zn and plant Zn concentration (r = -.20) in contrast to the higher correlation between added Zn and plant yield (r = .65) may indicate that in the Hilo soil plant Zn concentration was not a reliable guide to the Zn status of plants. The negative correlation between dry matter yields and plant Zn concentration (r = -.72) gives further support to this suggestion probably because dry matter production increased and plant Zn concentration decreased mainly at the first Zn rates.

On the Halii soil pH as well as the pH x Zn interaction had significant effects on plant Zn concentration. Zn concentration decreased with increasing soil pH only in the treatments that received 4, 8 and 16 ppm Zn (Table 5). This may have been partly due to dilution effects from the increased yield at the higher pH.

Total Zn Uptake

Total Zn uptake generally increased with increasing levels of Zn from 0 to 16 ppm in both soils. Liming to increase soil pH from 5.0 to about 5.7 on the Hilo soil reduced total Zn uptake by an overall average of 14% (Table 3). On the Halii soil, however, increasing soil pH from 3.8 to 4.8 increased total Zn uptake by an overall average of 8% (Table 5). This increased Zn uptake may be related to increased yields with increasing soil pH. At the highest Zn level (16 ppm) in the Halii soil, however, increasing pH decreased total Zn uptake (see Table 5). Meuer, et al. (1971) reported that increasing soil pH from about 4.9 to 6.4 reduced Zn availability by an average of 31%.

On the Hilo soil the P x pH interaction was highly significant. Increasing soil pH generally decreased Zn uptake sharply at all levels of added Zn and the decrease was greater where Zn was limiting than where Zn was adequate, $>$ 8 ppm (Table 3). On the Halii soil only the pH x Zn interaction was significant. Increasing soil pH increased Zn uptake at 0, 2 and 4 ppm added Zn at both P levels and at 8 ppm Zn with the low P level only. On the other hand, increasing soil pH decreased Zn uptake at 8 ppm Zn with the high P level and at 16 ppm Zn regardless of P level.

While P itself had no effect on total Zn uptake in the Hilo soil (Table 2), it had a highly significant effect on the Halii soil (Table 4). The mean Zn uptake increased 26% with increasing P, which may be associated with the increase in dry matter yield with P fertilization. There was a highly significant P x Zn interaction on the Hilo soil but not in the Halii soil. Increasing P decreased Zn uptake on treatments where available Zn was not adequate for optimum growth on the Hilo soil. Once Zn demand was met, increasing P increased total Zn uptake as well. A similar pattern was observed on the Halii soil where increasing P increased Zn uptake at all Zn levels except at the combination of zero added Zn and high pH where Zn uptake decreased. This suggests that Zn levels probably were sufficiently high to meet plant requirements at all treatment combinations except for the one mentioned above. Wallace, et al. (1974) reported that when soil Zn was adequate, P application increased absolute Zn uptake by bush beans. These results again suggest the possibility of soil Zn becoming limiting in the Halii soil if pH is raised above 5.5. Seatz, et al. (1959) observed increased response of flax to Zn as the rate of liming increased. The reduced availability of soil Zn to plants with increasing soil pH has been reported by several workers (e.g. Rogers and Wu, 1948; Woltz, et al. 1953; Langin, et al. 1962).

P Concentration and Total P Uptake

In both soils P concentration in tissue generally increased with increasing P (Tables A.2 and A.4, respectively). However, only in the Hilo soil were the effects of P, pH, Zn and the P x Zn and pH x Zn interactions significant (Table A.3). Plant P concentration increased with increasing P and pH but decreased with increasing Zn in those treatments where Zn was not adequate for optimum growth. The same "dilution effect" discussed earlier for Zn concentration, possibly occurred here with P concentration as well. However at adequate Zn levels, P concentration increased with increasing P, but no further decrease in plant P concentration was observed with increasing Zn. On the Halii soil, Zn fertilization decreased P concentration only slightly. Terman, et al. (1972) reported that concentration of P in young corn plants was not affected by applied Zn. However, Takkar, et al. (1976) reported that Zn fertilization significantly depressed P concentration in corn grain and stover. Ellis, et al. (1964) also found a negative correlation between Zn concentration and P concentration in plant tissue. These contrasting reports in the literature regarding effects of Zn on P concentration may be due to the fact that different rates of Zn were used in the various studies.

Total P uptake followed the pattern of dry matter production in both soils (Tables A.2 and A.4). On the Hilo soil, total P uptake was reduced with increasing P only in those treatment combinations where Zn was limiting plant growth. This may be due to an induced Zn deficiency. In the treatment combinations where Zn supply was adequate for optimum growth, P uptake increased with increasing P. In the Halii soil total P uptake increased with increasing P and total P uptake was generally higher at high pH. Thus the beneficial effects of high pH on yields and total P uptake may have resulted from higher P availability as well as increased availability of micronutrients at the higher pH.

Effect of P, pH and Zn on Growth and Zn Content of Root

Dry Matter Production

Dry matter production of roots generally followed the same pattern as the tops in the two soils (Tables 7 and 8). Correlation coefficients between yield of the tops and roots were .91 and .72 for the Hilo and Halii soils, respectively.

In the Hilo soil, added Zn resulted in a significant increase in root yield (Tables 7 and 9). As mentioned previously for yield of the tops, the amount of Zn required for optimum yield of roots also varied with applied P and soil pH. As with the tops, no further yield increase occurred above 8 ppm Zn. On the Halii soil, however, root yields did not increase significantly with increasing rates of Zn (Tables 8 and 9). These results suggest that this soil probably had adequate available Zn at the pH attained (3.8 and 4.8).

P application resulted in a significant increase in root dry weight in the Halii soil but not in the Hilo soil. In the Halii soil at pH 3.8 the mean increase in yield due to P was 75% compared to 1% at pH 4.8. Again, the larger response to P was observed at

Table 7. Effect of P and Zn fertilization and soil pH on yield, Zn concentration, and Zn uptake by corn roots in the Hilo soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	Yield (g/pot)	Zn Conc (ppm)	Zn Uptake (µg/pot)
7.8	4.9	0	2.91	14.5	42.24
10.8	5.0	0	1.86	18.5	32.83
7.8	5.1	2	5.10	9.0	45.75
10.8	5.1	2	4.58	8.0	33.86
7.8	5.1	4	4.60	8.0	35.58
10.8	5.1	4	5.34	9.0	48.02
7.8	5.1	8	5.52	9.0	48.93
10.8	5.1	8	5.41	9.0	48.64
7.8	5.1	16	5.32	10.5	56.23
10.8	5.1	16	5.17	10.5	55.50
7.8	5.4	0	1.27	21.5	27.74
10.8	5.4	0	.62	13.0	7.59
7.8	5.7	2	2.58	13.5	35.05
10.8	5.7	2	1.99	17.0	33.62
7.8	5.7	4	4.46	8.0	35.36
10.8	5.7	4	4.02	7.5	30.25
7.8	5.7	8	5.84	7.5	44.02
10.8	5.7	8	4.77	9.0	42.89
7.8	5.7	16	5.15	10.5	53.90
10.8	5.7	16	5.91	9.0	53.48
7.8	5.7	32[+]	5.44	15.0	77.92
10.8	5.7	32[+]	4.79	12.5	62.26

[+] Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 8. Effect of P and Zn fertilization and soil pH on yield, Zn concentration and Zn uptake by corn roots in the Halii soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied An (ppm)	Yield (g/pot)	Zn Conc (ppm)	Zn Uptake (µg/pot)
2.2	3.7	0	2.39	12.5	26.58
3.2	3.8	0	3.60	11.0	39.98
2.2	3.8	2	1.84	14.5	26.86
3.2	3.8	2	4.11	15.0	60.61
2.2	3.9	4	1.84	14.5	25.87
3.2	3.8	4	3.07	12.5	38.12
2.2	3.8	8	2.34	14.5	35.79
3.2	3.8	8	3.35	16.0	53.60
2.2	3.8	16	2.32	23.5	54.53
3.2	3.8	16	4.68	18.0	84.50
2.2	4.8	0	5.83	6.5	38.08
3.2	4.8	0	3.80	13.0	50.41
2.2	4.8	2	3.79	9.0	35.28
3.2	4.8	2	4.50	11.0	50.06
2.2	4.8	4	3.70	10.0	32.59
3.2	4.8	4	4.51	11.5	47.52
2.2	4.8	8	5.12	13.0	66.79
3.2	4.8	8	5.54	14.0	78.30
2.2	4.8	16	4.17	12.5	54.08
3.2	4.8	16	4.55	13.5	62.24
2.2	4.8	32+	3.97	18.5	73.33
3.2	4.8	32+	5.63	17.5	94.27

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 9. Summary of statistical analyses of the effects of P, pH and Zn on yield, Zn concentration and uptake in corn roots in Hilo and Halii soils

Treatment	F Values					
	Hilo Soil			Halii Soil		
	Yield	Zn Conc	Zn Uptake	Yield	Zn Conc	Zn Uptake
Applied P	2.97	.02	1.77	8.69**	.16	9.45**
Soil pH	26.19****	1.04	10.11**	31.59**	9.19**	1.57
Applied Zn	60.62****	9.42***	11.55****	1.05	2.89*	4.07*
Interactions						
P x pH	.25	.85	.57	7.54*	2.30	.68
P x Zn	1.58	.36	1.37	1.44	.42	.15
pH x Zn	7.77***	2.00	1.26	.97	.80	1.41
P x pH x Zn	1.22	1.95	.71	.81	.39	.19

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

pH 3.8 probably for the reasons presented in the previous section. The magnitude of response to P at pH 3.8 was larger for root yield (75%) than for top yield (59%). However at pH 4.8 the reverse was found (1% for roots and 10% for tops).

The increase in root yield with P application varied with pH (Table 8) in the Halii soil and larger increases resulted at low pH than at high pH. This pH x P interaction was significant (Table 9). The pattern was similar at all Zn levels except with zero Zn at pH 4.8 a decrease in yield occurred with the higher P rate. This decrease in root yield was similar to the trend in top yield reported earlier. These findings support the suggestion made previously that if the Halii soil is limed to pH 5.0 or above and high rates of P are also applied, soil Zn may become limiting for plant growth.

Increase in soil pH resulted in an overall average decrease in root yield of 21% in the Hilo soil. This value is relatively close to the 24% yield decrease obtained for top yield. The consistently lower yield with the higher pH is apparent only at Zn levels below 8 ppm in Table 7 and is most striking in the control treatments. This pH x Zn interaction was found to be significant. In the Halii soil, root yield increased by an average of 54% as soil pH increased, which was larger than the 37% increase observed for the yield of tops.

Zn Concentration

The pattern of response of Zn concentration in roots to applied Zn was different in the two soils (Tables 7 and 8). In the Hilo soil, root Zn concentration generally decreased with the first rates of Zn then tended to increase gradually as Zn application increased. A generally similar trend was reported for Zn concentration in the tops and a correlation coefficient of .58 was found for this relationship. On the Halii soil, however, root Zn concentration generally increased with applied Zn although the trend was not clear for high pH. The correlation coefficient ($r = .67$) suggests that Zn concentration in the tops and roots followed similar patterns.

Zn concentration did not vary significantly with P rates in either of the two soils (Table 9).

As pH increased, Zn concentration in the roots decreased significantly ($p > 0.01$) by an overall average of 25% in the Halii soil only. The pH and Zn interaction was not significant in either of the soils (Table 9).

Zn Uptake

Zn application generally increased total Zn uptake in corn roots in both soils (Tables 7 and 8). In the Hilo soil liming to increase soil pH from 5.0 to about 5.7 reduced total Zn uptake by an average of 19%. This result was close to the 14% reduction in Zn uptake in the tops. On the Halii soil, however, increased soil pH had no significant effect on Zn uptake in roots.

P did not affect Zn uptake in the roots significantly in the Hilo soil but did cause a significant increase in Zn uptake in roots in the Halii soil (Table 9). The mean increase in Zn uptake in the roots with increasing P in the Halii soil was 43% which is almost twice the increase noted in the tops (27%) due to P application. As in the tops, this increase may be associated with increased dry matter yield from P fertilization.

Soil Extractable Zn in Relation to Plant Response

Correlation coefficients relating soil-test extractable Zn with plant Zn concentration, yield and Zn uptake by plants are often used as criteria by which Zn soil tests are evaluated. In this study, correlation coefficients between soil-test extractable Zn and added Zn were also evaluated.

The relationship between soil extractants and added Zn was higher than the relationship between extractants and yield or plant Zn in both soils (Tables 10 and 11). Among the plant variables for the Hilo soil, correlation coefficients were generally higher for yield and total Zn uptake than for Zn concentration which had negative correlation coefficients (Table 10). On the Halii soil however, plant Zn concentration and total Zn uptake had higher correlation coefficients than yield which had very low correlation coefficients (Table 10).

The differences in the pattern of correlation coefficients for Zn concentration in the two soils may be due to the fact that there was a significant yield response to applied Zn on the Hilo soil but not on the Halii soil. Soil Zn was probably at deficiency levels in the Hilo soil but above deficiency levels in the Halii soil. A dilution of plant Zn with dry matter in the first Zn rates in the Hilo soil very likely is responsible for this negative correlation between extracted soil Zn and plant Zn concentration. On the other hand, in the Halii soil, added Zn resulted in increased concentration of plant Zn. Therefore high correlation between plant Zn concentration and extracted Zn was found.

Table 10. Correlation coefficients relating extractable Zn to added Zn, yield, Zn concentration and uptake of corn on Hilo and Halii soils, respectively[+]

I - Hilo Soil

Extraction Method	Correlation Coefficients (r) Added Zn	Yield	Zn Conc	Zn Uptake
0.1N HCl	.96***	.63***	-.24*	.68***
EDTA-$(NH_4)_2CO_3$	.99***	.68***	-.26*	.72***
DTPA - TEA	.97***	.58***	-.17	.63***
2N $MgCl_2$	.95***	.70***	-.32*	.73***

II - Halii Soil

Extraction Method	Correlation Coefficients (r) Added Zn	Yield	Zn Conc	Zn Uptake
0.1N HCl	.97***	.12	.85***	.79***
EDTA-$(NH_4)_2CO_3$	.97***	.07	.88***	.78***
DTPA - TEA	.98***	.13	.85***	.81***
2N $MgCl_2$	.82***	-.07	.90***	.68***

[+] n = 40

*Significant at 5% level

**Significant at 1% level

***Significant at .1%

Nonsignificant

Table 11. Correlation coefficients relating extractable Zn to added Zn, yield, Zn concentration and uptake of corn on Hilo and Halii soils together+

Extraction Method	Correlation Coefficients (r)			
	Added Zn	Yield	Zn Conc	Zn Uptake
0.1N HCl	.80***	.22**	.23**	.34***
EDTA-$(NH_4)_2CO_3$	.96***	.34***	.56***	.70***
DTPA - TEA	.91***	.31**	.68***	.75***
2N $MgCl_2$	.72***	.18	.77***	.70***

+n = 80

**Significant at 1% level

***Significant at .1% level

Nonsignificant

The correlation between plant Zn concentration and soil Zn extracted by 2N $MgCl_2$ was the highest in the Halii soil ($r = +.90$), the most negative in the Hilo soil ($r = -.32$) and the highest when data from the two soils were combined ($r = +.77$) (Tables 10 and 11). Stewart and Beger (1965) found that 2N $MgCl_2$ extractable Zn correlated better with plant Zn concentration than did either dithizone or 0.1N HCl extracted Zn values. Maclean (1974) also found high correlation between Zn concentration in corn, lettuce and alfalfa with Zn extracted with 2N $MgCl_2$ ($r = + 0.93$), 0.01M $CaCl_2$ ($r = + 0.90$), and 0.005M DTPA ($r = + 0.73$).

Total Zn uptake appears to be a better measure of plant available Zn than plant Zn concentration because it is not affected by the dilution of plant Zn by increased dry matter resulting from increased growth when Zn is applied to Zn-deficient soils. Therefore higher correlation coefficients were found between added Zn and total Zn uptake than between added Zn and plant Zn concentration in both soils.

On the Hilo soil, Zn extracted by 2N $MgCl_2$ and EDTA-$(NH_4)_2CO_3$ was the most highly correlated with Zn uptake while in the Halii soil, Zn extracted by DTPA, 0.1N HCl and EDTA had similar correlation coefficients (+.805, +.792, +.781, respectively) for the correlation with Zn uptake.

The correlation between yield and extractable soil Zn was not the same in the two soils. There was good correlation between yield and Zn extracted with the four methods in the Hilo soil, but there was poor correlation between these same variables in the Halii soil, (Table 10). This discrepancy may be due to the fact that the Hilo soil responded to Zn applications whereas the Halii soil did not.

Furthermore yields and total Zn uptake were highly correlated in the Hilo soil (r = .96), but this correlation was relatively low in the Halii soil (r = .52).

Since total Zn uptake and Zn extracted by the four methods from the two soils either alone or when combined gave relatively high correlation coefficients, total Zn uptake appears to be a good measure of plant extractable Zn for evaluation of soil Zn extractants.

Effect of P and Zn Fertilization and Soil pH on Extractable Soil P

Available soil P measured by Modified Truog extraction increased significantly with increasing amounts of applied P irrespective of the level of Zn applied in both soils (Tables 12, 13, 14, 15). However the effect of soil pH on extractable P differed in the two soils. In the Hilo soil increasing soil pH increased extractable P by an average of 4% whereas in the Halii soil increasing soil pH decreased extractable P by an average of 7%.

Effect of P and Zn Fertilization and Soil pH on Extractable Soil Zn

The amounts of Zn extracted by the four methods decreased in the following order 0.1N HCl $>$ EDTA $>$ DTPA $>$ 2N $MgCl_2$ in both soils (Tables 12 and 14).

Zn extracted by the four methods generally increased with application of Zn in both soils. The increase with the initial Zn increments, especially 2 and 4 ppm added Zn, was very small in the Hilo soil relative to the Halii soil. However Zn extracted by EDTA and DTPA seemed to reflect these initial Zn rates better than either 0.1N HCl or 2N $MgCl_2$.

Table 12. Effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Hilo soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Applied Zn (ppm)	Truog Ext. P. (ppm)	Extractable Zn (ppm)			
				0.1N HCl	EDTA	DTPA	2N $MgCl_2$
7.8	4.9	0	255	8.63	1.78	1.14	.90
10.8	5.0	0	357	8.52	1.76	1.00	1.04
7.8	5.4	0	280	7.58	1.75	1.07	1.09
10.8	5.4	0	379	7.99	1.60	1.12	.94
7.8	5.1	2	273	8.83	2.80	1.37	1.14
10.8	5.1	2	355	9.37	2.65	1.43	1.27
7.8	5.7	2	265	9.98	2.13	1.59	1.15
10.8	5.7	2	384	9.10	2.32	1.51	1.14
7.8	5.1	4	262	9.88	3.63	1.74	1.47
10.8	5.1	4	352	9.83	3.28	1.80	1.41
7.8	5.7	4	274	11.21	3.33	1.79	1.48
10.8	5.7	4	370	11.82	3.58	1.89	1.53
7.8	5.1	8	257	11.44	4.58	2.16	1.87
10.8	5.1	8	363	12.39	4.44	2.22	1.85
7.8	5.7	8	264	13.80	4.62	2.70	1.63
10.8	5.7	8	366	13.94	4.82	2.50	1.69
7.8	5.1	16	260	16.03	7.12	4.26	2.43
10.8	5.1	16	362	16.06	6.83	4.04	2.29
7.8	5.7	16	269	18.14	8.03	4.94	2.11
10.8	5.7	16	381	17.53	7.65	5.09	2.11
7.8	5.7	32+	267	29.33	13.85	9.85	2.93
10.8	5.7	32+	388	29.32	14.50	10.63	2.71

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 13. Summary of statistical analyses for the effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from Hilo soil

Treatment	Truog Extractable P	F Values			
		Extractable Zn			
		0.1N HCl	EDTA	DTPA	Mg Cl_2
Applied P	721.96****	.27	1.08	.10	.37
Soil pH	13.32**	26.57****	1.32	35.58****	2.38
Applied Zn	.43	249.08****	603.54****	585.63****	126.04****
Interactions					
P x pH	1.62	.76	1.65	.15	.85
P x Zn	.44	.59	.67	.24	.73
pH x Zn	.68	7.11**	7.80***	9.31***	2.10
P x pH x Zn	1.01	1.05	.74	1.19	1.19

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table 14. Effects of P, pH and Zn on extractable P and Zn extracted by 0.1N NCl, EDTA $(NH_4)_2CO_3$ and 2N $MgCl_2$ from the Halii soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Applied Zn (ppm)	Truog Ext. P (ppm)	Extractable Zn (ppm)			
				0.1N HCl	EDTA	DTPA	2N $MgCl_2$
2.2	3.7	0	42.5	4.16	1.50	1.94	1.20
3.2	3.8	0	60.1	3.79	1.56	.97	1.17
2.2	4.8	0	39.4	3.08	1.22	.64	.96
3.2	4.8	0	57.6	3.40	1.27	.70	.88
2.2	3.8	2	46.4	4.96	2.42	1.60	1.78
3.2	3.8	2	65.8	5.43	2.35	1.81	1.82
2.2	4.8	2	38.7	4.22	1.74	1.24	1.14
3.2	4.8	2	57.9	4.21	1.79	1.44	1.19
2.2	3.9	4	42.5	6.18	3.44	2.24	2.34
3.2	3.8	4	62.9	6.64	3.58	2.40	2.62
2.2	4.8	4	40.7	5.27	2.48	1.94	1.47
3.2	4.8	4	57.4	6.36	2.81	2.10	1.30
2.2	3.8	8	45.6	8.28	5.63	4.14	3.12
3.2	3.8	8	61.8	8.57	5.42	4.00	3.37
2.2	4.8	8	44.0	8.02	4.10	3.34	1.92
3.2	4.8	8	63.2	7.42	4.32	3.48	2.17
2.2	3.8	16	43.7	14.98	10.31	8.26	5.98
3.2	3.8	16	62.9	13.98	9.81	8.08	5.42
2.2	4.8	16	39.7	12.29	7.71	6.58	2.72
3.2	4.8	16	57.9	11.64	7.65	6.67	2.89
2.2	4.8	32+	45.3	22.79	13.43	13.81	4.78
3.2	4.8	32+	62.5	24.12	13.89	14.22	5.05

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 15. Summary of statistical analyses for the effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Halii soil

Treatment	Truog Extractable P	F Values: Extractable Zn 0.1N HCl	EDTA	DTPA	Mg Cl_2
Applied P	174.22****	.00	.00	1.19	.21
Soil pH	7.32*	68.55****	369.39****	89.32****	970.85****
Applied Zn	.85	645.89****	2376.07****	1229.25****	821.94****
Interactions					
P x pH	.01	.05	4.42*	.73	.32
P x Zn	.04	3.80*	2.26	.51	3.52*
pH x Zn	.81	7.18**	43.68****	12.67****	133.00****
P x pH x Zn	.15	1.43	.66	.24	6.10**

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Application of P did not have any consistant effect on Zn extracted by the four methods. These findings corroborate those of Boawn, et al. (1954), Bingham, et al. (1960), Stukenholtz, et al. (1966), Sharma, et al. (1968b) and Brown, et al. (1970) who did not observe any reduction in extractable soil Zn due to P application.

Several workers have indicated that P fertilization often increases extractable Zn (Bingham, et al. 1956; Langin, et al. 1962; Keefer, et al. 1968). One explanation for this increase is that Zn impurities are sometimes present in P fertilizer. Boawn, et al. (1954) and Langin, et al. (1962) have reported that a Western source of superphosphate contained approximately 2,400 ppm Zn as a natural impurity. Arain (1976) found 1,400 ppm Zn present in the superphosphate being used in Hawaii. Other explanations have been offered for the increase in extractable Zn with P fertilization. Lindsay (1972) and Marinho, et al. (1972) reported that the increase in available Zn due to P application seems to indicate that P may compete with Zn by reacting with free R_2O_3 or by forming a more soluble compound with Zn. On the other hand, a decrease in extractable soil Zn due to P application has been reported (Prasad and Sinha, 1968; Warnock, 1970).

Increasing soil pH generally decreased Zn extracted from the Halii soil but generally increased that from the Hilo soil (Tables 12 and 14, respectively). The decrease in the Halii soil was observed in the four methods but the magnitude of the decrease varied with the extractant. The largest decrease in extractable soil Zn with increasing pH occurred with 2N $MgCl_2$ (42%), followed by EDTA (24%), DTPA (18%) and 0.1N HCl (14%). Although the effects were relatively small in the Hilo soil, increasing pH tended to increase extractable Zn, but it was significant only in the case of Zn extracted by 0.1N HCl (9%) and DTPA (14%) (Table 13).

The interaction between pH and Zn was significant in the four methods in the Halii soil (Table 15). Extractable Zn decrease with increasing pH at all Zn levels but the magnitude of the decrease tended to be greater at high Zn levels (Table 14). In the Hilo soil, this interaction was significant for all methods except 2N $MgCl_2$ (Table 13). Extractable Zn generally increased with increasing pH at all Zn levels and the increase was greater at higher Zn levels (Table 12).

Sites of P-Zn Interaction

Soil

As reported earlier and shown in Tables 13 and 15, P rates did not have any effect on Zn extracted from both soils by the four methods. These data and the high solubility of $Zn_3(PO_4)_2$ in the soil (Lindsay, 1972) suggest that the Zn disorder observed especially in the Hilo soil was not caused by precipitation of Zn resulting from high P rates. These results agree with those of Pauli, et al. (1968); Sharma, et al. (1968b) Warnock (1970); Takkar, et al. (1976).

In addition, Stuckenholtz, et al. (1966) observed no change in in 0.1N HCl soluble Zn in an alkaline soil as rate of P increased from 10 to 1000 ppm. Brown, et al. (1970) found that rates of P did not greatly affect soil Zn extracted with ammonium acetate-dithizone, but tended to increase rather than decrease extractable Zn. Marinho, et al. (1972) reported an increase in Na_2-EDTA soluble Zn as a result of P applications, however, this was not reflected in total Zn uptake by corn in most cases.

Plant

In the Hilo soil, Zn uptake in the roots as well as in the tops decreased with increasing P, especially in the treatment combinations where available Zn was not adequate for normal growth. However, in the Halii soil, Zn uptake generally increased in the roots and tops with P fertilization. One exception was the control treatments at high pH in which Zn uptake increased in the roots and decreased in the tops.

There was no evidence of Zn accumulation in the roots of corn plants grown in the Hilo soil although P significantly reduce Zn uptake (Tables 3, 4 and 7). These data suggest that high levels of P may reduce total Zn uptake especially when soil is deficient or near deficient in available Zn. This may be caused by P in some way reducing entry of Zn into the roots. A similar mechanism was suggested by Takkar, et al. (1976). Bingham and Garber (1960), Burleson, et al. (1961) and Bingham (1963) suggested that P reduced uptake of Zn and Cu by some process in the soil external to the plant.

Terman, et al. (1972) reported that P- induced Zn deficiencies are largely the result of dilution of Zn caused by growth response to P. This may be the case of the reduced Zn uptake on the control treatments in the Halii soil at high pH and P. However, Terman reported that on extremely Zn or P- deficient soils, application of one nutrient may cause reduced plant uptake of the other. This reduced Zn uptake may be caused by poor translocation of Zn from roots to tops or by some other unidentified physiological effect. This was also noted by Burleson and Page (1967). Safaya, et al. (1976) suggested that while P application at a relatively low rate induced Zn deficiency by restricting the translocation of Zn to the shoots, at high P rates the absorption at the root surface itself was slowed to the extent that the total uptake of Zn by the entire plant was reduced. In both cases, P reduced Zn flux into the roots. These suggestions may explain the pattern found in the present data, from the Hilo soil. In the Hilo soil, where the total Zn uptake by the entire plant was reduced with P application, the amounts of extractable soil P (Table 12) were almost 5 times as high as the amounts extracted from the Halii soil (Table 14) where this effect was not observed. However, the possible lower amounts of available Zn in the Hilo soil than in the Halii soil may also have contributed to the larger reduction in Zn uptake with P fertilization in the Hilo soil as compared to the Halii soil.

Keefer and Singh (1968) found that added P fertilizer reduced Zn content to the same extent in roots, stems and leaves. They postulated that the interaction was physiological and might be the result of a change in the permeability of the cell wall or some other associated phenomenon. Recently Youngdahl, et al. (1977) have reported that high applications of P increased the amount of Zn bound to root cell walls which may reduce the amount of Zn available for transport to the upper portions of the plant, resulting in Zn deficiency. The present data did not show any obvious accumulation as reported earlier. However, this possibility may not be excluded because the washing process to free the roots from soil may have released some Zn from the roots although the amounts should not be large. Burleson, et al. (1961) also suggested the possibility of a P-Zn antagonism within the roots. Dwivedi, et al. (1975) reported that in Zn deficient corn plants the concentration of Zn significantly increased in roots and nodes and decreased in leaves and the internodes.

Figure 1 shows that a P induced Zn deficiency may be prevented by adding a small amount of Zn with the fertilizer. This was also suggested by Viets (1966) and Brown, et al. (1970).

P/Zn Ratios in Corn

Relationship with Yields, Zn Concentration and Uptake

The data shown in Table 3 indicated that application of Zn to the Hilo soil resulted in significant yield increases (Table 4). However, neither the Zn disorder, nor its correction was well correlated with plant Zn concentration, since Zn concentration decreased with the first rates of Zn and then tended to increase gradually with higher rates of applied Zn. In addition, the lowest yield (1.30 g/pot) in the Hilo soil occurred with plants which had the highest Zn concentration (34 ppm Zn) (Table 3). In the Hilo soil Zn concentration in plants from the lowest Zn treatments which had inadequate Zn was above the optimum (22 ppm) established in this study. These variations are due largely to the concentration or dilution of plant Zn by varying amounts of dry matter.

These findings suggest that plant Zn concentration may not reflect the Zn nutritional status of the plant. However, total Zn uptake as discussed earlier seems to do so. A major problem with determining total uptake of any nutrient is that both nutrient concentration and dry weight must be obtained and the determination of dry weight under field conditions can be difficult. The ratio of the concentration of P and Zn may provide a better measure of the Zn status of plants, since the dilution or concentration of Zn by dry matter is avoided. Table 16 shows that Zn uptake was more highly correlated with the P/Zn ratio than with Zn concentration.

In the Hilo soil yields were highly correlated with the P/Zn ratios as well as with total Zn uptake (Table 16). However in the

Table 16. Correlation coefficients relating yield, Zn concentration, Zn uptake and P/Zn ratios in Hilo and Halii soils[+]

I - Correlation Coefficients - Hilo Soil

	Yield	Zn Conc	Zn Uptake
P/Zn	-.92***	.58***	-.91***
Zn Uptake	.96***	-.55***	--
Zn Concentration	-.72***	--	--

II - Correlation Coefficients - Halii Soil

	Yield	Zn Conc	Zn Uptake
P/Zn	-.07	-.78***	-.63***
Zn Uptake	.65***	.59***	--
Zn Concentration	-.18	--	--

[+] n = 40

*** Significant at .1% level

Nonsignificant

Halii soil correlation between the P/Zn ratios and yields was much lower than that between total Zn uptake and yields (Table 16). This discrepancy may be due to the fact that in the Hilo soil, increasing Zn increased yield and total Zn uptake (Table 3) but decreased P/Zn ratios (Table A.2). In the Halii soil, however, increasing Zn did not affect yields but increased Zn uptake (Table 5) and decreased P/Zn ratios (Table A.4). There was a significant yield increase with increased P and pH in this soil (Table 6). Total Zn uptake reflects these responses because it integrates dry matter production and Zn concentration. However P/Zn ratios do not reflect these responses since yield increases due to P and pH did not necessarily change P and Zn concentrations in the plant. Therefore better correlation was found between yield and Zn uptake than yield and P/Zn ratio.

Effects of P, pH and Zn on P/Zn Ratio

In both soils results have shown that the P/Zn ratio decreased fairly consistently with increasing Zn application (Tables A.2 and A.4). This is probably a consequence of the fact that increasing amounts of Zn were applied while rates of P applied were constant.

Applied P, however, significantly increased the P/Zn ratio in the two soils (Tables A.2 and A.5). This might be associated with an increase in P uptake as a result of P fertilization and/or a decrease in Zn uptake resulting from the application of P as discussed earlier. The P/Zn interaction was significant in the Hilo soil (Tables A.3 and A.5). As added P was increased in the Hilo soil the P/Zn ratios increased at almost all Zn levels but the magnitude of the increase varied (Table A.2).

Soil pH as well as its interaction with Zn had significant effects on the P/Zn ratio only in the Hilo soil. This was probably due to the fact that the P/Zn ratio was high at 0 and 2 ppm Zn at high pH then decreased very sharply when applied Zn was increased above 2 ppm. This did not occur at low pH. One explanation for this is that increasing pH reduced Zn availability, especially at 0 and 2 ppm Zn while availability of P was relatively unaffected by the increase in pH. This differential effect of pH on uptake of Zn and P was probably the cause of the increased P/Zn ratios with increasing pH.

In the Halii soil, pH and its interaction with Zn probably had no significant effect on P/Zn ratio because, as discussed earlier, the pH values attained (3.8 and 4.8) are not likely to cause a reduction in Zn availability.

Critical Values for the P/Zn Ratios

The data presented in Table A.2 reveal that the values of the P/Zn ratio that coincide with the optimum yield for each combination of pH and P in the Hilo soil are as follows:

	pH 5.0		pH 5.7	
P in solution (ppm)	.05	1	.05	.1
Applied Zn (ppm)	2	4	4	8
P/Zn	104	124	112	102

These figures suggest that P/Zn values in the range of 100-125 are critical and that values above this range indicate a Zn disorder in corn and/or that a response to Zn fertilization is likely while values below this indicate adequate Zn. Boawn and Leggett (1964) observed a P induced growth disorder in potatoes that could be eliminated by an increased supply of Zn and the metabolic upset correlated better with the P/Zn ratio. They reported that Zn-deficient plants had P/Zn ratios above 400. Stuckenholtz,et al. (1966) pointed out that the P/Zn critical level in corn tissue varied from 100 to 350 depending upon the soil type and other conditions of the test. Warnock (1970) reported that P/Zn ratios ranged from 11 to 743 with both P and Zn varing from deficiency to excess. Reddy, et al. (1973) suggested that a value of 250 may be the critical P/Zn ratio above which P-induced Zn deficiency might be observed in corn. Gattani, et al. (1976) indicated a value of 150 as the critical ratio of P/Zn concentrations above which P-induced Zn-deficiency in wheat plants might be expected. Takkar, et al. (1976) found critical P/Zn values to be 90 in the stover, 100 in the leaves and 150 in the corn grain.

The critical range found in this study (100-125) is in close agreement with that of Takkar, et al. Furthermore his data were from field experiments repeated in 3 consecutive years. It should be pointed out that the general accepted optimum P and Zn concentrations in corn tissue are .20% and 20 ppm, respectively. Based on these figures a calculated P/Zn ratio of 100 is obtained which is in close agreement with the range of 100-125 inferred from data of this study.

As mentioned earlier, this critical range of P/Zn values was established on data for the Hilo soil since application of P and lime (pH) reduced Zn availability which significantly reduced yields (Table 4) only in the Hilo soil. However it is interesting to note that in the Halii soil, the P/Zn ratio was about 125 in the control treatments at high pH in which increased P may have decreased Zn availability to the point of reducing yield (Table A.3). These observations indicate that this P/Zn ratio may be considered a "critical" ratio which is similar to that found in the Hilo soil.

In the Hilo soil the reduction in Zn uptake by increased soil pH and/or P was reflected in the P/Zn ratio. This is especially evident in the P/Zn ratios of the control treatments at low and high pH. This data suggest that the P/Zn ratio may reflect Zn disorders caused by high P fertilization as well as those caused by other factors that may restrict uptake of Zn but not P.

P/Zn ratios may be useful in evaluating plant Zn nutritional status, especially when total Zn uptake cannot be obtained. However in order to do so P must be adequate because if the concentration of both P and Zn are below the optimum levels, for example, 0.08% P and 9 ppm Zn, the P/Zn ratio would be 89. This ratio would appear to be satisfactory for plant growth even though both soil P and Zn are deficient.

Comparison of Chemical Extractants for Soil Zn

As discussed earlier, Zn uptake appears to be a better plant parameter to use to evaluate soil Zn extractants than either plant Zn concentration or dry matter production alone. Therefore it will be the plant parameter used for evaluation of extractants.

To assess the generality of the soil Zn extractants used in this study, an experiment with soils having a range of mineralogy was conducted. In addition to different mineralogies, two of four soils used in this experiment were reported to be Zn deficient. These two Zn deficient soils were used in the main experiment reported earlier, in which several levels of Zn were added to measure response to Zn application. Thus, the ability of an extractant to separate deficient from sufficient Zn soils could be evaluated and a tentative critical level for soil Zn could be established.

Evaluation of Extractants on the Hilo and Halii Soils Separately

Correlation coefficients presented in Table 17 suggest that the Zn extracted by the four extractants are generally highly correlated with total Zn uptake by plants in these two soils.

The use of the log transformation of soil extractable Zn increase correlation coefficients for the four extractants in the Hilo soil but decreased then slightly in the Halii soil (Table 17). This result may have been due to the fact that in the Hilo soil the increase in total Zn uptake was greater with the first rates of added Zn than with the higher Zn rates (Table 3). However in the Halii soil, there was no response to added Zn so that the increase in Zn uptake with increasing added Zn was generally linear. Therefore a linear relationship fits the data better in the Halii soil, whereas in the Hilo soil the relationship is linear for the first Zn levels then it become curvilinear when Zn uptake levels off at higher Zn rates; therefore, the log transformation of extractable Zn gives a higher correlation than the linear form.

Table 17. Correlation coefficients for the relationship between extractable soil Zn and Zn uptake by corn in the Hilo and Halii soils separately+

Extraction Method	Correlation Coefficents (r) Total Zn Uptake	
	Hilo Soil	Halii Soil
0.1N HCl	.68***	.79***
EDTA - $(NH_4)_2CO_3$	.72***	.78***
DTPA	.63***	.81***
2N $MgCl_2$	.73***	.68***
ln 0.1N HCl	.72***	.77***
ln EDTA - $(NH_4)_2CO_3$	.81***	.76***
ln DTPA	.72***	.78***
ln 2N $MgCl_2$	.76***	.66***

*** Significant at 0.1% level

+ n = 40

Since all extractants generally were highly correlated with total Zn uptake in these two soils, it was difficult to evaluate the extractants solely on these figures at this point.

Evaluation of Extractants on the Hilo and Halii Soils Combined

Data for the two soils were combined to evaluate the generality of the extractants and correlation coefficients relating soil Zn extracted by the four methods with total Zn uptake are shown in Table 18. Linear and log relationships were used because they were found to give higher correlation coefficient for the Halii and Hilo soils, respectively, in previous studies. However the log transformation generally gave higher correlation for both total Zn uptake and relative total Zn uptake (Table 18).

A marked improvement in the correlation coefficients for 0.1N HCl and to some extent for those of EDTA (Table 18) occurred using relative Zn uptake rather than Zn uptake. This improvement is probably due to the fact that 0.1N HCl and EDTA extracted relatively more Zn from the Hilo soil than from the Halii soil, whereas the amounts of Zn uptake by the plants were relatively larger for the Halii than for the Hilo soil (Tables 12 and 14). Therefore the use of relative Zn uptake partially eliminated these differences in total Zn uptake between the two soils. However in the case of DTPA and 2N $MgCl_2$, there was a decrease in the correlation coefficients with the use of relative Zn uptake. One explanation may be that the relative amount of Zn extracted from the two soils and the total Zn uptake followed the same pattern, i.e. larger quantities from the Halii soil than from the Hilo soil (Tables 3 and 5).

Table 18. Correlation coefficients relating extractable soil Zn and Zn uptake by corn in Hilo and Halii soils combined+

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r) Total Zn Uptake	Relative Zn Uptake
0.1N HCl	(w/w)	.34***	.68***
EDTA	(w/w)	.70***	.71***
DTPA	(w/w)	.74***	.61***
2N $MgCl_2$	(w/w)	.70***	.48***
ln 0.1N HCl	(w/w)	.31**	.65***
ln EDTA	(w/w)	.69***	.76***
ln DTPA	(w/w)	.73***	.67***
Ln 2N $MgCl_2$	(w/w)	.72***	.55***
0.1N HCl	(w/v)	.75***	.60***
EDTA	(w/v)	.77***	.50***
DTPA	(w/v)	.76***	.44***
2N $MgCl_2$	(w/v)	.68***	.30**
ln 0.1N HCl	(w/v)	.74***	.65***
ln EDTA	(w/v)	.82***	.59***
ln DTPA	(w/v)	.79***	.50***
ln 2N $MgCl_2$	(w/v)	.72***	.55***

+n = 80

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level
Nonsignificant

The greater uptake of Zn by plants from the Halii soil than from the Hilo soil relative to the larger amount of Zn extracted from the Hilo than from the Halii soil may be partially explained by the fact that the bulk density of the Halii soil is greater than that of the Hilo soil. The laboratory data for extracted Zn are expressed on a weight basis (μg/g). However, the volume of soil in pots available to roots to extract Zn was the same for both soils, but the total amount of Zn present in each soil was different because it was applied on the basis of soil weight (ppm) and the bulk density of the soil in pots was .25 g/cm^3 and .50 g/cm^3 for the Hilo and the Halii soils, respectively.

Under field conditions the bulk densities of these soils are about .5 g/cm^3 and 1 g/cm^3 for the Hilo and Halii soils, respectively. However in the pots the bulk densities decreased about 50%. Uehara (pers. comm.) has found that once soil is sieved and placed in pots, it is difficult to achieve the previous field bulk density even if it is a sandy soil which is compacted after being placed in pots.

The amounts of Zn extracted on the soil weight basis will probably not reflect the amounts taken up by plants when soils with different bulk densities are compared. Therefore an adjustment of the extracted Zn was made by multiplying Zn extracted from the soils by the bulk density for the soil that is 0.25 for the Hilo soil and 0.50 for the Halii soil. Thus the results are expressed on the basis of weight of extractable Zn/volume of soil (w/v).

Correlation coefficients for the relationships between soil Zn extracted by the four methods on the w/v basis with total Zn uptake and with relative Zn uptake are presented in Table 18. It is apparent that expression on the w/v basis results in higher correlation coefficients than on the w/w basis for all extractants except 2N $MgCl_2$. The log form also had higher correlation coefficients than the linear form.

It is interesting to observe that on the w/v basis all methods have relatively high correlation coefficients, which decrease in the following order: EDTA $>$ DTPA $>$ 0.1N HCl $>$ 2N $MgCl_2$. Also the correlation coefficients for all extractants with Zn uptake presented in Table 17 for the two soils separately follow a pattern similar to that presented in Table 18 on the w/v basis. These data support the suggestion that the difference in Zn uptake may be partly due to the difference in bulk densities for these two soils.

It should be pointed out that the highest correlation coefficient in Table 18 were found for a relationship between total Zn uptake and the log transformation of extractable Zn on the w/v basis. In the case of relative Zn uptake, however, the highest correlation coefficients were found with the log transformation of extractable Zn on the w/w basis (Table 18). These results suggest that the use of relative Zn uptake adjusted for some of the differences in the plant parameter between the two soils while the transformation of soil extractable Zn from the w/w basis to the w/v basis possibly adjusted the soil parameter responsible for the differences in Zn uptake in the two soils. Therefore when the log of extractable Zn on the w/v basis is correlated with relative Zn uptake, the correlation coefficients are generally lower than those of either log of soil Zn on the w/w basis with relative Zn uptake or of log of extractable Zn on w/v basis with Zn uptake (Table 18). Since the correlation between total Zn uptake and log of extractable Zn on the w/v basis gave the highest correlation coefficients of all correlations in Table 18 it was selected for use in the evaluation of extractants.

It appears that extractable Zn on the w/v basis is probably a better parameter than extractable Zn on the w/w basis for predicting Zn uptake, especially when bulk densities of soils differ greatly.

Evaluation of Extractants on Soils Varying in Mineralogy

A good soil Zn extractant should extract all or a proportionate part of the available form or forms of Zn from soils with variable properties and should also be able to separate Zn-deficient from non-Zn-deficient soils.

Data from the corn experiment suggest critical levels for soil extractable Zn on the w/v basis to be about 3-4 $\mu g/cm^3$ for 0.1N HCl method, 1.25 $\mu g/cm^3$ for EDTA-$(NH_4)_2CO_3$ method, .75 $\mu g/cm^3$ for DTPA method and .45 $\mu g/cm^3$ for 2N $MgCl_2$. These values are the amounts of soil Zn extracted from the Hilo soil by each method (Table 12) from treatments that received 8 ppm Zn, multiplied by .25 (bulk density of Hilo soil). This soil and level were chosen because a yield response to added Zn up to 8 ppm Zn was observed and there was no yield increase beyond 8 ppm added Zn.

These values obtained on the w/v basis are comparable to the values reported as critical for soil Zn on the w/w basis i.e. 2-3 ppm for 0.1N HCl (Kanehiro, 1964); 1.4-3.0 ppm for EDTA-$(NH_4)_2CO_3$ (Lindsay, et al. 1969); .5 - .8 ppm for 0.05M DTPA (Maclean, et al.

1974); .4 ppm for 2N $MgCl_2$ (Stewart, et al. 1965). This may indicate that these critical values were obtained on soils in which the bulk density was close to 1 g/cm^3.

When the amounts of Zn extracted from the four soils by the four extractants on the w/w basis (Table 19) are compared to the critical level reported on the w/w basis, only EDTA identifies the Hilo and Halii soils as deficient in soil Zn. However, when the amounts of soil extractable Zn are expressed on w/v basis and compared to the critical levels on the w/v basis, the four extractants separate the Hilo and Halii soils from the Molokai and Lualualei soils (Table 19).

Adjustment of extractable Zn from the w/w basis to the w/v basis results in higher correlation coefficient with total Zn uptake (Table 20) as reported earlier. Only the log of extractable Zn is presented because it gave higher correlation coefficients than the linear form as described earlier.

Correlation coefficients between extractable soil Zn on the w/v basis and total Zn uptake decreased in the following order: EDTA $>$ DTPA $>$ 0.1N HCl $>$ 2N $MgCl_2$, but values for the first three extractants were very similar, .82, .80 and .77, respectively. In addition all 4 extractants separate the Hilo and Halii soils from the Molokai and Lualualei soils when extractable Zn was expressed on the w/v basis.

It is interesting to observe that when the extractants were evaluated on the Hilo and Halii soils combined in the previous section, the correlation for the relationship between log of extractable soil Zn (w/v) and Zn uptake (Table 18) decreased in the same

Table 19. Extractable soil Zn expressed on the w/w and w/v basis and total Zn uptake by corn grown on soils varying in mineralogy[a]

Extraction Method	Basis for Expressing Results		Amounts of Zn Extracted from Soils			
			Hilo (.25)[b]	Halii (.50)[b]	Molokai (.84)[b]	Lualualei (.69)[b]
0.1N HCl	μg/g	(w/w)	9.36	3.62	11.85	11.87
	μg/cm^3	(w/v)	2.34	1.81	9.95	8.19
EDTA	μg/g	(w/w)	1.82	1.77	7.69	5.21
	μg/cm^3	(w/v)	.45	.89	6.46	3.60
DTPA	μg/g	(w/w)	2.13	.89	10.24	6.10
	μg/cm^3	(w/v)	.53	.45	9.61	4.21
2N $MgCl_2$	μg/g	(w/w)	1.62	.98	1.36	1.02
	μg/cm^3	(w/v)	.41	.49	1.14	.71
Zn Uptake	μg/pot		355.90	527.10	759.20	1087.30

[a]Means are values of three replicates

[b]Bulk density in pots (g/cm^3)

Table 20. Correlation coefficients relating soil Zn extracted by four methods with Zn uptake by corn grown on soils varying in mineralogy+

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r) Total Zn Uptake
ln 0.1N HCl	w/w	.33
ln EDTA	w/w	.68**
ln DTPA	w/w	.73**
ln 2N $MgCl_2$	w/w	.52*
ln 0.1N HCl	w/v	.77**
ln EDTA	w/v	.82***
ln DTPA	w/v	.80***
ln 2N $MgCl_2$	w/v	.52*

+n = 12

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

order described above for the four soils and were of the same order of magnitude except for the 2N $MgCl_2$ extractant.

Evaluation of Extractants on all Soils Combined

In order to evaluate the extractants under a wider range of conditions, data from the main experiment in which the Hilo and Halii soils received Zn applications were combined with data from the mineralogy experiment in which the Hilo, Halii, Lualualei and Molokai soils did not receive added Zn.

Correlation coefficients in Table 21 are highest when total Zn uptake is related to the log of extractable soil Zn on the w/v basis. Only the log of extractable Zn is presented because it gave higher correlation coefficients than the linear form. As discussed earlier correlation coefficients generally are higher for relative Zn uptake related to extractable soil Zn expressed on the w/w basis but they are generally lower than correlation coefficients for Zn uptake related to extractable soil Zn expressed on either basis (Table 21).

The improvement in the relationship between Zn uptake and extractable soil Zn expressed on the w/v basis instead of the w/w basis was greatest with 0.1N HCl and EDTA. This improved relationship is illustrated by comparing scattergrams in Figures 5 and 6 which have the data expressed on the w/w basis with scattergrams in Figures 7 and 8 with the data expressed on the w/v basis. Also the relationship between total Zn uptake and soil Zn extracted with DTPA and 2N $MgCl_2$, expressed on the w/v basis is shown in Figures 9 and 10, respectively.

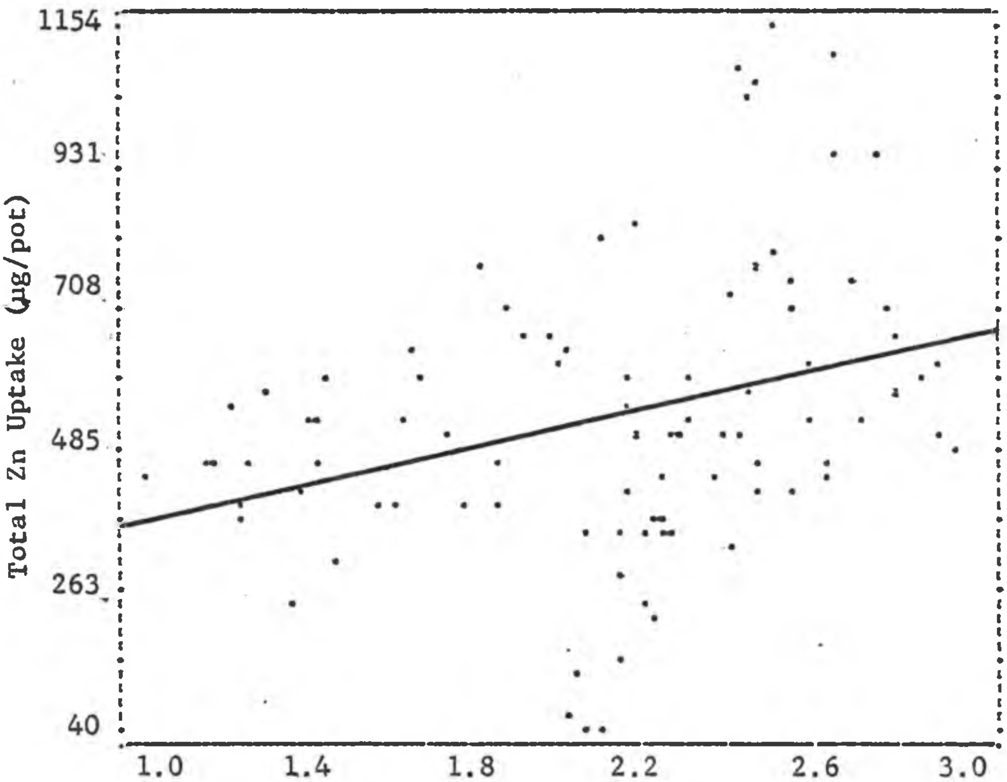
The results suggest that transformation of extractable soil Zn from the w/w basis to the w/v basis minimizes the differences among

Table 21. Correlation coefficients relating extractable soil Zn by four methods to total Zn uptake and relative Zn uptake by corn on the four soils from the two experiments combined[+]

Chemical Extractant	Basis for Expressing the Results	Correlation Coefficients (r)	
		Total Zn Uptake	Relative Zn Uptake
ln 0.1N HCl	w/w	.33***	.62***
ln EDTA	w/w	.68***	.76***
ln DTPA	w/w	.73***	.66***
ln 2N $MgCl_2$	w/w	.53***	.48***
ln 0.1N HCl	w/v	.77***	.65***
ln EDTA	w/v	.82***	.62***
ln DTPA	w/v	.80***	.53***
ln 2N $MgCl_2$	w/v	.53***	.48***

***Significant at 0.1% level

[+]n = 92



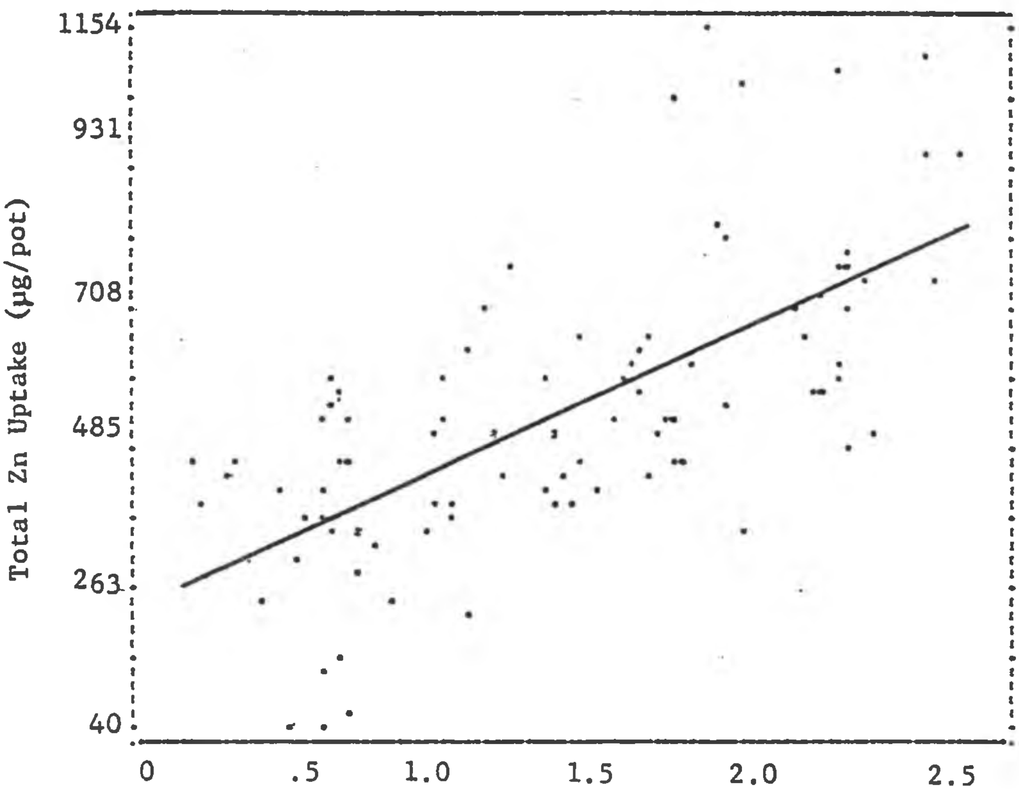
ln 0.1N HCl Extractable Zn Expressed on the w/w Basis (x)

$Y = 208.73 + 154.21(x)$

$r = .32$

$n = 92$

Figure 5. Relationship between Zn uptake by corn and soil Zn extracted by the 0.1N HCl method expressed on the (w/w) basis



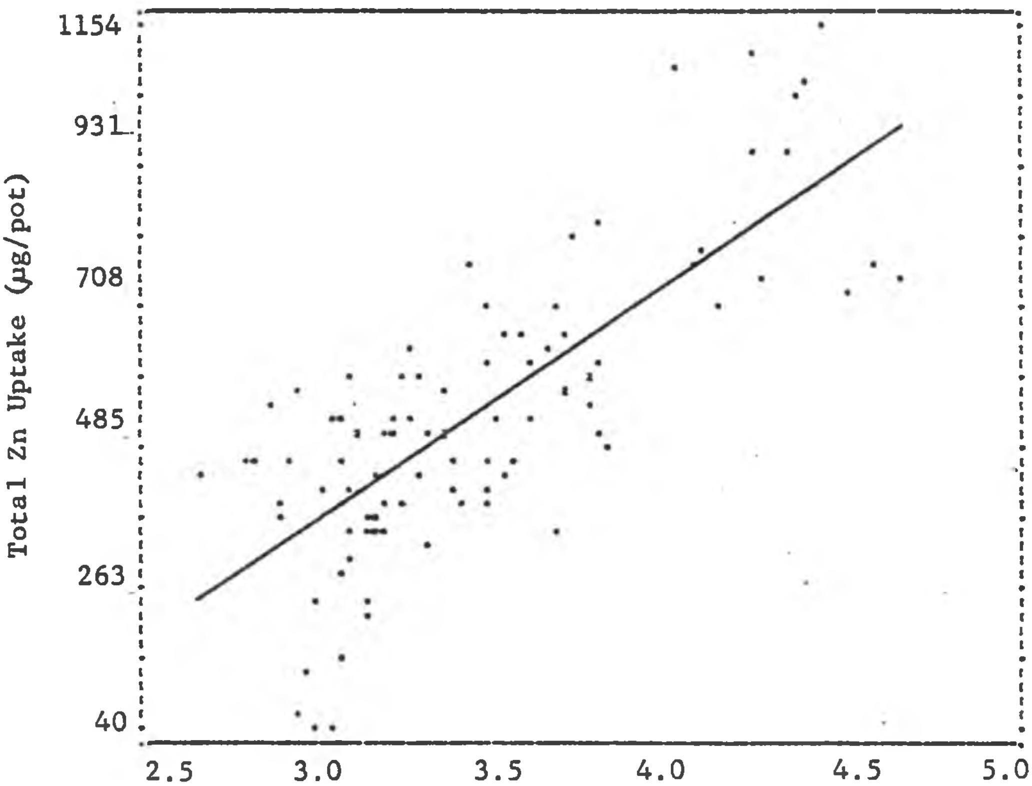
ln EDTA-$(NH_4)_2CO_3$ Extractable Zn Expressed on w/w Basis (x)

Y = 231.13 + 253.35(x)

r = .68

n = 92

Figure 6. Relationship between Zn uptake by corn and soil Zn extracted by the EDTA-$(NH_4)_2CO_3$ method expressed on the (w/w) basis



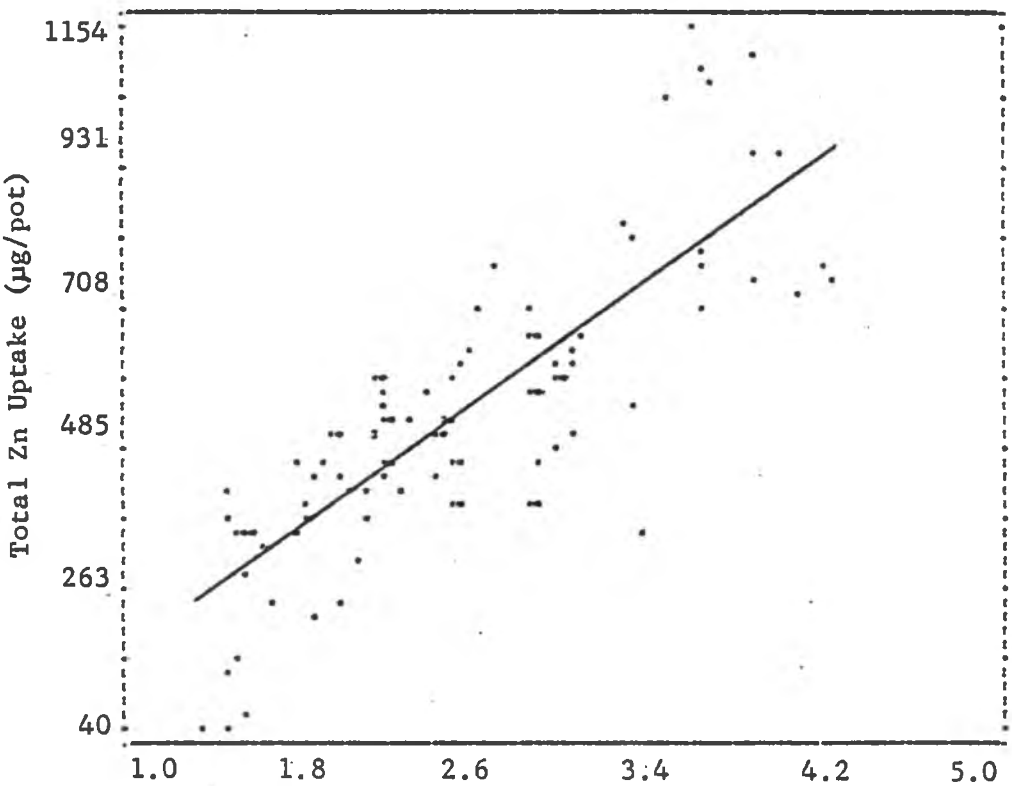
ln(0.1N HCl Extractable Zn Expressed on w/v basis x 10) (x)

Y = -733.25 + 368.87(x)

r = .77

n = 92

Figure 7. Relationship between Zn uptake by corn and soil Zn extracted by the 0.1N HCl method expressed on the (w/v) basis



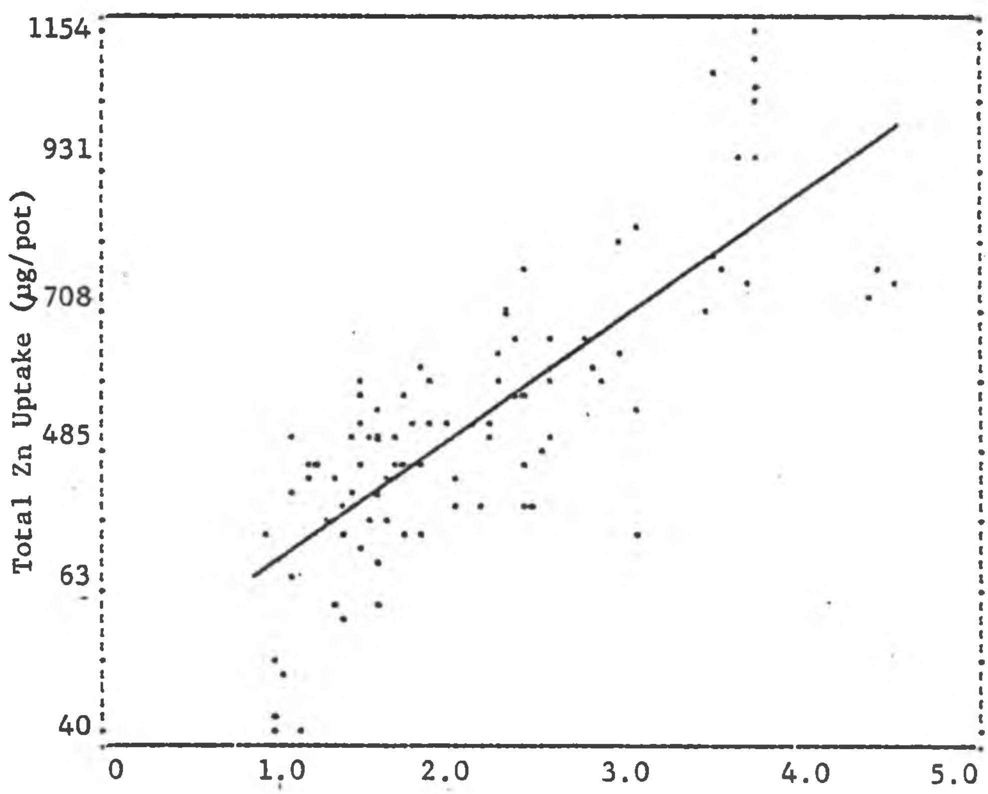
ln(EDTA-$(NH_4)_2CO_3$ Extractable Zn on Expressed w/v Basis x 10) (x)

Y = -80.71 + 245.28(x)

r = .82

n = 92

Figure 8. Relationship between Zn uptake by corn and soil Zn extracted by the EDTA-$(NH_4)_2CO_3$ method expressed on the (w/v) basis



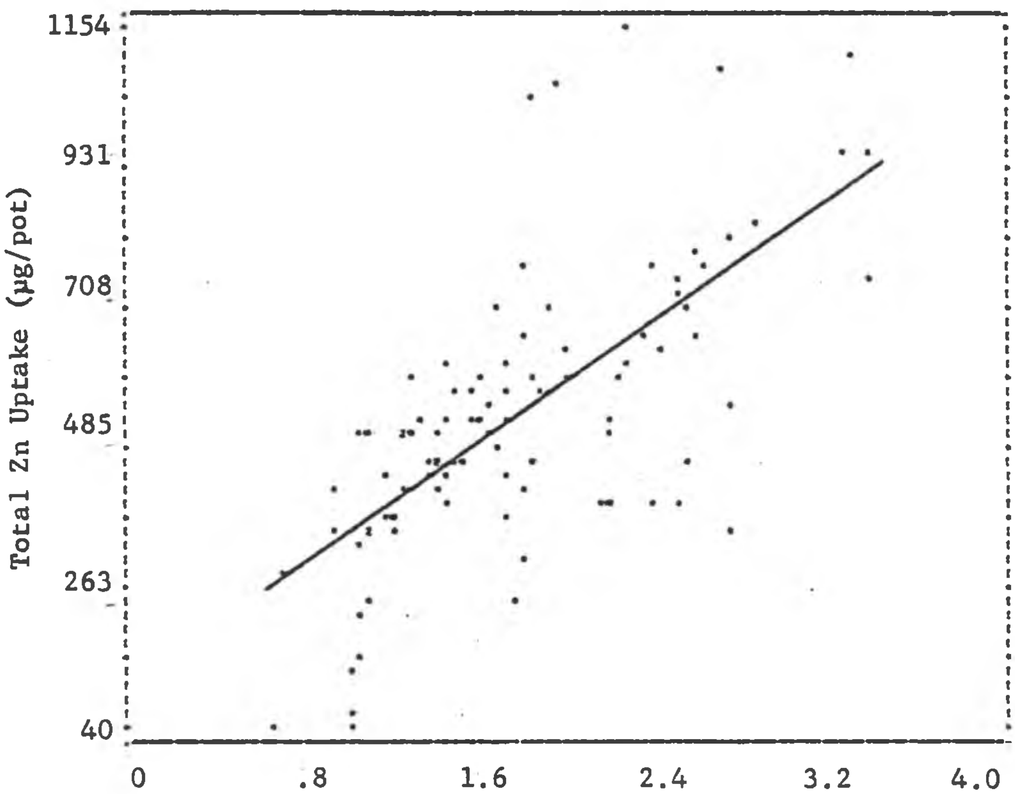
ln(DTPA Extractable Zn Expressed on w/v basis x 10) (x)

$Y = 116.75 + 197.19(x)$

$r = .80$

$n = 92$

Figure 9. Relationship between Zn uptake by corn and soil Zn extracted by the DTPA method expressed on the (w/v) basis



ln(2N $MgCl_2$ Extractable Zn Expressed on w/v Basis x 10) (x)

$Y = 110.65 + 239.26(x)$

$r = .68$

$n = 92$

Figure 10. Relationship between Zn uptake by corn and soil Zn extracted by the 2N $MgCl_2$ method expressed on the (w/v) basis

soils which may be related to Zn uptake by plants. This is supported by the fact that the data for different soils when combined gave higher correlation values between extractable soil Zn and Zn uptake when extractable soil Zn was expressed on the w/v basis than on the w/w basis.

In this general evaluation, correlation coefficients between total Zn uptake and Zn extracted on the w/v basis by different methods decreased in the following order: EDTA $>$ DTPA $>$ 0.1N HCl $>$ 2N $MgCl_2$ (Table 21). However the correlation coefficients for EDTA, DTPA and 0.1N HCl were very similar and these extractants may be considered comparable.

Other authors have compared extractants and selected one of these three extractants as most suitable for assessing soil Zn (Lindsay and Norvell, 1969; Trieweiller and Lindsay, 1969; Brown, et al., 1971; Juang, 1971; Haq, et al., 1972; Marinho, et al., 1972; Evans, et al., 1974; Arain, 1976).

According to Bray (1948) a good soil test should meet the following 3 criteria:

1. The extractant used should extract all or a proportionate part of the available form or forms of a nutrient from soils with variable properties.

2. The amount of nutrient extracted should be measured with reasonable accuracy and speed.

3. The amount extracted should be correlated with the growth and response of each crop to that nutrient under various conditions.

The 0.1N HCl method has been recommended for Hawaiian soils by other workers (Kanehiro, et al. 1967; Juang, 1971; Arain, 1976) and in this study it also was found to be a suitable method for assessing soil Zn as were the DTPA and EDTA methods. According to the data presented here, these 3 extractants adequately meet the criteria for a good soil extractant described above. However the precision of measurements is likely to be higher with 0.1N HCl because it extracts larger amounts of Zn than EDTA and DTPA. The major difference between this study and those mentioned above is the adjustment of extractable soil Zn for soil bulk density. The 0.1N HCl method was the poorest extractant when extractable soil Zn was expressed on the w/w basis and it did not separate deficient from non-deficient soils.

Correlation of Zn extracted by the 0.1N HCl method on the w/w and w/v basis with that extracted by the other three methods on the w/w and the w/v basis resulted in high correlation coefficient, especially with 0.1N HCl on the w/v basis (Table 22). The highest correlation coefficients were found between Zn extracted by the 0.1N HCl method on the w/v basis and Zn extracted by EDTA on the w/v basis and DTPA on both the w/w and w/v basis. It should be noted that the two chelating agents were more highly correlated with the 0.1N HCl method than with the 2N $MgCl_2$ method. Table 22 also shows the relatively low correlation between 0.1N HCl on the w/w basis and 0.1N HCl on the w/v basis ($r = .55$).

Tucker and Kurtz (1955) found that Zn extracted by acetic acid, EDTA, and 0.1N HCl were significantly correlated. Brown, et al. (1971) reported that soil Zn extracted by 0.1N HCl had a higher correlation coefficient with Na EDTA than with DTPA. Juang (1971) also reported

Table 22. Correlation coefficients for the relationship between Zn extracted by 0.1N HCl expressed on the w/w and w/v basis and Zn extracted by other methods+

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r) 0.1N HCl w/w	w/v
0.1N HCl	w/w	--	--
	w/v	.55***	1.00***
EDTA	w/w	.79***	.81***
	w/v	.42***	.96***
DTPA	w/w	.61***	.96***
	w/v	.33***	.95***
2N $MgCl_2$	w/w	.43***	.50***
	w/v	.18*	.63***

+n = 92

*Significant at 5% level

***Significant at .1% level

high correlation coefficients between soil Zn extracted by 0.1N HCl and soil Zn extracted by DTPA, EDTA, EDTA-$(NH_4)_2CO_3$, 2.5% HOAC, N NH_4OAC (pH 4.8). These findings are generally in agreement with the results in the present study.

SUGARCANE EXPERIMENT

Effects of pH, P, Zn on Growth of the Plant Crop of Sugarcane

As mentioned in the materials and methods section the plant crop of sugarcane had to be harvested early because of spray damage which killed the spindles of some plants. Of all the pots only one complete set of the added Zn treatments (0, 2, 4, 8 and 16 ppm Zn) at pH 6.0 and P .05 was found which had at least one live plant out of two in each pot for both reps. Therefore the dry weight, Zn concentration and Zn uptake by these plants were statistically analyzed to evaluate the effect of added Zn on sugarcane grown in the Hilo soil.

Yield and Zn uptake generally increased with added Zn although plant Zn concentration remained relatively unchanged where Zn was applied but was higher without added Zn (Table 23). Only the increases in yield with added Zn were statistically different at the 5% level. Yields with 8 and 16 ppm Zn were significantly larger than yields with lower levels of Zn (Table 23).

Data for the plants which were alive at harvest are presented in Appendices 11 and 12 for the Hilo and Halii soils, respectively. Although no statistical analysis was carried out on the remaining data from the Hilo soil because there were so many dead plants, there appears to be some yield increase with increasing Zn application especially at high pH with 8 and 16 ppm Zn. On the Halii soil, there appears to be some yield increase with increasing Zn application

Table 23. Effect of Zn on yield, Zn concentration and Zn uptake on plant crop of sugarcane grown on the Hilo soil

A - Table of Means

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Applied Zn (ppm)	Yield (g/plant)	Zn Conc (ppm)	Zn Uptake (μg/plant)	No. of Plants Alive
24.3	5.3	0	23.00b[+]	18.3	420.16	3
24.3	5.2	2	24.82b	16.5	412.58	3
24.3	5.3	4	23.88b	17.3	411.56	3
24.3	5.3	8	28.88a	16.0	514.68	2
24.3	5.0	16	31.46a	17.0	529.72	3

[+]Means not followed by the same letters are statistically different at the .05 level.

B - Summary of Analyses of Variance

Treatment	Yield	Zn Uptake	Zn Conc
Applied Zn	6.15*	.14	.46

*Significant at 5% level
Nonsignificant

to 8 ppm Zn followed by a decrease at higher Zn levels at high pH even though the data are not very reliable because of the small number of live plants in these treatments.

Effects of pH, P and Zn on Yield, Zn Concentration in the Plant Tissues and Total Zn Uptake by the Ratoon Crop of Sugarcane

Dry Matter Production

Plant yields did not differ significantly with added Zn on the Hilo and Halii soils. These soils probably had adequate available Zn for sugarcane at the pH attained. As indicated in Tables 24 and 26 the average soil pH values were 4.8 and 5.2 for the Hilo soil and 3.8 and 4.8 for the Halii soil, respectively. At these pH's, soil Zn is highly available to plants especially for sugarcane which has an extensive root system in the ratoon crop.

It was pointed out earlier that a yield response to applied Zn was observed in the plant crop grown in the Hilo soil at high pH. A possible explanation for this reversal may be the fact that for about one third of the growing period of the plant crop the cane was dependent on sett roots for uptake of water and nutrients. It has been reported that nutrient uptake by sett roots is very low. Also the shoot roots which appear after three to four weeks are not extracting Zn from much of the soil volume and thus may have been unable to extract sufficient Zn from these soils with low Zn. However in the ratoon crop a larger volume of roots developed which enabled the plant to explore more of the soil in the pot so that its

Table 24. Effect of P, pH and Zn on yield, Zn concentration of the sheath, T.V.D. leaf and meristem and total Zn uptake by a ratoon crop of sugarcane grown on the Hilo soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Added Zn (ppm)	Yield (g/pot)	Zn Concentration (ppm)			Total Zn Uptake (µg/pot)
				Sheath	T.V.D. Leaf	Meristem	
24.3	4.8	0	163.9	15.5	26.5	343.2	3,836
31.8	4.8	0	181.6	15.0	27.0	345.9	4,163
24.3	4.8	2	162.4	16.0	26.0	376.5	3,433
31.8	4.8	2	171.4	15.5	25.5	365.5	3,905
24.3	4.8	4	172.1	12.5	26.0	425.9	3,416
31.8	4.8	4	175.9	15.0	27.0	373.8	4,247
24.3	4.8	8	149.0	14.0	29.5	463.1	3,660
31.8	4.8	8	168.7	14.5	25.5	438.0	3,823
24.3	4.9	16	185.6	15.5	28.5	537.5	4,619
31.8	4.9	16	179.6	16.5	28.0	561.4	4,537
24.3	5.3	0	182.3	16.0	25.5	223.2	3,816
31.8	5.3	0	182.0	14.0	30.0	238.3	3,827
24.3	5.2	2	176.7	18.0	26.0	334.3	3,991
31.8	5.2	2	181.5	14.5	25.5	283.1	4,118
24.3	5.3	4	172.3	16.0	26.0	502.7	4,077
31.8	5.2	4	184.0	13.0	26.0	344.1	4,458
24.3	5.3	8	170.4	15.0	24.5	469.6	3,957
31.8	5.2	8	183.3	14.5	25.0	345.4	3,818
24.3	5.0	16	166.4	20.0	27.5	538.6	4,034
31.8	5.0	16	193.0	15.5	26.5	539.3	4,118
24.3	5.0	32+	166.7	18.0	27.5	566.5	4,278
31.8	5.0	32+	184.3	19.0	25.0	519.8	4,409

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Zn requirement was met. Uehara (pers. comm.) has observed Zn deficiencies in sugarcane fields in Hawaii after land levelling operations which usually remove the top soil. However, after P fertilization, the Zn deficiency disappeared. He concluded that in such cases P fertilization corrects Zn deficiency by promoting rooting of sugarcane. The possible addition of contaminant Zn present in P fertilizers (1,400 ppm Zn reported by Arain (1976), for superphosphate being used in Hawaii at that time) may also have corrected the Zn deficiency. Soil pH was measured after the ratoon crop was harvested in the present study and this pH was probably somewhat lower than that when the plant crop was growing. It is known that absorption of cations by plants with simultaneous release of H^+ decreases soil pH. Leachate from the pots was recycled, thus plant released H^+, as well as H^+ produced by the added urea, probably accumulated in the pots. Therefore this pH drop may have enhanced availability of soil Zn to the ratoon crop in relation to the plant crop.

As in the corn experiment, the amounts of P added to both soils were based on the P absorption curve method and it was found that 24.3 and 31.8 g $Ca(H_2PO_4)_2$/pot which are equivalent to 1,940 and 2,530 kg P/ha (35 cm depth) for the Hilo soil were supposed to give .05 and .1 ppm P in solution, respectively. With the Halii soil, these concentrations were achieved by adding 69 and 96 g $Ca(H_2PO_4)_2$/pot which are equivalent to 540 and 750 kg P/ha (35 cm depth), respectively. These levels are reported to be adequate and excessive, respectively, for corn growth (Fox, et al. 1972).

Although these levels may be high for sugarcane because its growth rate is slower than that of corn, they were used on the assumption that P requirement of young sugarcane may equal that of mature corn. The reason for having adequate and excessive P levels was also to minimize yield response to P so that a better understanding of the P - Zn interaction could be obtained.

Sugarcane yields did not increase significantly with applied P in the Halii soil, but they did, although to a very small extent, in the Hilo soil (Tables 24, 25, 26 and 27). The overall mean increase in yield due to P application in the Hilo soil was 5.7%. Neither soil pH nor the second order interactions between P, pH and Zn had significant effects on both soils.

These results support the conclusion that sugarcane at late stage of growth is probably less susceptible to Zn deficiency than corn. However, the observed response to applied Zn on the plant crop in contrast to the lack of response on the ratoon crop indicates that Zn deficiency may appear at the beginning of the crop, but disappear after a certain stage of crop growth. The significance of this early deficiency to final crop yield remains an unanswered question. Since the response to applied Zn in the plant crop was observed only at one pH and P level due to missing data, the effects of pH and P at that stage of growth could not be evaluated. Since the response was found at high pH, it is very likely that liming Hilo soil to pH 5.5 or above may cause Zn to become limiting for sugarcane especially early in the crop. In the Halii soil, however, sugarcane growth may not be affected by reduced Zn availability

Table 25. Summary of statistical analyses for the effects of P, pH and Zn on yield, Zn concentration of the sheaths, T.V.D. leaf and meristem and Zn uptake by a ratoon crop of sugarcane grown on the Hilo soil

Treatment	F Values				
	Yield (g/pot)	Zn Conc Sheath	Zn Conc T.V.D. Leaf	Zn Conc Meristem	Total Zn Uptake
Applied P	5.70*	2.39	.00	10.29**	2.55
Soil pH	3.77	.92	1.08	11.87**	.18
Applied Zn	1.14	2.18	1.12	53.67****	1.84
Interactions					
P x pH	.05	5.91*	1.08	4.56*	.84
P x Zn	.16	.34	1.14	3.75*	.67
pH x Zn	.82	.23	.87	3.81*	1.69
P x pH x Zn	1.02	.50	.76	.91	.15

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table 26. Effect of P, pH and Zn on yield, Zn concentration of the sheath, T.V.D. leaf and meristem and total Zn uptake by a ratoon crop of sugarcane grown on the Halii soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Added Zn (ppm)	Yield (g/pot)	Zn Concentration (ppm)			Total Zn Uptake (μg/pot)
				Sheath	T.V.D. Leaf	Meristem	
6.9	3.7	0	189.4	15.0	24.5	363.1	3,555
9.6	3.8	0	207.3	15.0	27.0	379.8	4,458
6.9	3.8	2	199.8	13.0	22.0	460.9	4,611
9.6	3.9	2	191.3	15.0	24.0	401.8	4,624
6.9	3.8	4	193.3	14.0	24.5	449.3	4,286
9.6	3.8	4	202.8	14.0	23.5	435.5	4,312
6.9	3.7	8	205.4	15.5	24.5	543.0	5,148
9.6	3.8	8	205.1	17.5	24.5	484.7	5,305
6.9	3.7	16	188.6	18.5	23.0	670.1	5,552
9.6	3.8	16	206.5	16.5	27.5	665.4	6,779
6.9	4.8	0	208.1	13.5	23.0	306.9	4,222
9.6	4.8	0	232.3	13.5	23.5	292.7	4,385
6.9	4.8	2	193.5	15.0	25.0	294.1	4,625
9.6	4.8	2	206.7	14.0	24.5	274.7	4,548
6.9	4.7	4	185.2	18.5	28.0	430.2	4,612
9.6	4.8	4	199.0	16.0	27.0	399.2	5,140
6.9	4.7	8	207.0	16.0	27.0	501.9	5,268
9.6	4.8	8	202.6	18.5	28.5	464.6	4,896
6.9	4.8	16	214.0	16.5	24.0	582.8	6,344
9.6	4.8	16	220.5	15.0	30.5	547.6	6,248
6.9	4.7	32+	204.2	19.5	30.0	567.7	6,113
9.6	4.7	32+	208.3	17.5	28.5	515.2	6,972

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 27. Summary of statistical analyses for the effects of P, pH and Zn on yield, Zn concentration of the sheaths, T.V.D. leaf and meristem and Zn uptake by a ratoon crop of sugarcane grown on the Halii soil

Treatment	F Values				
	Yield (g/pot)	Zn Conc Sheath	Zn Conc T.V.D. Leaf	Zn Conc Meristem	Total Zn Uptake
Applied P	2.66	.01	8.23**	6.26*	2.31
Soil pH	2.09	.25	9.32**	54.93****	1.04
Applied Zn	1.01	5.00**	3.20*	99.33****	19.38****
Interactions					
P x pH	.09	.80	.08	.03	1.79
P x Zn	.55	1.97	4.01*	.69	.73
pH x Zn	1.00	3.25*	3.65*	4.85**	.61
P x pH x Zn	.25	.58	.78	.49	.89

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

****Significant at .01% level

Nonsignificant

even if it is limed to pH 5.5 or above, but it is not certain because reliable data were not available to evaluate this.

Zn Concentration

The standard tissue sampled to assess the nutritional status of sugarcane in Hawaii and other parts of the world where sugarcane is grown for about 24 months is sheaths 3, 4, 5 and 6 (Clements, et al. 1945). However in recent years the meristem has also been used, especially for Zn, since it has been shown to be one of the most sensitive indicator tissues for Zn (Bowen, 1972). In other parts of the world where sugarcane is grown for a period of about 9 to 15 months, the tissue sampled for nutrient analysis is generally the top visible dewlap leaf (T.V.D. leaf) (Evans, 1959). Because of their importance, these 3 tissues, which were described in the materials and methods section (page 22), were sampled in this study.

Sheaths 3, 4, 5 and 6

Humbert (1968) reported that the critical level for Zn in sheaths was 10 ppm. The Zn concentration in sheaths 3, 4, 5 and 6 was not below 10 ppm and there was no yield response to added Zn in either the Hilo or Halii soil (Tables 24 and 26).

In the Halii soil, applied Zn and the pH x Zn interaction had significant effects on Zn concentration in sheaths 3, 4, 5 and 6 (Table 27). At low pH it appears that increasing Zn generally decreased Zn concentration in sheaths 3, 4, 5 and 6 at 2 and 4 ppm added Zn. Thereafter increasing Zn application tended to increase Zn concentration of this tissue. At high pH, however, increasing

Zn generally increased Zn concentration of this tissue especially at the 2 and 4 ppm Zn levels. At higher Zn levels no particular trend was apparent. Increasing soil pH tended to decrease Zn concentration of these sheaths in the 0 and 16 ppm Zn treatments. However it generally increased Zn concentration in this tissue at 4 and 8 ppm Zn.

In the Hilo soil, only the P x pH interaction was found to significantly affect Zn concentration in sheaths 3, 4, 5 and 6 (Table 24). Zn concentration decreased with increasing P at all Zn levels except at the 4, 8 and 16 ppm Zn levels at low pH where it increased (Table 24).

Top Visible Dewlap Leaf

Evans (1959) reported that the probable adequacy level for Zn in the T.V.D. leaf is below 10 ppm. However this value was based on solution culture studies. Meyer (1976) reported that field experiments in South Africa have indicated that economic response to Zn application is obtained whenever T.V.D. leaf samples contained 15 ppm Zn or less. Since this critical level was based on field experiments, it seems more reliable than that reported by Evans.

In the present study, Zn concentration in the T.V.D. leaf ranged from a low of 23.0 ppm in the Halii soil to a high of 30.5 ppm in the same soil (Tables 24 and 25). Since this range is well above the suggested critical level of 15 ppm, no benefit from added Zn would be expected in either of the soils studied. The lack of yield response to Zn observed in this study agrees with this conclusion.

Significant effects of P, pH, Zn, the P x Zn and pH x Zn interactions on Zn concentration in the T.V.D. leaf were found in the Halii soil (Table 27). However in the Hilo soil none of these factors (P, pH, Zn) or their interactions had significant effects on the T.V.D. leaf Zn concentration (Table 25).

Increasing Zn, at low pH, either decreased or had no effect on the T.V.D. leaf Zn concentration in the Halii soil (Table 26). However at high pH, increasing Zn generally increased T.V.D. leaf Zn concentration. Increasing P, in the Halii soil, increased T.V.D. leaf Zn concentration by an average of 6.1%. At low pH, the P x Zn interaction is more evident where increasing P increased Zn concentration of the T.V.D. leaf at 0.2 and 16 ppm Zn, but had almost no effect at 4 and 8 ppm Zn (Table 26). At high pH, however, this increase occurred only at 8 and 16 ppm added Zn (Table 26). Increasing soil pH increased the T.V.D. leaf Zn concentration by an average of 6.5%. The T.V.D. leaf Zn concentration on the control treatments decreased with increasing pH, but at all higher Zn levels, T.V.D. leaf Zn concentration increased with increasing pH. This resulted in a significant pH x Zn interaction.

Meristem

The meristem is reported to be one of the most sensitive indicator tissues for Zn in the sugarcane plant (Evans, 1959; Kunimitsu, 1969; Bowen, 1972) However the critical level for Zn in this tissue has not been established. Although a precise statement cannot be made, a first approximation of the critical level may be obtained from data presented by Kunimitsu (1969) in which it appears that a critical level of about 150 ppm Zn is adequate. Some variation in this critical level may be expected for different varieties.

In the present study the lowest Zn concentration observed was 223 ppm in the Hilo soil and the highest was 670 ppm Zn in the Halii soil (Tables 24 and 26, respectively). As mentioned earlier, no yield response to applied Zn was observed, which suggests that the critical Zn concentration in the meristem is below 223 ppm.

Applied Zn generally increased Zn concentration in the meristem on both soils. The average Zn concentration of the 2, 4, 8 and 16 ppm Zn treatments increased by 50% and 43% in the meristem while in the sheaths it increased by 2% and 11% and in the T.V.D. leaf by 0 and 4.1%, over the control treatments, on the Hilo and Halii soils respectively. This indicates that the meristem is one of the most sensitive Zn indicator tissues.

Increasing P decreased Zn concentration in the meristem, at most Zn levels, by an average of 9.0% on the Hilo and 5.6% on the Halii soil. It is interesting to note that increasing P tended to increase Zn concentration on the control treatments in the Hilo soil and on the control treatment only at low pH on the Halii soil (Tables 24 and 26).

Soil pH also had a significant effect on Zn concentration in the meristem in both soils (Tables 25 and 27). However the decrease in Zn concentration due to an increase in soil pH was greater in the Halii soil (15.6%) than on the Hilo soil (9.7%) (Tables 24 and 26). This greater decrease in the Halii soil may have been caused by the wider pH range found in this soil (3.8 and 4.8) than in the Hilo soil (4.8 and 5.2).

The pH x Zn interaction was significant in both soils (Tables 25 and 27). By increasing soil pH, regardless of P treatment, Zn concentration in the meristem generally decreased rather sharply at low Zn levels (0, 2 and 4 ppm Zn) but to a smaller extent at higher Zn levels (Tables 24 and 26). P x pH and P x Zn interactions were significant only in the Hilo soil (Table 25). At high pH, increased P generally decreased meristem Zn concentration to a greater extent than at low pH for all Zn levels except zero Zn on the Hilo soil. Also increased P decreased meristem Zn concentration at all Zn levels but the magnitude of the decrease differed with Zn level (Table 24).

Total Zn Uptake

Total Zn uptake generally increased with increasing levels of Zn in both soils (Tables 24 and 26). However this increase was only significant for the Halii soil (Tables 25 and 27). One possible explanation is related to the fact that Zn applied to these soils was based on the soil dry weight. Since the dry weight of the Hilo soil in pots was less than half of the dry weight of the Halii soil because of the low bulk density of the Hilo soil (.25 g/cm^3) in pots, the amount of Zn applied to the soil was consequently less than half of that applied to the Halii soil. Therefore, a difference in the capacity factor due to the different amounts of added Zn required to attain the same Zn concentration in these two soils may have been partially responsible for these differences in total Zn uptake.

Applied P, soil pH, their interactions, as well as their interactions with Zn, had no significant effects on total Zn uptake in either soil (Tables 25 and 27).

These results suggest that the root system of sugarcane is very efficient in taking up Zn. Evans (1959) reported that in many cases, symptons of certain micronutrient deficiencies are not due to complete lack of such micronutrients in the soil, nor even to the failure of the root system to take them up, but rather to the immobility of the element within the plant, resulting in failure to maintain an adequate supply of the element in the metabolic centers where it is required.

Relationship Between Added Zn, Total Zn Uptake, Dry Matter Yield and Zn Concentration in Sheaths, T.V.D. Leaf and Meristem of Sugarcane

The data presented in Table 28 indicate that the meristem of sugarcane is probably the most sensitive Zn indicator tissue among the three tissues examined since it had the highest correlation coefficient with added Zn in both soils.

Although Zn concentration in the sheaths and T.V.D. leaf did not appear to be outstanding indicators of added Zn, they indicated that no response to applied Zn would be observed because Zn concentrations in these tissues for all treatments in both soils were above the concentrations reported as critical. This indication was in agreement with the lack of response found.

Total Zn uptake was highly correlated with meristem Zn concentration in the Halii soil, but not in the Hilo soil (Table 28). This is probably due to the fact that total Zn uptake as well as meristem Zn concentration increased significantly with increasing

Table 28. Correlation coefficients for the relationship between added Zn, total Zn uptake, yield and Zn concentration in different tissues and total Zn uptake by sugarcane⁺

I - Correlation Coefficients - Halii Soil

	Added Zn	Total Zn Uptake	Yield
Zn Conc in Sheaths	.46***	.32*	-.24
Zn Conc in T.V.D. Leaf	.30*	.35*	.09
Zn Conc in Meristem	.88***	.66***	-.12
Total Zn Uptake	.80***	--	.37**

II - Correlation Coefficients - Hilo Soil

	Added Zn	Total Zn Uptake	Yield
Zn Conc in Sheaths	.23	.14	.05
Zn Conc in T.V.D. Leaf	.16	.16	-.08
Zn Conc in Meristem	.83***	.16	-.10
Total Zn Uptake	.29*	--	.57***

⁺n = 40

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

levels of applied Zn in the Halii soil whereas in the Hilo soil only Zn concentration in the meristem increased significantly.

Yield was more highly correlated with Zn uptake than with Zn concentration in any of the three tissues in both soils. The correlation between Zn uptake and yield was higher in the Hilo than in the Halii soil (Table 28). This is probably because yield and Zn uptake did not increase with increasing applied Zn in the Hilo soil. However in the Halii soil yield did not increase but Zn uptake increased significantly with increasing applied Zn.

As discussed previously, these three tissues have proven to be useful indices of the Zn nutritional status of sugarcane, although total Zn uptake may be more reliable. This is due to the fact that total Zn uptake integrates Zn concentration and plant growth. However, total Zn uptake is not always easy to measure, especially under field conditions. In this case, information about the appropriate index tissue to be sampled as well as its Zn critical level are very useful.

Since Zn concentration in the meristem was the most highly correlated with added Zn and Zn uptake in both the Halii and Hilo soils, it may be a better indicator tissue than either sheaths or the T.V.D. leaf.

No conclusions regarding Zn critical levels can be drawn from this study, since no yield response to applied Zn was observed. However these data suggest that Zn critical levels in each of these tissues apparently are below the Zn levels observed in the control treatments (Tables 24 and 26). Also these data indicate that the reported Zn critical levels of 10 ppm in sheaths 3, 4, 5 and 6, 15 ppm in the T.V.D. leaf and 150 ppm in the meristem appear to be reliable because Zn levels for each tissue were higher than the levels described above and no benefit from added Zn was found.

Effect of P and Zn Fertilization and Soil pH on Extractable Soil Zn

The amounts of Zn extracted by the four methods decreased in the following order: 0.1N HCl $>$ EDTA $>$ DTPA $>$ 2N $MgCl_2$ in both soils (Tables 29 and 31).

Applied Zn significantly increased soil Zn extracted by the four methods in the two soils (Tables 30 and 32). Similar to the corn experiment, the increase in extractable Zn with the initial rates of Zn, mainly 2 and 4 ppm Zn, was very small in the Hilo soil compared to that of the Halii soil (Tables 29 and 31). However, Zn extracted by EDTA or DTPA reflected these initial Zn rates better than either 0.1N HCl or 2N $MgCl_2$.

P application did not affect the amounts of Zn extracted by the four methods (Tables 30 and 32). This is in agreement with the results reported by Boawn, et al. (1954), Bingham, et al. (1960), Stukenholtz, et al. (1966), Sharma, et al. (1968b) and Brown, et al. (1970), who did not find any reduction in extractable soil Zn due to P fertilization.

Some workers have indicated that P fertilization often increases extractable Zn (Bingham, et al. 1956; Langin, et al. 1962); Keefer, et al. 1968). Such increases may be due to Zn impurities present in P fertilizer. Boawn, et al. (1954) and Langin, et al. (1962) have reported that a western source of superphosphate contained approximately 2400 ppm Zn as a natural impurity. Arain

Table 29. Effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Hilo soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Added Zn (ppm)	Extractable P (ppm)	Extractable Zn (ppm)			
				0.1N HCl	EDTA	DTPA	2N $MgCl_2$
24.3	4.8	0	240	7.96	1.70	1.11	.78
31.8	4.8	0	340	8.57	2.10	1.18	.98
24.3	5.3	0	241	8.08	1.78	.91	.73
31.8	5.3	0	345	7.35	1.62	1.00	.72
24.3	4.8	2	248	9.96	2.34	1.28	1.08
31.8	4.8	2	308	8.30	2.05	1.20	1.12
24.3	5.2	2	262	8.18	2.02	1.30	.80
31.8	5.2	2	367	8.69	2.08	1.38	.85
24.3	4.8	4	264	9.44	2.51	1.88	1.26
31.8	4.8	4	297	9.09	3.10	1.78	1.29
24.3	5.3	4	271	9.88	2.50	1.57	1.24
31.8	5.2	4	359	8.89	2.44	1.62	1.47
24.3	4.8	8	239	10.82	4.45	2.15	1.59
31.8	4.8	8	341	11.77	4.53	2.40	1.68
24.3	5.3	8	264	12.32	4.61	2.69	1.47
31.8	5.2	8	339	11.97	4.09	2.23	1.66
24.3	4.9	16	261	14.52	7.37	4.03	2.65
31.8	4.9	16	358	14.90	7.47	3.94	2.49
24.3	5.0	16	249	16.66	7.65	4.39	2.10
31.8	5.0	16	333	15.73	7.90	4.66	2.23
24.3	5.0	32+	240	27.45	17.74	8.98	3.01
31.8	5.0	32+	342	27.81	18.67	8.30	3.09

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 30. Summary of statistical analyses for the effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Hilo soil

Treatment	Modified Truog Ext.	F Values			
		Extractable Zn			
		0.1N HCl	EDTA	DTPA	2N $MgCl_2$
Applied P	269.74****	.94	.42	.02	.94
Soil pH	6.57*	.85	1.60	1.81	13.59**
Applied Zn	.33	106.18****	859.31****	369.74****	111.80****
Interactions					
P x pH	1.45	.86	3.14	.00	.02
P x Zn	1.77	.45	1.59	.39	.39
pH x Zn	3.86*	2.50	2.59	5.58**	1.46
P x pH x Zn	2.59	1.65	2.08	2.42	.71

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table 31. Effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Halii soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Added Zn (ppm)	Extractable P (ppm)	Extractable Zn (ppm)			
				0.1N HCl	EDTA	DTPA	2N $MgCl_2$
6.9	3.7	0	40.1	3.69	1.56	1.25	1.26
9.6	3.8	0	58.1	3.64	1.47	1.28	1.31
6.9	4.8	0	38.6	2.69	.93	1.10	.98
9.6	4.8	0	55.1	2.54	1.00	.99	.90
6.9	3.8	2	45.7	3.80	2.24	1.92	1.58
9.6	3.9	2	63.0	4.35	2.21	2.13	1.30
6.9	4.8	2	40.7	3.64	1.65	1.52	1.03
9.6	4.8	2	59.2	3.99	1.69	1.60	1.11
6.9	3.8	4	45.1	5.36	3.23	2.67	2.04
9.6	3.8	4	67.5	5.34	3.02	2.44	1.84
6.9	4.7	4	40.9	4.70	2.15	2.15	1.32
9.6	4.8	4	57.2	4.64	2.44	2.30	1.40
6.9	3.7	8	46.7	7.24	4.89	4.17	2.44
9.6	3.8	8	61.9	7.11	4.41	4.05	2.46
6.9	4.7	8	38.9	6.68	3.85	3.60	1.89
9.6	4.8	8	59.7	6.69	4.19	3.27	1.90
6.9	3.7	16	46.2	11.52	8.64	7.13	4.54
9.6	3.8	16	62.3	11.47	8.68	7.84	4.27
6.9	4.8	16	40.6	10.58	7.04	6.62	2.33
9.6	4.8	16	58.7	10.12	6.89	6.02	2.35
6.9	4.7	32+	42.1	19.71	14.97	11.52	4.45
9.6	4.7	32+	60.3	19.84	14.64	12.06	4.49

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table 32. Summary of statistical analyses for the effects of P, pH and Zn on extractable P and Zn extracted by 0.1N HCl, EDTA-$(NH_4)_2CO_3$, DTPA and 2N $MgCl_2$ from the Halii soil

Treatment	Modified Truog Ext. P	F Values			
		Extractable Zn			
		0.1N HCl	EDTA	DTPA	2N $MgCl_2$
Applied P	159.25****	.01	.11	.00	2.50
Soil pH	11.00**	16.06***	57.80****	15.02***	508.83****
Applied Zn	1.41	243.42****	391.24****	155.31****	551.28****
Interactions					
P x pH	.01	.18	.05	.02	5.28
P x Zn	.08	.46	.09	.34	.60
pH x Zn	.32	.89	3.26*	1.99	87.17****
P x pH x Zn	.48	.06	.33	.40	1.92

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

(1976) reported 1400 ppm Zn in the superphosphate being used in Hawaii at that time. Apart from Zn, contamination, other explanations have been given for this increase in extractable Zn with P application. Lindsay (1972) and Marinho, et al. (1972) suggested that the increase in available Zn due to P application appears to indicate that P either competes with Zn by reacting with free R_2O_3 or by forming a more soluble compound with Zn. On the other hand, a decrease in extractable soil Zn as a result of P application has been reported by Prasad and Sinha (1968) and Warnock (1970).

Increased soil pH significantly decreased soil Zn extracted by all four extractants in the Halii soil (Tables 31 and 32) but only with 2N $MgCl_2$ in the Hilo soil (Tables 29 and 30). However, in the case of the corn experiment, soil pH had a significant effect on soil Zn extracted by three out of the four extractants on the Hilo soil (Table 13). This difference in extractable Zn in the corn and sugarcane experiments was possibly due to the difference in the soil pH observed in the two experiments, i.e. 5.0 and 5.7 for corn and 4.8 and 5.1 for sugarcane.

In the Halii soil, the magnitude of the decrease in extractable Zn caused by soil pH varied with extractant. The largest decrease was observed in the case of 2N $MgCl_2$, followed by EDTA, DTPA and 0.1N HCl (Table 31). A similar order was observed in the corn experiment for this soil. The decrease in extractable Zn with increasing soil pH may be due to formation of Zn compounds of low solubility (Malavolta, et al. 1962 and Udo, et al. 1970).

P Concentration in the Sheaths and T.V.D. Leaf and Total P Uptake by the Sugarcane Ratoon Crop

Soil pH was the only factor which had a significant effect on P concentration in sheaths 3, 4, 5 and 6 in the Halii soil (Table A.11). Increasing soil pH increased P concentration in the sheaths by an average of 9.6% (Table A.10).

In the Hilo soil, at low pH, increasing Zn tended to decrease P concentration in the sheaths at 0, 2 and 4 ppm Zn (Table A.8). At higher Zn levels and at high pH no trend was evident at all Zn levels. The pH x Zn interaction was also significant in the Hilo soil (Table A.9). Increasing pH decreased P concentration in the sheaths at zero Zn but at higher Zn levels soil pH apparently had no effect on sheath P concentration.

P concentration in the T.V.D. leaf was significantly affected only by P application and pH in the Halii soil (Table A.11). In the Hilo soil, however, none of the factors (P, pH, Zn) or their interactions had significant effects on P concentration (Table A.9). Increasing P in the Halii soil increased P concentration in the T.V.D. leaf by an average of 6.5%. The effect of pH on P concentration in the T.V.D. leaf was larger than that of P. Increased pH resulted in an average increase of 10.4% in P concentration in the T.V.D. leaf which may be due to the greater availability of P at pH 4.8 than at 3.8.

Total P uptake increased significantly with applied P in both soils (Tables A.14 and A.16). The increase in P uptake with P fertilization was larger in the Halii soil (13.1%) than in the Hilo soil (4.4%) (Tables A.8 and A.10).

Increased soil pH increased total P uptake significantly only in the Halii soil (Tables A.9 and A.11). This might be due to the fact that raising soil pH from 3.8 to 4.8 decreased the solubility of heavy metals which complex P. Therefore the availability of P increased, however a greater increase in P availability would be expected if soil pH were raised to about 5.5.

Comparison of Chemical Extractants for Soil Zn with Zn Uptake

As discussed earlier, total Zn uptake may be the most appropriate plant parameter to use in this evaluation of soil Zn extractants, since it integrates plant Zn concentration and growth.

To assess the generality of the extractants, an experiment with soils with a range of mineralogy was conducted. Two out of four soils used in this experiment were reported to be Zn deficient. As mentioned earlier, these two deficient soils were used in the main experiment and several Zn levels were applied to determine their responsiveness to Zn application.

Therefore in this evaluation two main points were investigated: (1) the ability of a soil Zn extractant to separate deficient from non-deficient soils for sugarcane growth and (2) the consistency of the extractant on soils deferring in mineralogy.

Evaluation of Extractants on the Hilo and Halii Soil Separately

Generally higher correlation coefficients were found for the plant crop than for the ratoon crop for the relationship between Zn extracted from the Hilo soil by the four extractants and Zn uptake (Table 33). This may be due to the fact that Zn uptake may have followed the applied Zn more closely in the plant crop than in the ratoon crop. The higher Zn uptake by the plant crop than by the ratoon crop was possibly due to the fact that applied Zn increased yield significantly in the plant crop, but not in the ratoon crop. This is reflected by the highly significant correlation coefficient between soil Zn extracted by the four methods and yield in the plant

Table 33. Correlation coefficients relating yields and total Zn uptake by sugarcane plant and ratoon crops with soil Zn extracted by four methods from the Hilo soil+

I - Plant Crop

Extraction Method	Correlation Coefficient (r) Total Zn Uptake	Yield
0.1N HCl	.46***	.64***
EDTA	.48***	.63***
DTPA	.50***	.63***
2N $MgCl_2$	.52***	.64***
ln 0.1N HCl	.43***	.63***
ln EDTA	.51***	.66***
ln DTPA	.51***	.65***
ln 2N $MgCl_2$	.53***	.66***
Total Zn Uptake	--	.80***

+n = 35

II - Ratoon Crop

Extraction Method	Correlation Coefficients (r) Total Zn Uptake	Yield
0.1N HCl	.23	.06
EDTA	.29*	.07
DTPA	.31*	.14
2N $MgCl_2$	.24	.09
ln 0.1N HCl	.21	.04
ln ETPA	.26*	.03
ln DTPA	.31*	.09
ln 2N MgCl	.21	.03
Total Zn Uptake	--	.57***

+n = 40

*Significant at 5% level

***Significant at 1% level

Nonsignificant

crop in contrast to the non-significant correlation coefficients in the ratoon crop (Table 33). It is also apparent in Table 32 that the log form of extractable Zn generally gave higher correlation coefficients in the plant crop whereas the linear form gave higher correlation coefficients in the ratoon crop.

In the Halii soil, correlation coefficients between soil Zn extracted by the four methods and Zn uptake were generally highly significant for the plant crop as well as for the ratoon crop (Table 34). The linear form of soil extractable Zn generally gave higher correlation coefficients than the log form.

It is interesting to point out that in the Halii soil correlation coefficients between extractable soil Zn and yields of both the plant and ratoon crops were very low (Table 34). However in the Hilo soil, correlation coefficients between extractable soil Zn and plant crop yields were highly significant, whereas correlation coefficients relating extractable soil Zn with ratoon crop yields were not (Table 33). This is similar to what was found for the corn experiment where there was a yield response to added Zn in the Hilo soil but not in the Halii soil.

Similary in sugarcane a significant yield response to applied Zn was obtained in the plant crop on the Hilo soil, but not on the Halii soil while ratoon crop in both soils did not give significant yield responses.

Since correlation coefficients between Zn uptake and soil Zn extracted by the four methods for the plant crop as well as for the ratoon crop are generally very similar it is difficult to select the "best" extractant based on these data.

Table 34. Correlation coefficients relating yields and Zn uptake by sugarcane plant and ratoon crops with soil Zn extracted by four methods from the Halii soil+

I - Plant Crop

Extraction Method	Correlation Coefficient (r) Total Zn Uptake	Yield
0.1N HCl	.76***	.00
EDTA	.77***	-.03
DTPA	.77***	-.06
2N $MgCl_2$	.78***	.02
ln 0.1N HCl	.73***	.04
ln EDTA	.71***	.01
ln DTPA	.70***	.09
ln 2N $MgCl_2$	.76***	.04
Total Zn Uptake	--	.42**

+n = 29

II - Ratoon Crop

Extraction Method	Correlation Coefficient (r) Total Zn Uptake	Yield
0.1N HCl	.78***	.06
EDTA	.77***	.04
DTPA	.81***	.08
2N $MgCl_2$	.65***	-.04
ln 0.1N HCl	.75***	-.00
ln EDTA	.72***	.03
ln DTPA	.78***	.03
ln 2N $MgCl_2$	.66***	-.05
Total Zn Uptake	--	.38**

+n = 40

**Significant at 1% level

***Significant at .1% level

Nonsignificant

Evaluation of Extractants in the Hilo and Halii Soils Combined

To evaluate the generality of the extractants, the Hilo and Halii soils discussed in the previous section are considered together. Correlation coefficients presented in Tables 35 and 36 indicate that the linear form of extractable soil Zn gave generally higher values than the log form when these two forms of extractable soil Zn were related to total Zn uptake by the plant and ratoon crops.

When the plant parameter is relative Zn uptake there is marked improvement in the correlation coefficients between 0.1N HCl extractable soil Zn and Zn uptake by both the plant and ratoon crops (Tables 35 and 36) and some improvement with soil Zn extracted by EDTA and Zn uptake by the ratoon crop. These improvements may be due to the fact that these chemicals extracted relatively more Zn from the Hilo soil than from the Halii soil, whereas the amounts of Zn taken up by plants were relatively larger on the Halii than on the Hilo soil (Tables 24 and 26; Tables A.6 and A.7). Therefore the use of relative Zn uptake partially eliminated these differences in total Zn uptake in the two soils so that correlation coefficients are higher. However correlation coefficients with relative Zn uptake decreased for DTPA and 2N $MgCl_2$ extractable soil Zn in both the plant and ratoon crops and also for EDTA in the plant crop. This may be due to the fact that the relative amount of Zn extracted from the two soils and total Zn uptake by the sugarcane crops followed the same pattern, i.e. larger amounts from the Halii soil than from the Hilo soil.

As discussed earlier for corn, these differences between the two soils in total Zn uptake by sugarcane may be explained by the

Table 35. Correlation coefficients relating extractable soil Zn and Zn uptake by a sugarcane plant crop on the Hilo and Halii soils combined

Extraction Method	Basis for Expressing Results	Correlation Coefficient (r)	
		Total Zn Uptake	Relative Zn Uptake
0.1N HCl	(w/w)	-.06	.67***
EDTA	(w/w)	.59***	.51***
DTPA	(w/w)	.78***	.37***
2N $MgCl_2$	(w/w)	.79***	.35***
ln 0.1N HCl	(w/w)	-.10	.66***
ln EDTA	(w/w)	.52***	.52***
ln DTPA	(w/w)	.73***	.33***
ln 2N $MgCl_2$	(w/w)	.79***	.31**
0.1N HCl	(w/v)	.66***	.35**
EDTA	(w/v)	.81***	.45***
DTPA	(w/v)	.85***	.30**
2N $MgCl_2$	(w/v)	.87***	.20*
ln 0.1N HCl	(w/v)	.60***	.45***
ln EDTA	(w/v)	.79***	.25*
ln DTPA	(w/v)	.85***	.09
ln 2N $MgCl_2$	(w/v)	.79***	.31**

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
Nonsignificant

Table 36. Correlation coefficients relating extractable soil Zn and Zn uptake by a sugarcane ratoon crop on the Hilo and Halii soils combined+

Extraction Method	Basis for Expressing Results	Correlation Coefficient (r)	
		Total Zn Uptake	Relative Zn Uptake
0.1N HCl	(w/w)	.01	.66***
EDTA	(w/w)	.49***	.52***
DTPA	(w/w)	.72***	.42***
2N $MgCl_2$	(w/w)	.60***	.31**
ln 0.1N HCl	(w/w)	.02	.69***
ln EDTA	(w/w)	.44***	.52***
ln DTPA	(w/w)	.66***	.38***
ln 2N $MgCl_2$	(w/w)	.57***	.25*
0.1N HCl	(w/v)	.63***	.49***
EDTA	(w/v)	.75***	.32**
DTPA	(w/v)	.81***	.23*
2N $MgCl_2$	(w/v)	.73***	.08
ln 0.1N HCl	(w/v)	.55***	.49***
ln EDTA	(w/v)	.68***	.24*
ln DTPA	(w/v)	.76***	.09
ln 2N $MgCl_2$	(w/v)	.57***	.25*

+ n = 80

* Significant at 5% level

** Significant at 1% level

*** Significant at .1% level

Nonsignificant

different bulk densities of these soils. The laboratory data used in this study are expressed on a weight/weight basis (μg/g or w/w). However, plant roots in spite of having the same volume of soil to search for Zn had different relative amounts of Zn present in each soil since bulk densities of these two soils were different (.25 and .50 g/m^3 for the Hilo and Halii soils, respectively).

It was observed that the bulk densities of these soils in pots were reduced by about 50% compared to their field bulk densities (.50 and 1.0 g/cm^3 for the Hilo and Halii soils, respectively). Uehara (pers. comm.) has observed that once a soil is sieved and placed into pots, it is almost impossible to attain the previous field bulk density even by compacting the soils in the pots.

In such cases, where soil bulk density deviates greatly from 1.0, Zn extracted on the soil weight basis will probably not reflect the amounts taken up by plants. Therefore, a correction of the Zn values obtained by extraction with the four methods was made by multiplying extractable Zn by the appropriate bulk density, e.g. extractable Zn from Hilo soil times .25 g/cm^3 and extractable Zn from Halii soil times .50 g/cm^3. Thus, the results are expressed on the basis of weight of extractable Zn/volume of soil.

Correlation coefficients between soil Zn extracted by the four methods expressed on the w/v basis with total Zn uptake and relative Zn uptake are shown in Tables 35 and 36. There is general improvement of correlation coefficients when soil Zn extracted by the four methods is expressed on the w/v basis instead of the w/w basis (Tables 35 and 36). This improvement was more marked in the case of

0.1N HCl extractable soil Zn as was also observed in the corn experiment.

The linear form of extractable Zn generally had higher correlation values with either Zn uptake or relative Zn uptake than the log form. Therefore it was used in these evaluations. This is in contrast to the result in corn where log values gave higher correlation coefficients than linear values.

It is interesting to observe that soil Zn extracted by the four methods on the w/v basis gave relatively high correlation coefficients with total Zn uptake and they decreased in the following order: 2N $MgCl_2$ > DTPA > EDTA > 0.1N HCl for the plant crop and DTPA > EDTA > 2N $MgCl_2$ > 0.1N HCl for the ratoon crop, although the values are similar (Tables 35 and 36).

As mentioned earlier for corn and observed for sugarcane, when total Zn uptake was used as the plant parameter, soil extractable Zn on w/v basis had the highest correlation coefficients for the four methods whereas when relative Zn uptake was used, extractable soil Zn by the four methods on the w/w basis gave the highest correlation (Tables 35 and 36). This pattern was consistent in the plant and ratoon crops.

These results may suggest that relative Zn uptake adjusted for some of the differences in Zn uptake between the two soils, while the correction for soil bulk density, possibly adjusted the amounts of Zn extracted from the soils to the amounts of Zn that were available for plant uptake. Therefore when both are correlated, i.e. relative Zn uptake with soil extractable Zn on the w/v basis, correlation coefficients are generally lower than for either relative Zn uptake with soil extractable Zn on the w/w basis or total Zn uptake with soil extractable Zn on the w/v basis.

It is apparent that correlation coefficients for extractable soil Zn on the w/v basis for combined soils (Tables 35 and 36) are more closely related to the correlation values for the soils separately (Tables 33 and 34) than are the correlation values for extractable soil Zn on the w/w basis for the combined soils (Tables 35 and 36). These data support the suggestion that extractable soil Zn values should be adjusted for bulk density to make soil test values from soils having different bulk densities comparable.

Evaluation of Extractants on Soils Varying in Mineralogy

As pointed out earlier in the corn experiment, a good soil Zn extractant should extract all or a proportionate part of the available form or forms of Zn from soils with variable properties. In addition it should be able to separate Zn deficient soils from soils with adequate Zn.

Data from the sugarcane experiment (plant crop) indicate that critical levels for soil Zn on the w/v basis are about 3-4 $\mu g/cm^3$ for the 0.1N HCl method, 1.25 $\mu g/cm^3$ for the EDTA-$(NH_4)_2CO_3$ method, .75 $\mu g/cm^3$ for the DTPA method, and .45 $\mu g/cm^3$ for the 2N $MgCl_2$ method. These values are the amounts of soil Zn extracted from Hilo soil by each method (Table 29) from treatments that received 8 ppm Zn, multiplied by .25 (bulk density of Hilo soil). This soil and levels were chosen because a yield response to added Zn was observed up to 8 ppm added Zn (Table 23) and there was no significant yield increase above 8 ppm added Zn.

These values expressed on the w/v basis are comparable to the values reported as critical for soil Zn for sugarcane growth on the w/w basis, i.e. 3 ppm for 0.1N HCl (Juang, 1971) and 1.5 ppm for EDTA-$(NH_4)_2CO_3$ (Meyer, 1976). Although critical levels for DTPA and 2N $MgCl_2$ methods were not found for sugarcane, they may be assumed to be close to those reported for corn, i.e. .5-.8 ppm and .4 ppm, respectively since Zn requirement of young sugarcane and corn appear to be similar. In addition, Zn critical levels reported for the other two methods for corn growth are similar to those reported for sugarcane growth.

When extractable soil Zn is expressed on the w/w basis, only EDTA classifies both the Hilo and Halii soils as being Zn deficient for sugarcane and corn. However a yield response to added Zn was observed only for the plant crop of sugarcane on the Hilo soil. Similarly a yield response to added Zn was observed only on the Hilo soil with corn. When extractable soil Zn is expressed on the w/v basis, three extractants (0.1N HCl, EDTA and DTPA) out of the four identified the Hilo and Halii soils as Zn deficient and the Molokai and Lualualei soils as having adequate Zn (Table 37). This was also observed in the corn experiment.

Correlation coefficients relating soil Zn extracted by the four methods with Zn uptake by the plant and ratoon crops show the improvements in correlation achieved by adjusting the extractable soil Zn from the w/w basis to the w/v basis, especially in the case of 0.1N HCl (Table 38). Extractable soil Zn values are correlated on the linear form with Zn uptake by the plant crop and on the log form with

Table 37. Extractable soil Zn expressed on the w/w and w/v basis and total Zn uptake by sugarcane plant and ratoon crops grown on soils varying in mineralogy

Extraction Method	Basis for Expressing Results	Zn Extracted from Soils[a]			
		Hilo (.25)[b]	Halii (.50)	Molokai (.84)	Lualualei (.69)
0.1N HCL	w/w (μg/g)	11.89	4.88	13.14	11.80
	w/v ($\mu g/cm^3$)	2.97	2.44	11.04	8.14
EDTA	w/w	2.60	1.97	7.80	4.92
	w/v	.65	.99	6.66	3.40
DTPA	w/w	2.17	1.45	9.18	6.44
	w/v	.54	.73	7.71	4.44
2N $MgCl_2$	w/w	1.65	1.69	1.16	1.01
	w/v	.41	.85	.97	.70
Total Zn Uptake	μg/pot				
Plant Crop		1670.5	2728.0	4654.9	3823.9
Ratoon Crop		1879.5	3132.3	4160.6	6076.4

[a] Values are means of three replicates

[b] Bulk density in pots (g/cm^3)

Table 38. Correlation coefficients relating soil Zn extracted by four methods with Zn uptake by sugarcane grown on soils varying in mineralogy+

A - Sugarcane Plant Crop

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r) Total Zn Uptake
0.1N HCl	(w/w)	.36
EDTA	(w/w)	.85***
DTPA	(w/w)	.90***
2N $MgCl_2$	(w/w)	-.78***
0.1N HCl	(w/v)	.91***
EDTA	(w/v)	.91***
DTPA	(w/v)	.93***
2N $MgCl_2$	(w/v)	.77**

B - Sugarcane Ratoon Crop

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r) Total Zn Uptake
ln 0.1N HCl	(w/w)	.26
ln EDTA	(w/w)	.59*
ln DTPA	(w/w)	.69**
ln 2N $MgCl_2$	(w/w)	-.88***
ln 0.1N HCl	(w/v)	.72**
ln EDTA	(w/v)	.73**
ln DTPA	(w/v)	.77**
ln 2N MgO_2	(w/v)	.88***

+n = 12

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

Zn uptake by the ratoon crop because higher correlation values were found with these terms for these two stages of the crop. In spite of the fact that correlation coefficients between extractable soil Zn on the w/v basis and total Zn uptake decreased in the following order: DTPA > EDTA > 0.1N HCl > 2N $MgCl_2$ and 2N $MgCl_2$ > DTPA > EDTA > 0.1N HCl for the plant and ratoon crops, respectively the values for EDTA, DTPA and 0.1N HCl extractable soil Zn are very similar (Table 38). Zn extracted by 2N $MgCl_2$ had the highest correlation value among the four methods with Zn uptake in the ratoon crop (Table 38) but it did not separate the Halii soil from the Lualualei and Molokai soils, although total Zn uptake by sugarcane from these three soils is very different (Table 37).

Therefore it becomes difficult to select the most suitable extractant among 0.1N HCl, DTPA and EDTA since their correlation values with soils, having a wide range of mineralogy, are similar (Table 38). In addition, these three extractants clearly separated the Hilo and Halii soils from the Lualualei and Molokai soils.

Evaluation of Extractants on all Soils Combined

The extractants were compared under a wide range of conditions obtained by combining in this final evaluation the data from the experiments with the Hilo and Halii soils which had variable Zn levels as well as variable P and pH with data from the mineralogy experiment which include the Hilo, Halii, Lualualei and Molokai soils without added Zn.

Correlation coefficients show that the highest correlation values are generally attained when total Zn uptake is related to the linear form of extractable soil Zn on the w/v basis for the plant crop (Table 39) and to the log form of extractable soil Zn on the w/v basis for the ratoon crop (Table 40). Extractable soil Zn on the w/w basis had higher correlation values for relative Zn uptake than for total Zn uptake. However extractable soil Zn on the w/v basis had higher correlation coefficients with Zn uptake than with relative Zn uptake. These improvements as explained earlier may be caused by the correction of the differences in Zn uptake between the soils brought about by the use of relative Zn uptake or transformation of extractable soil Zn to the w/v basis.

Larger increases in correlation coefficients resulted from the adjustment of extractable soil Zn for bulk density than from adjustment of plant uptake to relative Zn uptake for the plant or ratoon crops (Tables 39 and 40, respectively). Among the extractants, the greatest improvements from adjusting the w/w to the w/v basis was observed in the case of 0.1N HCl and EDTA-$(NH_4)_2CO_3$. The improved correlation obtained by the adjustment for bulk density is illustrated by comparing Figures 11 and 12 without the adjustment and Figures 13 and 14 with the adjustment. Figures 15 and 16 show the relationship between soil Zn extracted by DTPA and 2N $MgCl_2$ expressed on the w/v basis and total Zn uptake by the ratoon crops of sugarcane. As reported earlier for corn, these results suggest that the transformation of extractable soil Zn from the w/w basis to the w/v basis may be a way of making soil Zn values from a range of soils comparable.

Correlation coefficients between extractable soil Zn on the w/v basis and total Zn uptake decreased in the following order: 0.1N HCl $>$

Table 39. Correlation coefficients relating soil Zn extracted by four methods to total Zn uptake and relative Zn uptake by sugarcane plant crop on the four soils from the two experiments combined+

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r)	
		Total Zn Uptake	Relative Zn Uptake
0.1N HCl	(w/w)	.25*	.56***
EDTA	(w/w)	.34***	.58***
DTPA	(w/w)	.63***	.57***
2N $MgCl_2$	(w/w)	.02	.18*
ln 0.1N HCl	(w/w)	.21*	.55***
ln EDTA	(w/w)	.33**	.56***
ln DTPA	(w/w)	.53***	.48***
ln 2N $MgCl_2$	(w/w)	.01	.13
0.1N HCl	(w/v)	.81***	.60***
EDTA	(w/v)	.66***	.55***
DTPA	(w/v)	.79***	.53***
2N $MgCl_2$	(w/v)	.23*	.21*
ln 0.1N HCl	(w/v)	.70***	.57***
ln EDTA	(w/v)	.55***	.46***
ln DTPA	(w/v)	.63***	.37***
ln 2N $MgCl_2$	(w/v)	.36***	.13

+n = 76

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

Table 40. Correlation coefficients relating soil Zn extracted by four methods to total Zn uptake and relative Zn uptake by sugarcane ratoon crop on the four soils from the two experiments combined+

Extraction Method	Basis for Expressing Results	Correlation Coefficients (r)	
		Total Zn Uptake	Relative Zn Uptake
0.1N HCl	(w/w)	.01	.43***
EDTA	(w/w)	.45***	.43***
DTPA	(w/w)	.56***	.32***
2N $MgCl_2$	(w/w)	.43***	.20*
ln 0.1N HCl	(w/w)	.02	.46***
ln EDTA	(w/w)	.41***	.44***
ln DTPA	(w/w)	.56***	.32***
ln 2N $MgCl_2$	(w/w)	.37***	.12
0.1N HCl	(w/v)	.38***	.24*
EDTA	(w/v)	.52***	.22*
DTPA	(w/v)	.48***	.15
2N $MgCl_2$	(w/v)	.50***	.07
ln 0.1N HCl	(w/v)	.42***	.31**
ln EDTA	(w/v)	.59***	.24*
ln DTPA	(w/v)	.62***	.14
ln 2N $MgCl_2$	(w/v)	.55***	.12

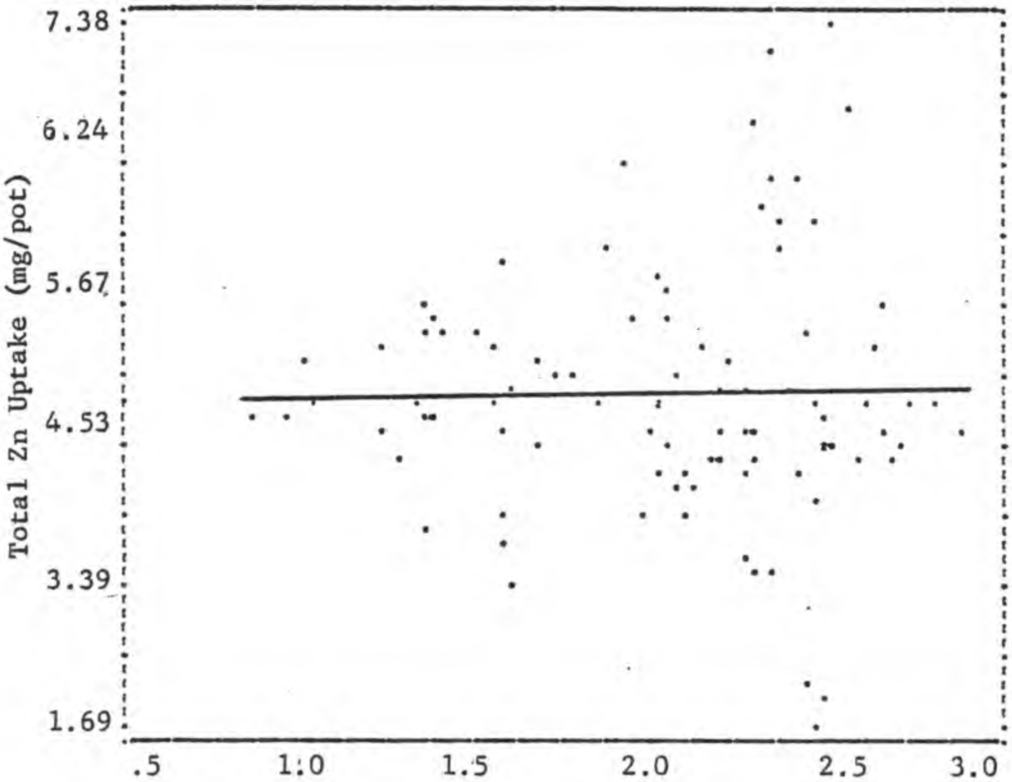
+n = 92

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

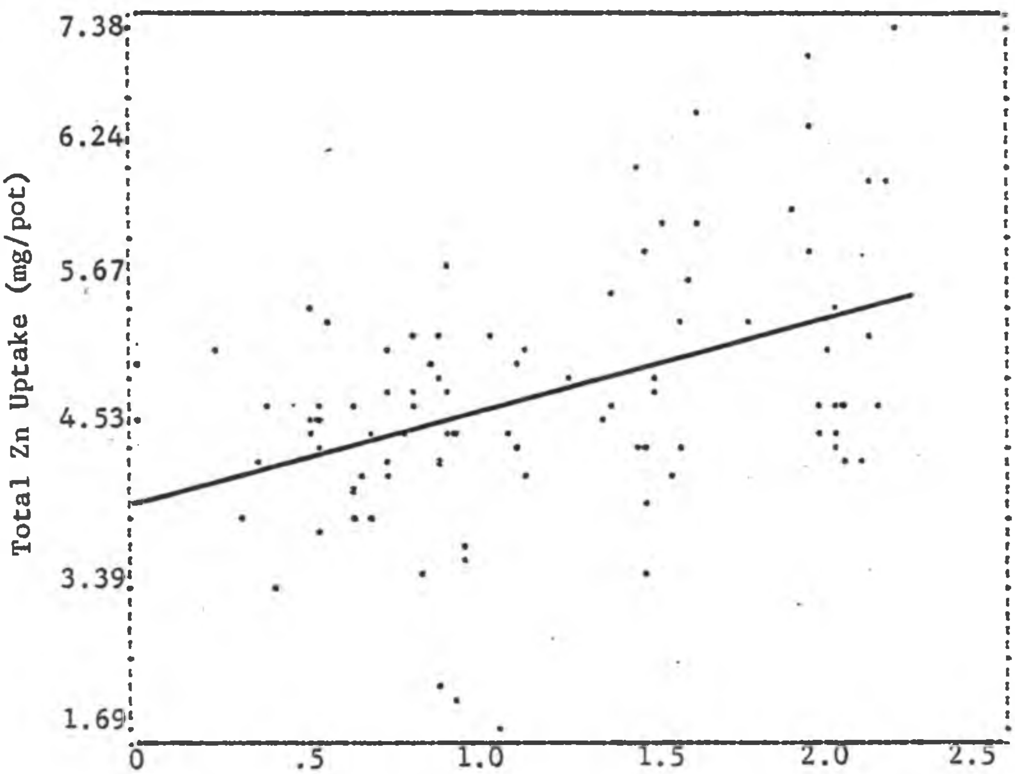


ln 0.1N HCl Extractable Zn Expressed on the w/w Basis (x)

Y = 4300.9 + 40.46(x)

r = .02

Figure 11. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by the 0.1N HCl method expressed on the (w/w) basis

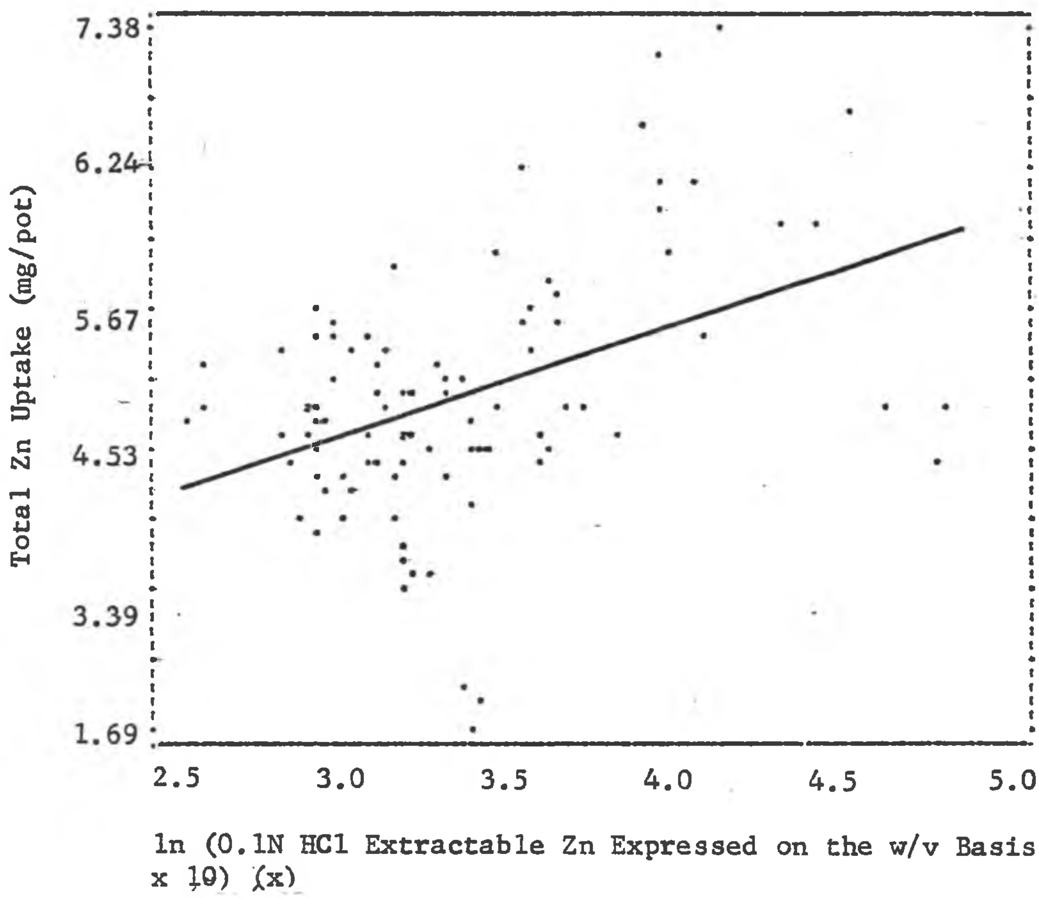


ln EDTA-$(NH_4)_2CO_3$ Extractable Zn Expressed on the w/w Basis (x)

Y = 3524.63 + 737.06(x)

r = .43

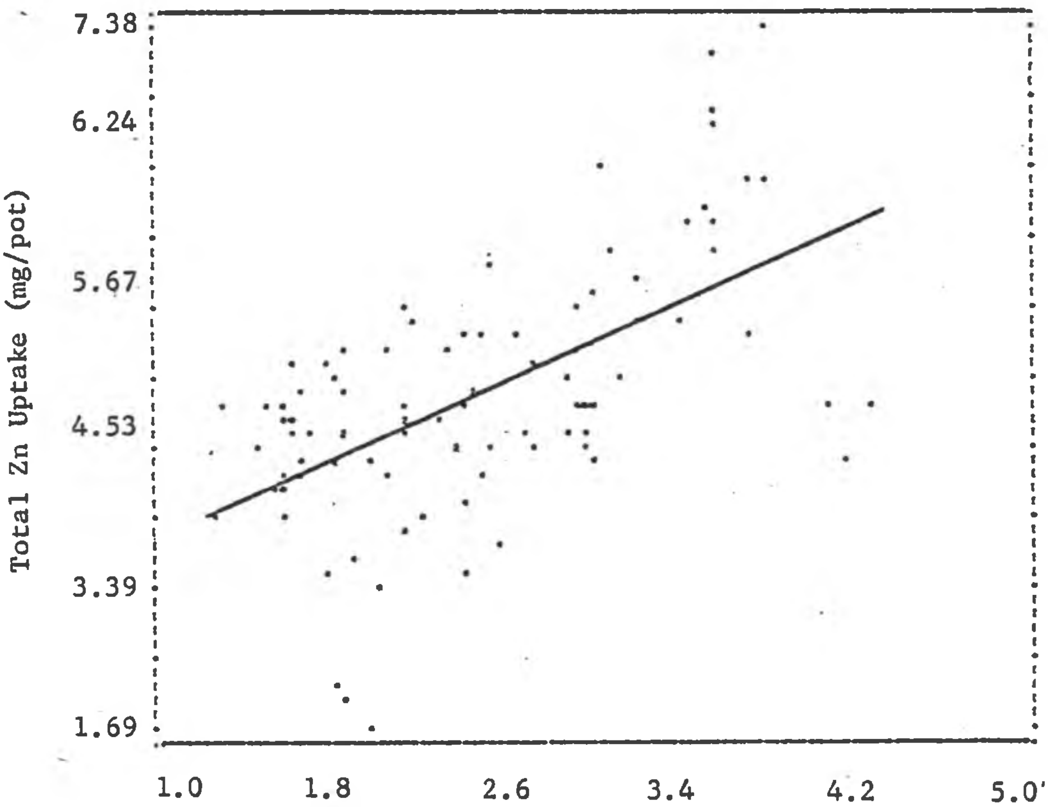
Figure 12. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by EDTA-$(NH_4)_2CO_3$ method expressed on the (w/w) basis



Y = 1251.98 + 930.95(x)

r = .43

Figure 13. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by the 0.1N HCl method expressed on the (w/v) basis

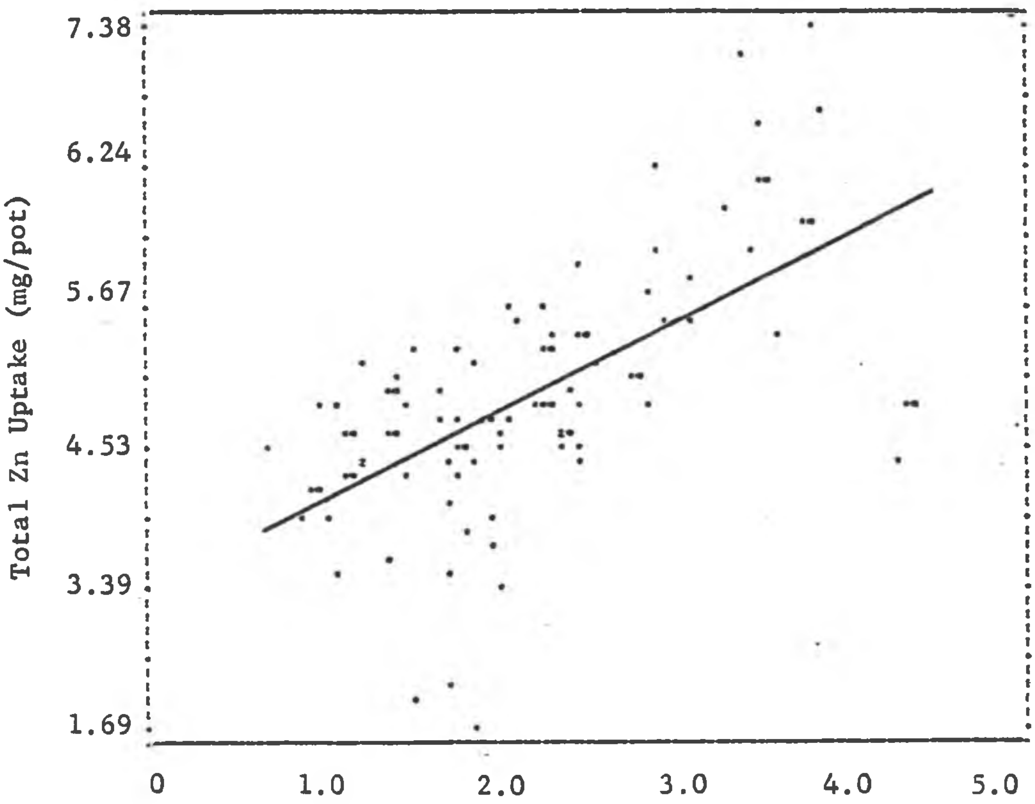


ln(EDTA-$(NH_4)_2CO_3$ Extractable Zn Expressed on the w/v Basis x 10) (x)

Y = 2445.83 + 789.47(x)

r = .59

Figure 14. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by the EDTA-$(NH_4)_2CO_3$ method expressed on the (w/v) basis

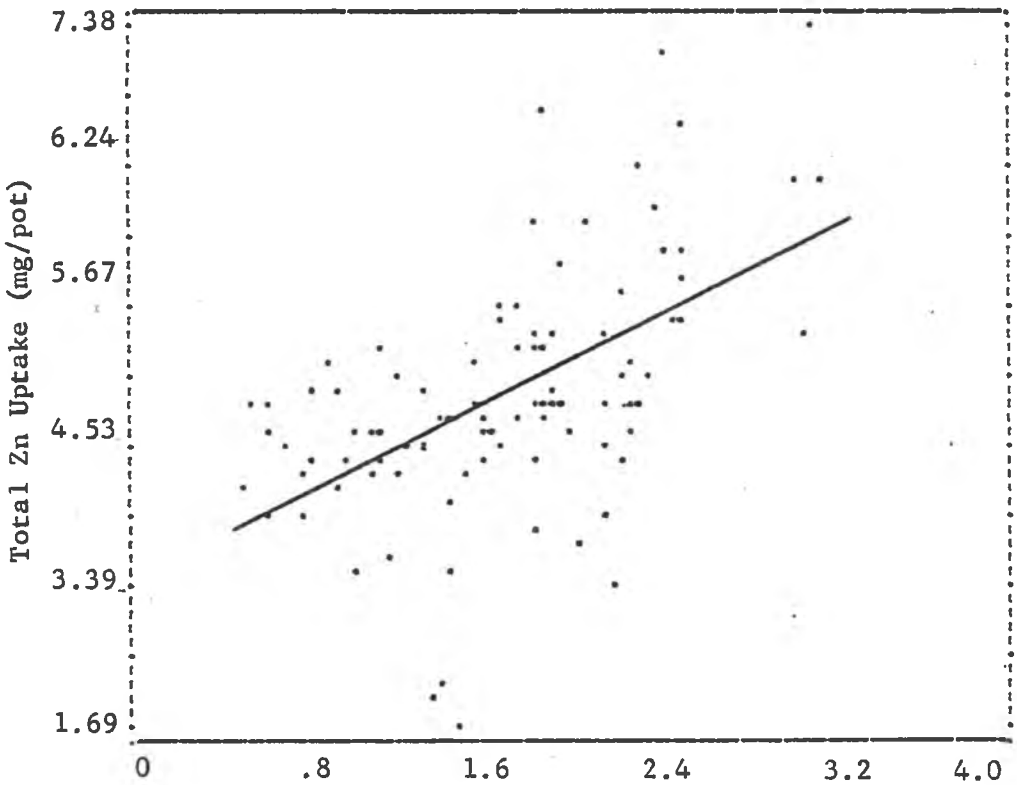


ln(DTPA Extractable Zn Expressed on the w/v Basis x 10) (x)

Y = 2849.71 + 706.79(x)

r = .62

Figure 15. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by the DTPA method on expressed(w/v) basis



ln(2N $MgCl_2$ Extractable Zn Expressed on the w/v Basis x 10) (x)

Y = 2887.68 + 883.86(x)

r = .55

Figure 16. Relationship between Zn uptake by a sugarcane ratoon crop and soil Zn extracted by the 2N $MgCl_2$ method expressed on the (w/v) basis

DTPA > EDTA > 2N $MgCl_2$ and DTPA > EDTA > 2N $MgCl_2$ > 0.1N HCl for the plant and ratoon crops of sugarcane, respectively. Soil Zn extracted by EDTA-$(NH_4)_2CO_3$ and DTPA had relatively high correlation coefficients with Zn uptake by both plant and ratoon crops, whereas Zn extracted by 0.1N HCl had the highest correlation for the plant crop, but the lowest for the ratoon crop (Tables 39 and 40). The increase in Zn uptake with increasing Zn application apparently was more striking in the plant crop than in the ratoon crop (Tables A.6 and A.7; Tables 24 and 26), and the amounts of soil Zn extracted by 0.1N HCl were relatively higher than those extracted by EDTA and DTPA. Therefore these relatively high amounts of soil Zn extracted by 0.1N HCl in relation to the larger increase in Zn uptake by the plant crop than by the ratoon crop as added Zn increased, may have caused these discrepancies in correlation values. Juang (1971) reported the 0.1N HCl method was the most suitable method for assessing available soil Zn for sugarcane growth. Kao, et al. (1974) also found 0.1N HCl to be the best method for relating soil Zn to cane growth in a pot experiment. However Meyer (1976) reported that on a wide range of soil types, Zn extracted from soils by the EDTA-$(NH_4)_2CO_3$ method was more closely correlated with T.V.D. leaf Zn than Zn extracted by the 0.1N HCl, 1N HCl, 1N NH_4OAC or 2N $MgCl_2$ methods.

In the present study, soil Zn extracted by 0.1N HCl and DTPA seems to be the most highly correlated with total Zn uptake by the plant crop (Table 39), while soil Zn extracted by DTPA and EDTA-$(NH_4)_2CO_3$ appears to be the most highly correlated with total Zn uptake by the ratoon crop. These findings partially agree with those reported by Juang (1971) and Kao, et al. (1974), who selected 0.1N HCl method as the most suitable for assessing Zn uptake by a sugarcane crop.

Yield increases with applied Zn were observed at the early stage of growth (plant crop) of sugarcane grown in the Hilo soil and soil Zn extracted by 0.1N HCl was highly correlated with yield (Table 23) as well as with Zn uptake by the plant crop when all soils were considered together (Table 39). These observations agree with the findings by Kao, et al. (1974) who selected the 0.1N HCl method as the best for young sugarcane.

The three methods found to be more highly correlated with the plant and ratoon crops are 0.1N HCl, EDTA-$(NH_4)_2CO_3$, and DTPA. The correlation coefficient for the relationship between soil Zn extracted by 2N $MgCl_2$ and Zn uptake was higher than that between Zn extracted by 0.1N HCl with Zn uptake in the ratoon crop but the reverse occurred in the plant crop. These three methods (0.1N HCl, EDTA-$(NH_4)_2CO_3$ and DTPA) appear to meet the criteria for a good soil test method described by Bray (1948) and presented earlier.

The 0.1N HCl method has been recommended for Hawaiian soils by other workers (Kanehiro, et al. 1967; Juang, 1971; Arain, 1976) and it extracts higher amounts of soil Zn than either EDTA or DTPA which make determinations of Zn in solution easier. In addition it was found to be a suitable extractant for assessing soil Zn, according to the present data. However the adjustment for soil bulk density is necessary because as mentioned earlier, without such a transformation the 0.1N HCl method is not suitable. This is evident from the data in Table 39.

COMPARISON OF ZN REQUIREMENTS OF CORN AND SUGARCANE

Growth Response to Added Zn

There was a good visual response to added Zn in both corn and the sugarcane plant crop grown in the Hilo soil. Figures 17 and 18 illustrate the difference in growth of these crops with different levels of Zn. However the ratoon crop of sugarcane did not show any visual response to Zn (Figure 19). As discussed earlier, this change in the pattern of response may be due to the extensive root system that sugarcane plants usually develop in later growth stages but lack in the early growth stage.

Careful examination of Figures 17 and 18 suggests that in the Hilo soil similar amounts of Zn are required for optimum growth of young corn and sugarcane with this treatment combination (P .05 and pH 6.0). This was pointed out and discussed in detail earlier. The fact that yield response to added Zn was marked in the plant crop, but not in the ratoon crop of sugarcane suggests the need for future research to estimate the effect of this initial growth reduction on final yields. In addition, it points out the possible error in extrapolating the Zn requirement of another crop, such as corn, to sugarcane, since they appear to have similar Zn requirements only at the early stage of growth.

Effect of Applied Variables on Zn Uptake by Corn and Sugarcane

The applied variables P and pH generally had little or no effect on soil Zn extracted by the four methods as discussed earlier. However,

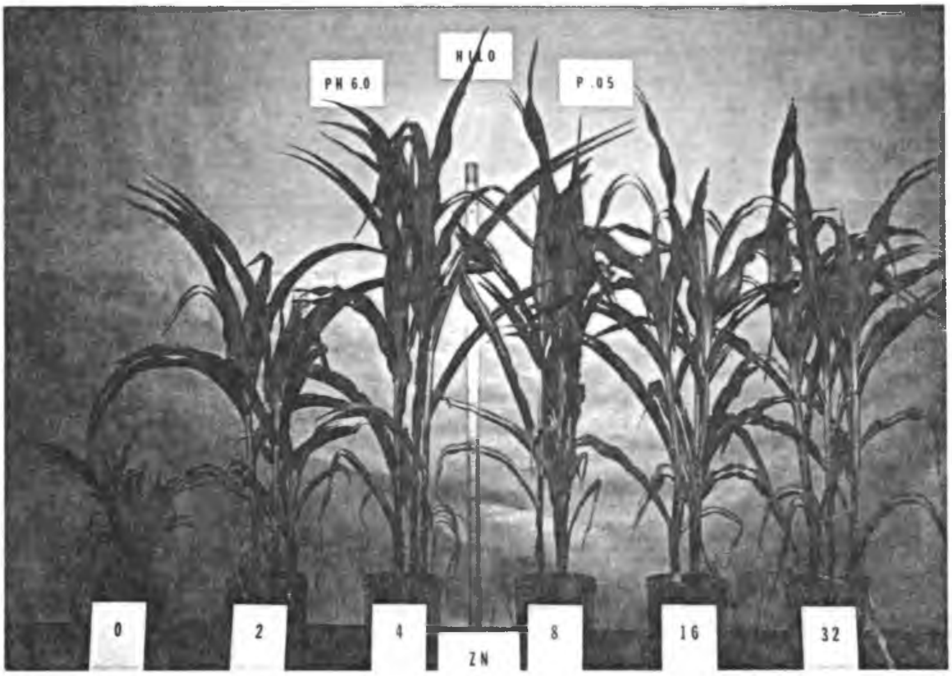


Figure 17. Response of corn to Zn application on the Hilo soil

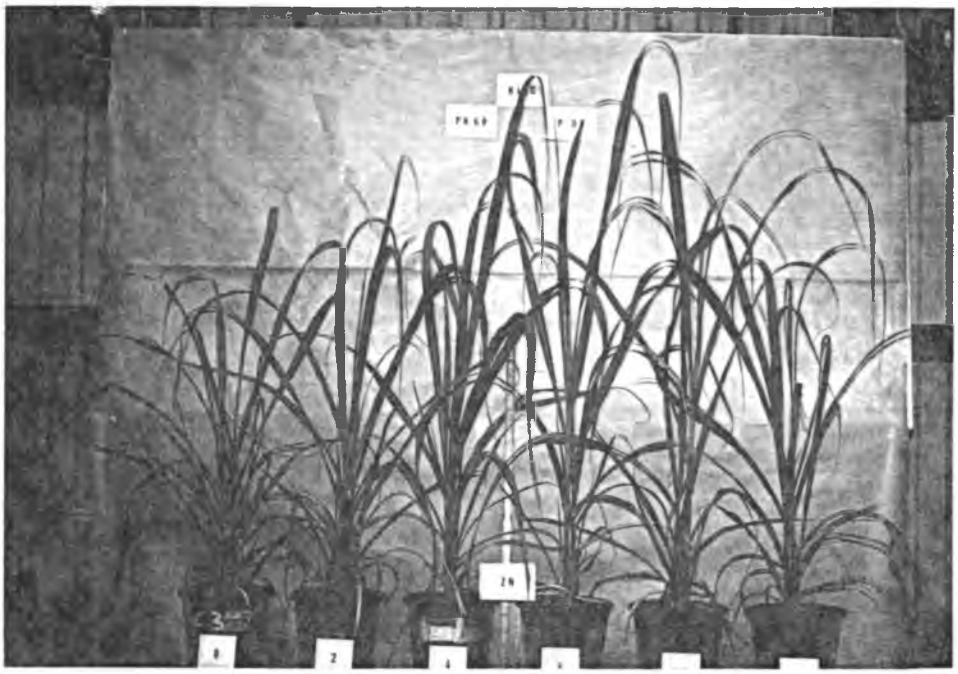


Figure 18. Response of a sugarcane plant crop to Zn application on the Hilo soil

Figure 19. Response of a sugarcane ratoon crop to Zn application on the Hilo soil

these variables had a large effect on Zn uptake by corn in both the Hilo and Halii soils. Data for corn in Tables 41 and 42 (item A) show that there is reasonable improvement in the correlation coefficients between Zn uptake and extractable soil Zn when P, pH and their interactions with extractable soil Zn are added to the regression equations for each of the four methods. These improvements were observed in both soils, but the magnitude of the improvements varies with the extraction methods.

With sugarcane, on the other hand, both the plant and ratoon crops showed little increase in the correlation coefficients in both soils with inclusion of the additional variables presented in Tables 41 and 42. This may suggest that P and pH are less likely to affect Zn uptake by sugarcane than by corn, so that inclusion of P and pH added little to the correlation coefficient. It also should be noted that extractable soil Zn did not cause as great a change in R for sugarcane as it did for corn, especially in the Hilo soil (Table 41).

Zn Distribution in the Sugarcane Plant

The Zn concentration of Zn, Cu and Si in various tissues of sugarcane grown in four soils having different amounts of extractable Zn are shown in Table 43. It is apparent that large amounts of Zn accumulate in the top 0.5 centimeter of the growing point (meristem). There is a gradual decrease in Zn concentration from the top to the bottom of the plant. A similar pattern has been described by Evans (1959). The high Zn concentration in the meristem is expected because Zn plays an important role in the production of auxins, and the

Table 41. Increase in R by successive addition of applied variables and extractable soil Zn to the prediction equation for total Zn uptake in the Hilo soil

Extraction Method	P	Soil pH	Ext. Soil Zn	ln Ext. Soil Zn	pH X P	Ext. Soil Zn X pH	Ext. Soil Zn X P	Multiple R	Simple r*
					A - Corn (n = 40)				
0.1N HCl	.002	.005	.540	.193	.005	.004	.055	.90	.72
EDTA	.002	.005	.559	.225	.002	.001	.054	.92	.81
DTPA	.002	.005	.445	.264	.003	.018	.052	.89	.72
2N $MgCl_2$	.002	.005	.555	.100	.005	.021	.054	.86	.76
					B - Sugarcane Plant Crop (n = 35)				
0.1N HCl	.000	.008	.210	.029	.018	--	.000	.51	.43
EDTA	.000	.008	.229	.025	.039	--	.004	.55	.51
DTPA	.000	.008	.247	.010	.020	--	.000	.53	.51
2N $MgCl_2$	.000	.002	.039	.001	.019	.280	.008	.59	.53
					C - Sugarcane Ratoon Crop (n = 40)				
0.1N HCl	.025	.000	.053	.016	.000	--	--	.31	.21
EDTA	.025	.000	.082	.009	.000	--	.008	.35	.26
DTPA	.025	.000	.091	.003	.001	--	.003	.35	.31
2N $MgCl_2$	.025	.000	.058	.018	.000	--	.001	.32	.21

*Simple correlation coefficient for relation between Zn uptake and extractable soil Zn only.

Table 42. Increase in R by successive addition of applied variables and extractable soil Zn to the prediction equation for total Zn uptake in the Halii soil

Extraction Method	P	Soil pH	Ext. Soil Zn	pH X P	Ext. Soil Zn X pH	Ext. Soil Zn X P	Multiple R	Simple r*
				A - Corn (n = 40)				
0.1N HCl	.108	.035	.670	.017	.011	.045	.94	.79
EDTA	.108	.035	.668	.022	.006	.028	.93	.78
DTPA	.108	.035	.670	.020	.011	.026	.93	.81
2N $MgCl_2$	.108	.035	.665	.017	.007	.013	.92	.68
				B - Sugarcane Plant Crop (n = 29)				
0.1N HCl	.002	.171	.456	.008	.015	.005	.81	.76
EDTA	.001	.171	.456	.014	.004	.001	.80	.77
DTPA	.002	.171	.453	.019	.001	.000	.80	.77
2N $MgCl_2$	.002	.024	.001	.006	.591	.000	.79	.78
				C - Sugarcane Ratoon Crop (n = 40)				
0.1N HCl	.041	.019	.621	.004	.001	.014	.84	.78
EDTA	.041	.019	.624	.004	.005	.004	.86	.77
DTPA	.041	.019	.670	.004	.004	.006	.83	.81
2N $MgCl_2$	.041	.019	.562	.008	.066	.008	.84	.65

*Simple correlation coefficient for relation between Zn uptake and extractable soil Zn only.

Table 43. Zn (ppm), Cu (ppm) and Si (%) concentration in various sugarcane tissues grown in four soils+

Sugarcane Tissues	Soil											
	Hilo			Halii			Molokai			Lualualei		
	Zn	Cu	Si	Zn	Cu	Si	Zn	Cu	Si	Zn	Cu	Si
Tillers	11	7	.8	14	11	.2	18	7	1.1	12	5	2.2
Mature stalk	10	4	.1	16	6	0	29	4	.2	17	5	.3
Dry leaves	6	6	1.0	5	8	.9	0	0	4.0	0	1	4.1
Lower sheaths	3	8	.9	5	11	.3	8	3	3.1	3	0	3.7
Lower blades	6	11	.9	12	9	.5	4	4	2.4	3	5	2.6
3, 4, 5, 6 sheaths	9	8	.3	10	9	.1	14	6	1.2	7	11	1.5
3, 4, 5, 6 blades	20	8	.6	19	10	.1	16	6	2.2	13	3	3.0
3, 4, 5, 6 midrib	8	4	.2	10	5	.0	7	4	.9	11	4	1.2
Immature stalk	21	9	0	30	13	0	61	12	.2	39	12	.3
Spindle	22	9	.2	25	10	0	30	9	.5	27	9	.8
Meristem	325	-	-	363	-	-	378	-	-	338	-	-

+Values are means of three replicates

concentration of auxin is high in the meristem (van Overbeek, 1943, 1945).

It appears from the data presented in Table 43 that there may be a relationship between Si and distribution of Cu and Zn. Plants grown in the Molokai and Lualualei soils which are known to have higher silica content than the Hilo and Halii soils, have higher Si and lower Zn and Cu concentration in some of the older tissues, i.e. dry leaves, lower blades and lower sheaths than plants grown in the Hilo and Halii soils. The pattern was generally reversed, however in some of the younger tissues, i.e. immature stalk, spindle, meristem.

Relationship Between Extractable Soil Zn and Zn Concentration and Total Zn Uptake by Sugarcane

As discussed earlier, the most suitable plant parameter for evaluating the Zn nutritional status of plants is probably total Zn uptake. However, this value is not always easy to obtain, especially under field conditions. Therefore the correlation of Zn concentration in the various tissues with Zn uptake and also with extractable soil Zn was determined to identify the tissue which was the most highly correlated with these variables.

Data in Table 44 show that the immature stalk (internode 3-5) is the most highly correlated with total Zn uptake followed by the spindle. The immature stalk and spindle also have the highest correlation with soil Zn on the W/W basis, extracted by the EDTA and DTPA methods. It is interesting to note that correlation coefficients between total

Table 44. Correlation coefficients relating Zn concentration in various sugarcane tissues to extractable soil Zn on the w/w basis and total Zn uptake+

Plant Tissues	Extractable Soil Zn (W/W)				Total Zn Uptake
	0.1N HCl	EDTA	DTPA	2N $MgCl_2$	
Tillers	-.05	.50*	.49	-.37	.65*
Mature stalk	.31	.86***	.83***	-.53	.77**
Dry leaves	-.51*	-.82***	-.84***	-.92***	-.79**
Lower sheaths	-.26	.12	.10	.08	.24
Lower blades	-.45	-.47	-.58*	.81***	-.62*
3, 4, 5, 6 sheaths	-.02	.46	.46	-.30	.70**
3, 4, 5, 6 blades	-.29	-.61*	-.68**	.64	-.74**
3, 4, 5, 6 midribs	.18	.50*	.60*	-.71**	-.79***
Immature stalk	.42	-.89***	.88***	-.67**	.92***
Spindle	.92	.67**	.72**	-.59*	.88***
Meristem	.48	.48	.42	-.20	.53*
Totan Zn uptake	-.36	.86***	.90***	-.78***	---

*Significant at 5% level

**Significant at 1% level

***Significant at .1% level

Nonsignificant

+n = 12

Zn uptake and extractable soil Zn by the four methods on the w/w basis are similar to the correlation coefficients for the immature stalk.

Improvements in the correlation coefficients from adjusting soil extractable Zn for soil bulk density may be observed by comparing the values in Tables 44 and 45. The correlation coefficients for the relationship between extractable soil Zn on the w/v basis with Zn concentration in the immature stalk, mature stalk, and also total Zn uptake are very similar (Table 45). It should be pointed out that correlation coefficients between the various tissues and extractable soil Zn by the four methods in Table 45 are much closer than those for the same relationship in Table 44. This may support the suggestion made earlier that adjustment of extractable soil Zn for soil bulk density minimizes the differences between soils responsible for variable Zn uptake. In the present case, the largest improvement was observed for the 0.1N HCl method although the other methods also showed some improvement.

Correlation coefficients between total Zn uptake and various plant tissues (Table 44) suggest that the immature stalk may be the appropriate tissue to sample to evaluate the Zn status of sugarcane, although the spindle also appears to be reliable. However additional investigations should be conducted to better evaluate these plant tissues.

It has been reported that the meristem is a very sensitive Zn indicator tissue (Bowen, 1972) and this was found to be so in the previous experiment. However its small size makes precise sampling and analysis difficult because there is some possibility of dilution

Table 45. Correlation coefficients relating Zn concentration in various sugarcane tissues to extractable soil Zn on the w/v basis+

Plant Parts	Correlation Coefficients (r) Extractable Zn (w/v) 0.1N HCl	EDTA	DTPA	2N $MgCl_2$
Tillers	.49	.59*	.57*	.73**
Mature stalk	.83***	.92***	.90***	.83***
Dry leaves	-.86***	-.81***	-.83***	-.44
Lower sheaths	.09	.18	.15	.36
Lower blades	-.58*	-.43	-.51	-.09
3, 4, 5, 6 sheaths	.52*	.57*	.54*	.72**
3, 4, 5, 6 blades	-.68**	-.64*	-.68**	-.52*
3, 4, 5, 6 midribs	.68**	.56*	.61*	.54*
Immature stalk	.86***	.92***	.91***	.70**
Spindle	.72**	.73**	.75**	.62*
Meristem	.36	.53*	.48	.58*
Total Zn uptake	.91***	.91***	.93***	.77**

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
Nonsignificant
+n = 12

of Zn by surrounding tissues which have very low Zn. Furthermore, the correlation between Zn concentration in the meristem and Zn uptake or extractable soil Zn was not as high as with other tissues.

The correlation coefficients between Zn concentration in the immature stalk, and soil extractable Zn on the w/v basis decreased in the following order: EDTA > DTPA > 0.1N HCl > 2N $MgCl_2$ (Table 45). The correlation coefficients for the former three methods are close, however, and therefore support the previous conclusion that either of these three extractants is suitable for assessing soil Zn if results are expressed on the w/v basis.

SUMMARY AND CONCLUSIONS

A greenhouse study was carried out to evaluate the effects of pH, P and Zn on growth, Zn concentration and Zn uptake by corn and sugarcane. In addition, a laboratory study was conducted to compare four methods for extraction of soil Zn.

Four pot experiments were set up using four soils: Hilo, Halii, Molokai and Lualualei series. The Hilo and Halii soils were used for the two main experiments since they were reported to be Zn deficient. They received two levels of P (.05 and .1 ppm in sol.), were limed or acidified to attain pH 5.0 and 6.0, although final pH values were about 5.1 and 5.7, 3.8 and 4.8 in the Hilo and Halii soils, respectively and five (0, 2, 4, 8, 16 ppm) or six (0, 2, 4, 8, 16, 32 ppm) levels of Zn were added for the low and high pH treatments, respectively. Other fertilizers were applied according to the known requirements for the test crops, corn and sugarcane. The other two experiments were conducted with the four soils and essential nutrients except Zn were supplied. Corn and sugarcane also were used as the test crops.

Dry matter yields were recorded after harvest and plants were then analyzed for nutrients. The soils were analyzed for extractable Zn using the 0.1N HCl, EDTA-$(NH_4)_2CO_3$, 0.05M DTPA and 2N $MgCl_2$ methods.

Results of the greenhouse study showed that increasing pH and/or applying P fertilizer at high rates enhanced Zn deficiency in corn grown in the Hilo soil but not in the Halii soil probably because at the pH values of 3.8 and 4.8 attained in this soil available Zn was adequate for corn growth. However there was some indication that liming the Halii soil to raise pH to 5.0 or above and applying high amounts of P fertilizer may cause Zn to become limiting for corn growth. These findings suggest that Zn deficiency induced by application of lime and P is more likely to occur in soils that have Zn levels that are near deficiency. Additions of small amounts of Zn overcome this disorder in plants caused by either natural low Zn levels in the soil or low Zn levels induced by P and lime application.

Analysis of corn roots did not show any Zn accumulation and P did not appear to have any significant effect on extractable soil Zn. Thus the present investigation suggests that the decrease in total Zn uptake from excess P fertilization may be caused by P in someway reducing the absorption rate of Zn by roots. Increasing soil pH also was found to greatly reduce Zn uptake by corn which may be due to formation of Zn compounds with low solubility in soil. The Zn disorder in corn brought about by increasing pH and/or high P fertilization was not well correlated with changes in Zn concentration in the tissues. However it was better correlated with the P/Zn ratios of the plant. When this ratio was less than 100 - 125, plants were healthy while in Zn deficient plants the ratio was above this range.

Sugarcane is probably less sensitive to Zn deficiency than corn and this may be especially true at later stages of growth. However in the early stages of growth, sugarcane and corn both appeared to have similar Zn requirements. Analysis of various sugarcane tissues revealed that Zn concentration in the immature stalk (internode 3-5) is highly correlated with total Zn uptake and was also found to be highly correlated with extractable soil Zn. The meristematic tissue was found to be very sensitive to Zn applications, but it was not as highly correlated with total Zn uptake as was Zn in immature stalk.

This study has shown that the 0.1N HCl, EDTA-$(NH_4)_2CO_3$ and 0.05M DTPA methods all appear to be suitable for assessing Zn in Hawaiian soils. However a major modification made was the adjustment of extractable soil Zn from the w/w basis to the w/v basis by multiplying extractable soil Zn by the appropriate soil bulk density. Although the three methods proved to be suitable, 0.1N HCl is recommended since it has been used traditionally in Hawaii. The adjustment for soil bulk density is especially necessary with this method.

Tentative critical levels were established for these three methods on the w/v basis. They were 3-4 $\mu g/cm^3$, 1.25 $\mu g/cm^3$, and 5-8 $\mu g/cm^3$ for 0.1N HCl, EDTA-$(NH_4)_2CO_3$ and 0.05M DTPA, respectively. These levels determined on the w/v basis are comparable to those reported in the literature, probably on the w/w basis. Sugarcane and corn may have similar Zn critical levels for soil Zn at early stages of growth, but at later stages of growth that of sugarcane is probably lower. It appears that whenever Zn concentrations are above 10 ppm, 15 ppm and 150 ppm in the sheaths 3, 4, 5, 6, T.V.D. leaf and meristem, respectively, Zn deficiency is not likely to occur in sugarcane.

APPENDIX

Table A.1. Nutrient content of sugarcane seed pieces - Var. 3775

Seed Piece Classes		Elemental Concentrations					
		Percent					
F. Wt.	D. Wt. (g/seed piece)	P	K	Ca	Mg	S	Si
36.86	9.60	0.10	0.20	0.14	0.09	0.10	0.08
47.67	12.58	0.11	0.23	0.13	0.11	0.11	0.08
75.38	15.72	0.16	0.83	0.16	0.14	0.14	0.08
		ppm					
F. Wt.	D. Wt. (g/seed piece)	Al	Mn	Fe	Cu	Zn	
36.86	9.60	29	42	74	4	7	
47.67	12.58	40	46	79	4	11	
75.38	15.72	40	65	85	10	20	

*Average of five seed pieces

Table A.2. Effect of Zn, P and Soil pH on concentration and uptake of P, Ca and Cu, P/Zn ratio and P/Cu ratio in corn grown on the Hilo soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	P Conc %	Total P Uptake mg/pot	Ca Conc %	Total Ca Uptake mg/pot	Cu Conc ppm	Total Cu Uptake mg/pot	P(%)/Zn(ppm) ratio	P(%)/Cu(ppm) ratio
7.8	4.9	0	.39	50.6	.73	95.1	14	189.1	147.2	272.6
10.8	5.0	0	.56	48.6	1.02	87.2	16	135.0	199.0	358.6
7.8	5.1	2	.24	53.7	.51	116.2	9	193.8	104.6	278.2
10.8	5.1	2	.29	53.8	.57	106.9	8	151.3	129.3	357.9
7.8	5.1	4	.24	54.9	.55	123.2	9	190.3	114.1	289.6
10.8	5.1	4	.24	59.3	.53	128.5	7	156.1	124.2	377.4
7.8	5.1	8	.21	46.6	.47	107.1	8	181.7	95.3	256.4
10.8	5.1	8	.25	56.4	.58	129.1	7	168.7	102.1	334.8
7.8	5.1	16	.19	45.7	.45	111.2	8	185.3	78.6	246.3
10.8	5.1	16	.26	64.1	.56	140.8	7	188.4	92.8	341.1
7.8	5.4	0	.59	20.2	1.27	44.4	18	62.0	205.0	325.0
10.8	5.4	0	.74	9.6	1.29	16.9	18	24.1	217.0	400.2
7.8	5.7	2	.41	50.7	.83	103.5	15	187.9	150.0	270.1
10.8	5.7	2	.54	50.2	1.18	109.7	15	139.4	221.2	360.0
7.8	5.7	4	.23	48.1	.55	116.3	9	191.9	112.4	251.3
10.8	5.7	4	.27	57.5	.56	118.8	8	180.9	123.2	318.1
7.8	5.7	8	.22	43.7	.57	112.6	8	159.1	100.0	364.3
10.8	5.7	8	.24	58.9	.54	135.2	7	163.1	102.8	292.1
7.8	5.7	16	.23	46.0	.59	117.0	8	159.9	92.2	321.4
10.8	5.7	16	.21	56.1	.53	141.6	7	187.0	91.3	300.0
7.8	5.7	32	.21	45.1	.57	126.4	8	165.1	78.8	273.2
10.8	5.7	32	.25	58.3	.64	129.3	8	151.8	91.1	326.8

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table A.3. Summary of statistical analyses of the effect of Zn, P and soil pH on concentration and uptake of P, Ca and Cu, P/Zn ratio and P/Cu ratio in corn grown on the Hilo soil

Treatment	F Values							
	P Conc	P Uptake	Ca Conc	Ca Uptake	Cu Conc	Cu Uptake	P/Zn Ratio	P/Cu Ratio
Applied P	29.13****	8.14*	3.28	3.20	.93	11.29**	17.22***	90.72****
Soil pH	43.88****	23.76****	17.19****	11.60**	28.21****	21.39***	24.82****	.29
Applied Zn	115.08****	19.16****	20.63****	41.16****	70.63****	22.36****	63.50****	3.37*
Interactions								
P x pH	.01	.15	.23	.09	.06	1.47	.01	1.50
P x Zn	4.82**	4.12*	.73	4.62**	.90	3.70*	3.39*	.61
pH x Zn	16.20****	11.32****	4.56**	10.27****	10.32****	14.20****	7.68***	4.04*
P x pH x Zn	1.56	.65	1.12	.55	.39	.19	2.27	1.27

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table A.4. Effect of Zn, P and soil pH on concentration and uptake of P, Ca and Cu, P/Zn ratio, P/Cu ratio in corn grown on the Halii soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	P Conc %	Total P Uptake mg/pot	Ca Conc %	Total Ca Uptake mg/pot	Cu Conc ppm	Total Cu Uptake mg/pot	P(%)/Zn(ppm) ratio	P(%)/Cu(ppm) ratio
2.2	3.7	0	.23	28.8	.25	33.1	18	227.3	106.5	127.3
3.2	3.8	0	.25	46.1	.31	57.6	15	284.0	116.7	163.3
2.2	3.8	2	.23	35.8	.23	35.8	17	271.3	91.7	131.9
3.2	3.8	2	.23	50.6	.27	59.4	15	318.9	96.0	158.8
2.2	3.9	4	.24	30.6	.26	31.7	17	220.4	76.8	139.9
3.2	3.8	4	.25	51.4	.30	58.2	15	315.2	92.8	164.8
2.2	3.8	8	.24	31.2	.25	32.9	17	215.3	68.6	145.4
3.2	3.8	8	.22	64.4	.26	75.6	14	405.7	77.5	159.4
2.2	3.8	16	.23	37.4	.26	44.1	17	277.4	44.1	136.8
3.2	3.8	16	.21	51.1	.29	70.2	14	328.5	49.4	155.5
2.2	4.8	0	.19	41.5	.49	110.0	10	235.7	90.5	175.9
3.2	4.8	0	.30	56.3	.72	137.9	13	251.0	125.7	225.0
2.2	4.8	2	.22	46.8	.54	115.5	12	261.7	93.6	179.2
3.2	4.8	2	.24	56.7	.54	119.0	12	277.3	99.7	203.8
2.2	4.8	4	.23	51.4	.54	121.3	13	283.4	83.2	181.7
3.2	4.8	4	.25	76.1	.50	148.6	11	314.9	102.3	247.2
2.2	4.8	8	.19	46.7	.52	124.6	11	268.9	76.6	173.3
3.2	4.8	8	.21	52.7	.52	134.8	11	282.4	80.6	186.7
2.2	4.8	16	.20	46.6	.54	121.7	13	284.2	62.3	164.1
3.2	4.8	16	.20	56.8	.54	148.7	13	359.1	60.3	157.7
2.2	4.8	32+	.19	46.7	.53	133.1	13	315.6	43.5	148.1
3.2	4.8	32+	.21	55.7	.50	138.3	12	312.4	54.0	178.8

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table A.5. Summary of statistical analyses of the effect of Zn, P and soil pH on concentration and uptake of P, Ca and Cu, P/Zn ratio and P/Zn ratio in corn grown on the Halii soil

Treatment	F Values							
	P Conc	P Uptake	Ca Conc	Ca Uptake	Cu Conc	Cu Uptake	P/Zn Ratio	P/Cu Ratio
Applied P	2.76	52.26****	4.58	56.03****	6.93*	19.33***	5.66*	12.50**
Soil pH	1.16	20.74***	247.41****	600.34****	76.96****	.11	1.48	29.78****
Applied Zn	1.56	1.66	1.21	2.43	.51	2.30	17.54****	1.66
Interactions								
P x pH	2.76	2.22	.01	2.22	8.13*	4.64*	.16	.12
P x Zn	1.58	.83	2.19	.66	.52	.87	.79	1.04
pH x Zn	.38	2.27	.68	1.08	1.05	.90	.43	1.35
P x pH x Zn	.50	1.35	1.55	1.24	.82	1.51	.40	.51

*Significant at 5% level
**Significant at 1% level
***Significant at .01% level
****Significant at .01% level
Nonsignificant

Table A.6. Effects of P, pH and Zn on yield, Zn concentration and Zn uptake on the plant crop of sugarcane grown on the Hilo soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Applied Zn (ppm)	Yield (g/plant)	Zn Conc ppm	Zn Uptake ug/plant	Total No.* of Plants Alive/ Treatment
24.3	4.8	0	25.92	17.3	449.4	3
31.8	4.8	0	25.13	17.0	427.1	2
24.3	4.8	2	28.77	14.0	402.8	1
31.8	4.8	2	27.94	14.5	405.4	2
24.3	4.8	4	-	-	-	0
31.8	4.8	4	27.10	17.7	478.1	3
24.3	4.8	8	33.17	16.0	530.7	1
31.8	4.8	8	27.63	16.0	442.1	1
24.3	4.9	16	-	-	-	0
31.8	4.9	16	26.09	17.0	443.5	1
24.3	5.3	0	22.69	18.0	408.6	3
31.8	5.3	0	22.64	16.7	376.3	3
24.3	5.2	2	25.29	17.3	441.8	3
31.8	5.2	2	23.88	16.0	382.1	1
24.3	5.3	4	24.33	17.7	419.0	3
31.8	5.2	4	28.19	20.0	563.8	2
24.3	5.3	8	28.87	16.0	461.5	2
31.8	5.2	8	32.24	18.0	580.3	1
24.3	5.0	16	32.51	17.0	552.6	3
31.8	5.0	16	-	-	-	0
24.3	5.0	32+	22.45	19.0	426.5	2
31.8	5.0	32+	27.06	23.0	622.4	1

*All values for yield, plant Zn conc and total Zn uptake are mean values from all live plants in the respective treatments.

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Table A.7. Effects of P, pH and Zn on yield, Zn concentration and Zn uptake on the plant crop of sugarcane grown on the Halii soil

Applied $Ca(H_2PO_4)_2$ (g/pot)	Soil pH	Applied Zn (ppm)	Yield (g/plant)	Zn Conc ppm	Zn Uptake ug/plant	Total No.* of Plants Alive/ Treatment
6.9	3.7	0	39.88	19.0	757.6	2
9.6	3.8	0	35.71	17.0	604.5	2
6.9	3.8	2	32.45	21.0	681.4	1
9.6	3.9	2	30.61	21.0	612.2	1
6.9	3.8	4	32.12	21.0	631.7	3
9.6	3.8	4	-	-	-	0
6.9	3.7	8	31.89	26.0	829.1	1
9.6	3.8	8	-	-	-	0
6.9	3.7	16	32.60	30.4	973.0	4
9.6	3.8	16	33.92	28.5	961.6	2
6.9	4.8	0	26.40	21.5	565.2	2
9.6	4.8	0	-	-	-	0
6.9	4.8	2	-	-	-	0
9.6	4.8	2	37.42	19.0	711.0	1
6.9	4.7	4	29.30	22.5	658.8	2
9.6	4.8	4	29.78	22.0	655.2	1
6.9	4.7	8	33.40	23.0	768.2	2
9.6	4.8	8	33.73	20.5	695.8	4
6.9	4.8	16	27.38	29.0	794.0	1
9.6	4.8	16	-	-	-	0
6.9	4.7	32+	31.68	32.5	1,020.0	4
9.6	4.7	32+	31.46	29.5	932.9	4

*All values for yield, plant Zn conc and total Zn uptake are mean values from all live plants in the respective treatments.

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Table A.8. Effect of Zn, P and soil pH on concentration of P, Ca and Cu in sheaths 3-6 and T.V.D. leaf and uptake of P, Ca and Cu by a ratoon crop of sugarcane grown on the Hilo soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	Sheaths 3-6			T.V.D. Leaf			Total Uptake		
			P%	Ca%	Cu (ppm)	P%	Ca%	Cu (ppm)	P (mg/pot)	Ca (mg/pot)	Cu (mg/pot)
24.3	4.8	0	.16	.33	13	.28	.35	11	308	700	2.04
31.8	4.8	0	.15	.32	12	.33	.41	11	332	785	2.10
24.3	4.8	2	.13	.32	13	.31	.35	11	302	699	1.74
31.8	4.8	2	.14	.32	14	.29	.33	11	311	737	2.08
24.3	4.8	4	.12	.30	12	.28	.34	10	293	673	1.75
31.8	4.8	4	.13	.30	12	.31	.32	11	326	719	1.94
24.3	4.8	8	.13	.31	13	.28	.33	11	261	627	1.80
31.8	4.8	8	.12	.31	12	.28	.32	11	287	711	1.87
24.3	4.9	16	.12	.28	12	.28	.36	10	291	674	1.96
31.8	4.9	16	.13	.31	12	.29	.38	11	319	724	1.99
24.3	5.3	0	.12	.35	14	.27	.37	11	302	849	2.13
31.8	5.3	0	.12	.36	14	.29	.40	11	318	882	2.21
24.3	5.2	2	.13	.33	13	.29	.41	11	297	797	2.05
31.8	5.2	2	.14	.33	14	.30	.46	11	313	802	2.12
24.3	5.3	4	.13	.36	14	.30	.42	11	310	779	2.09
31.8	5.2	4	.13	.34	12	.28	.41	11	314	860	2.20
24.3	5.3	8	.12	.34	13	.28	.42	10	334	777	2.05
31.8	5.2	8	.12	.33	12	.27	.36	11	295	807	1.94
24.3	5.0	16	.14	.33	15	.28	.39	11	287	712	2.04
31.8	5.0	16	.12	.35	13	.27	.44	11	300	814	2.04
24.3	5.0	32+	.12	.34	14	.25	.37	12	269	741	1.89
31.8	5.0	32+	.12	.31	13	.23	.37	11	279	790	2.06

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table A.9. Summary of statistical analyses of the effect of Zn, P and soil pH on concentration of P, Ca and Cu in sheaths and T.V.D. leaf and uptake of P, Ca and Cu by a ratoon crop of sugarcane grown on the Hilo soil

Treatment	F Values								
	Sheaths 3-6			T.V.D. Leaf			Total Uptake		
	P Conc	Ca Conc	Cu Conc	P Conc	Ca Conc	Cu Conc	P	Ca	Cu
Applied P	.00	.00	.82	.23	.21	.39	6.14*	9.81**	4.28*
Soil pH	3.35	12.00**	6.06*	.47	8.35**	.04	.02	34.21****	15.63***
Applied Zn	3.46*	.62	1.20	.99	.34	.33	2.52	2.30*	2.63
Interactions									
P x pH	.84	.00	.82	.34	.03	1.09	.69	.09	1.75
P x Zn	.64	.52	.36	.74	.58	.28	.04	.27	1.08
pH x Zn	3.53*	.52	1.23	.16	.64	.37	.43	.52	.93
P x pH x Zn	1.83	.15	.53	.47	.27	1.20	.16	.41	.44

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

Table A.10. Effect of Zn, P and soil pH on concentration of P, Ca and Cu in sheaths 3-6 and T.V.D. leaf and uptake of P, Ca and Cu by a ratoon crop of sugarcane grown on the Halii soil

Applied $Ca(H_2PO_4)_2$ g/pot	Soil pH	Applied Zn (ppm)	Sheaths 3-6			T.V.D. Leaf			Total Uptake		
			P%	Ca%	Cu (ppm)	P%	Ca%	Cu (ppm)	P (mg/pot)	Ca (mg/pot)	Cu (mg/pot)
6.9	3.7	0	.10	.16	12	.21	.19	11	234	445	2.09
9.6	3.8	0	.11	.16	11	.22	.22	11	277	463	2.28
6.9	3.8	2	.10	.15	11	.20	.19	11	246	423	2.25
9.6	3.9	2	.12	.16	12	.23	.20	11	274	442	2.19
6.9	3.8	4	.10	.15	11	.20	.20	12	230	394	2.12
9.6	3.8	4	.10	.17	11	.21	.20	10	259	485	2.04
6.9	3.7	8	.09	.15	11	.20	.20	12	234	437	2.26
9.6	3.8	8	.11	.17	12	.21	.19	11	264	469	2.26
6.9	3.7	16	.10	.14	11	.21	.18	11	225	398	2.15
9.6	3.8	16	.11	.17	11	.22	.22	11	266	469	2.36
6.9	4.8	0	.10	.30	11	.22	.36	10	285	800	2.10
9.6	4.8	0	.11	.30	11	.25	.38	9	340	846	2.13
6.9	4.8	2	.11	.30	12	.24	.34	9	276	813	2.13
9.6	4.8	2	.12	.28	11	.24	.35	10	310	789	2.04
6.9	4.7	4	.13	.36	13	.24	.44	12	275	787	2.07
9.6	4.8	4	.12	.29	11	.23	.31	11	290	826	2.04
6.9	4.7	8	.11	.34	12	.21	.36	11	293	846	2.28
9.6	4.8	8	.13	.32	12	.23	.38	10	319	855	2.15
6.9	4.8	16	.11	.30	11	.22	.35	10	281	861	2.44
9.6	4.8	16	.10	.29	10	.25	.35	11	316	850	2.21
6.9	4.8	32+	.10	.27	11	.22	.37	11	270	788	2.06
9.6	4.8	32+	.11	.30	11	.24	.39	11	313	825	2.28

+Values for 32 ppm added Zn were not included in the statistical calculations, due to distortion of the regression equation.

Values are means of two replicates.

Table A.11. Summary of statistical analyses of the effect of P, Zn and soil pH on concentration of P, Ca and Cu in sheaths 3-6 and T.V.D. leaf and uptake of P, Ca and Cu by a ratoon crop of sugarcane grown on the Halii soil

Treatment	F Values								
	Sheaths 3-6			T.V.D. Leaf			Total Uptake		
	P Conc	Ca Conc	Cu Conc	P Conc	Ca Conc	Cu Conc	P	Ca	Cu
Applied P	3.77	.15	1.32	18.17***	.05	3.74	43.61****	1.77	.14
Soil pH	6.45*	211.15****	1.32	57.93****	202.08****	16.69***	86.81****	313.00****	.60
Applied Zn	.76	.80	1.77	1.89	.30	2.15	1.71	.37	2.16
Interactions									
P x pH	.56	3.86	2.34	.00	1.39	1.16	.02	.63	1.83
P x Zn	1.43	.24	1.41	1.77	2.05	2.47	.83	.25	.42
pH x Zn	1.65	.56	1.22	.87	.27	1.32	.95	.25	.39
P x pH x Zn	.22	.37	.42	2.14	1.43	.35	.21	.18	.59

*Significant at 5% level
**Significant at 1% level
***Significant at .1% level
****Significant at .01% level
Nonsignificant

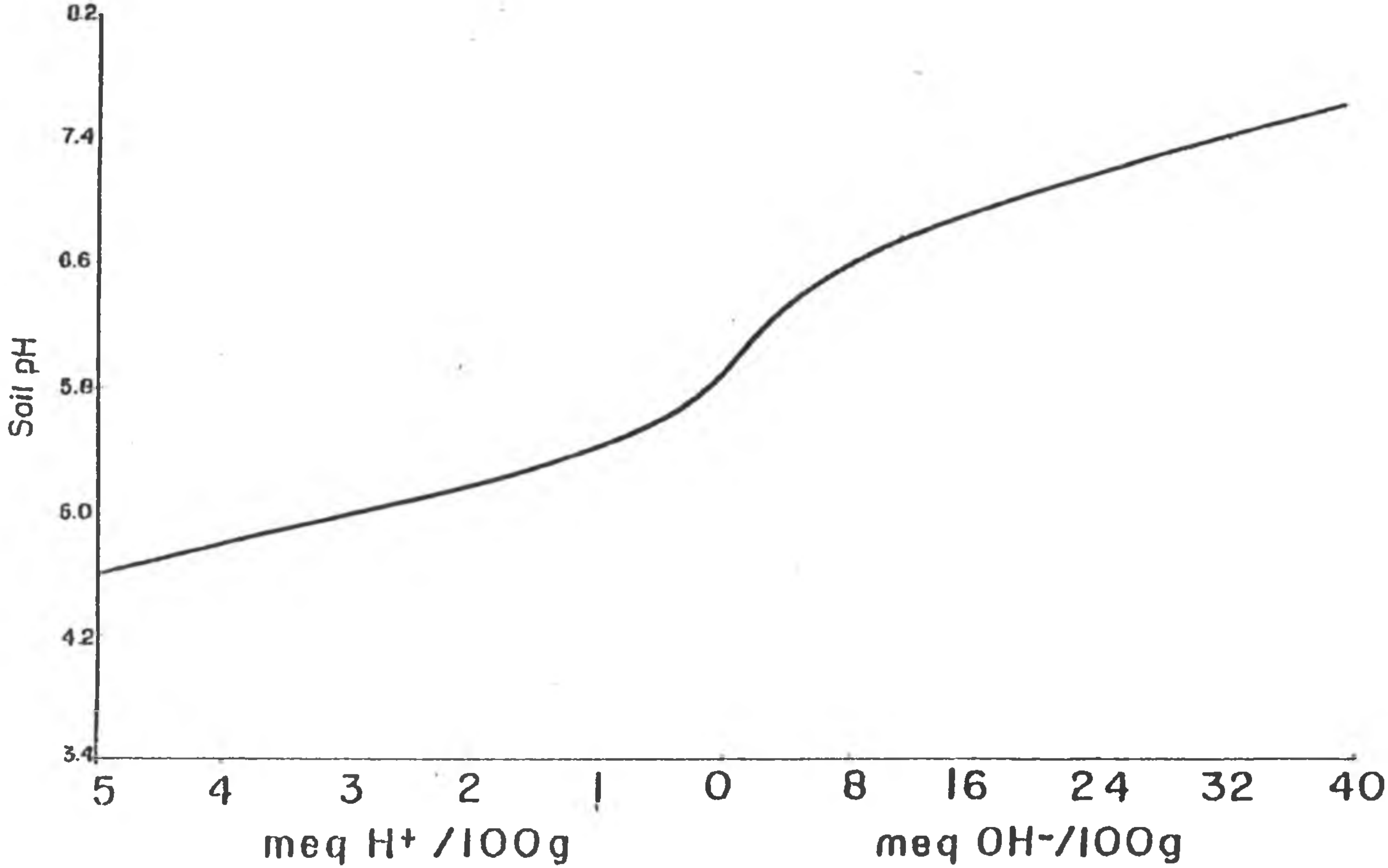


Figure B.1. Acidulation and titration curves for the Hilo soil

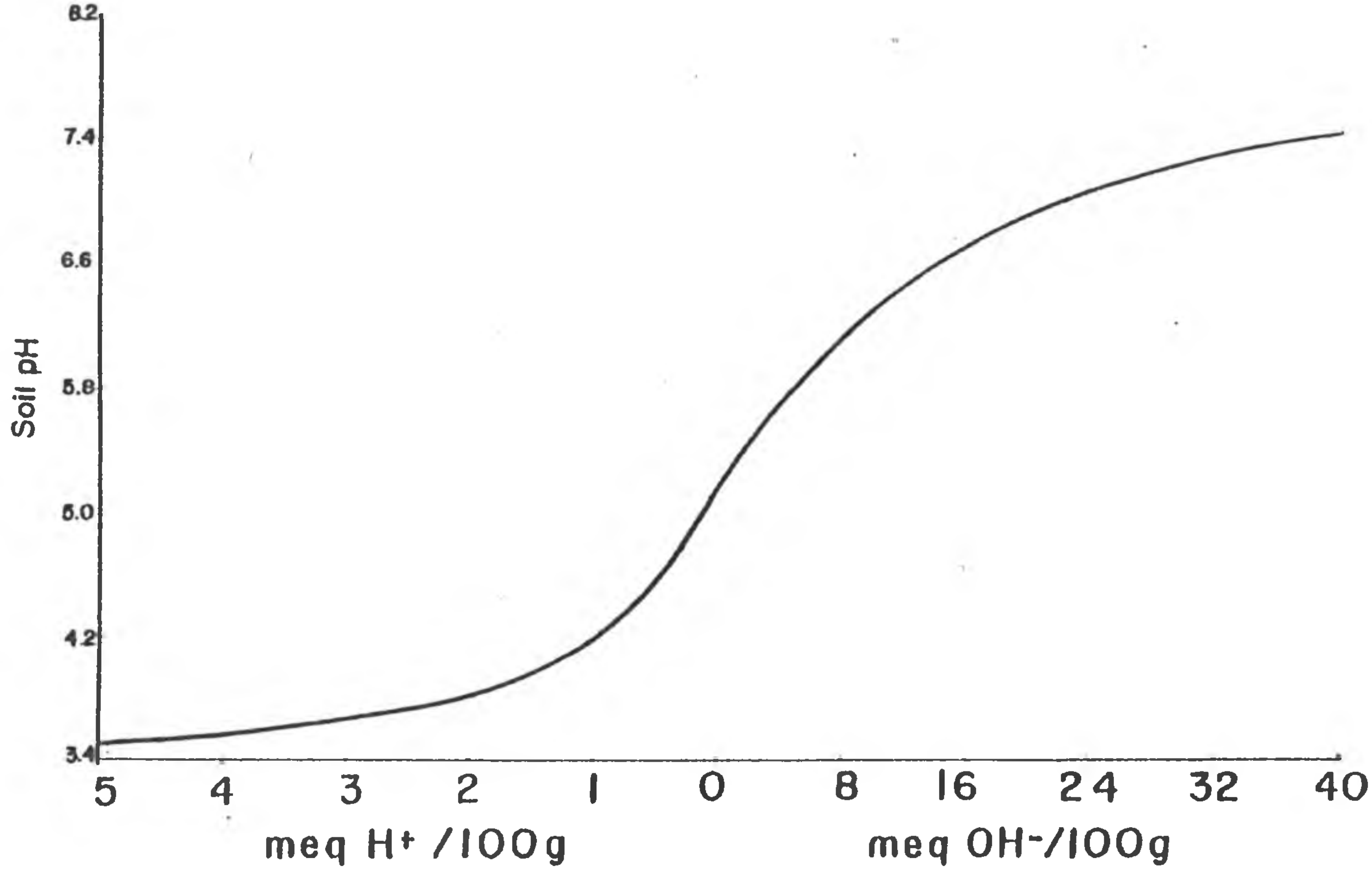


Figure B.2. Acidulation and titration curves for the Halii soil

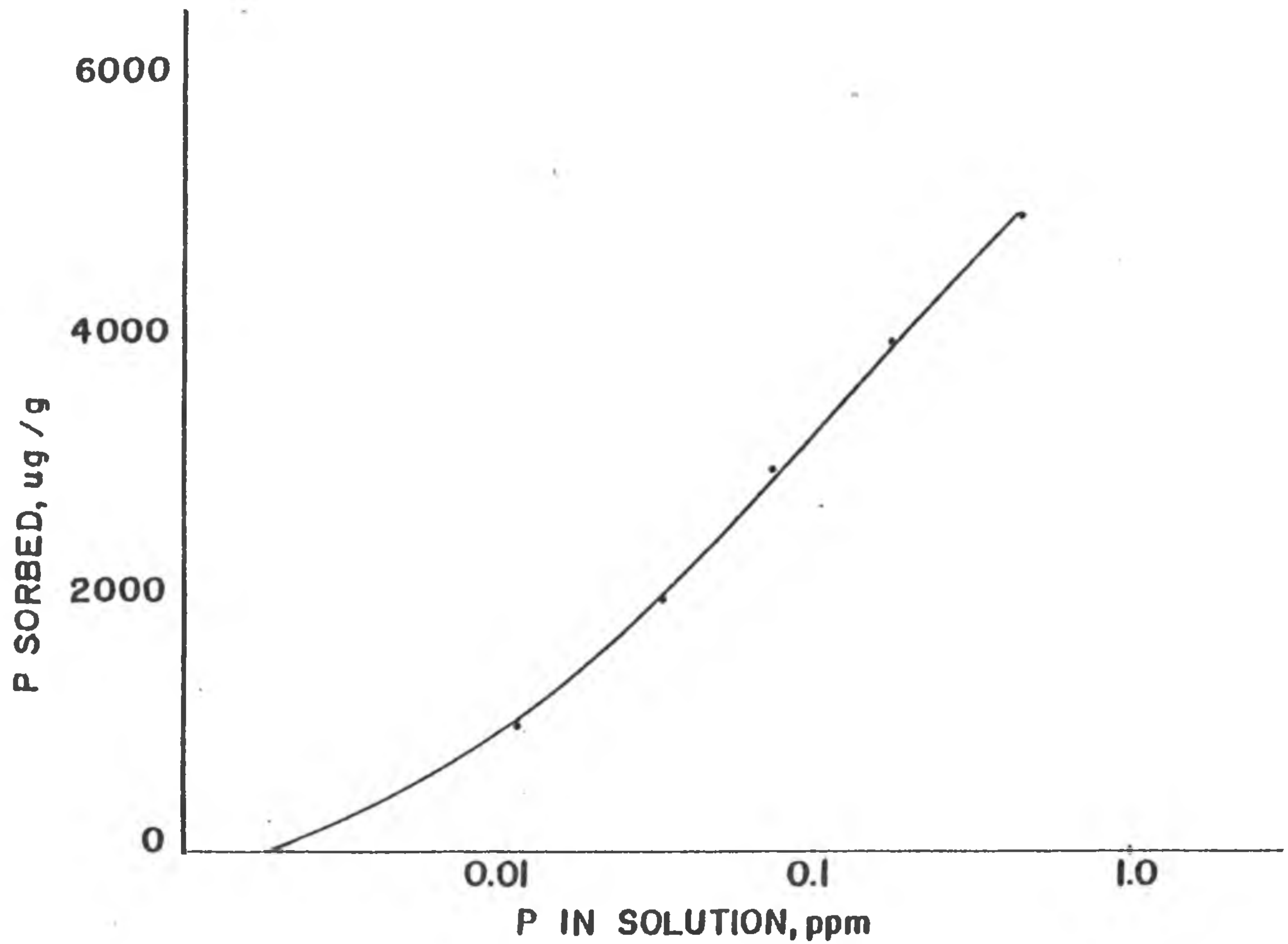


Figure B.3. P adsorption curve for the Hilo soil

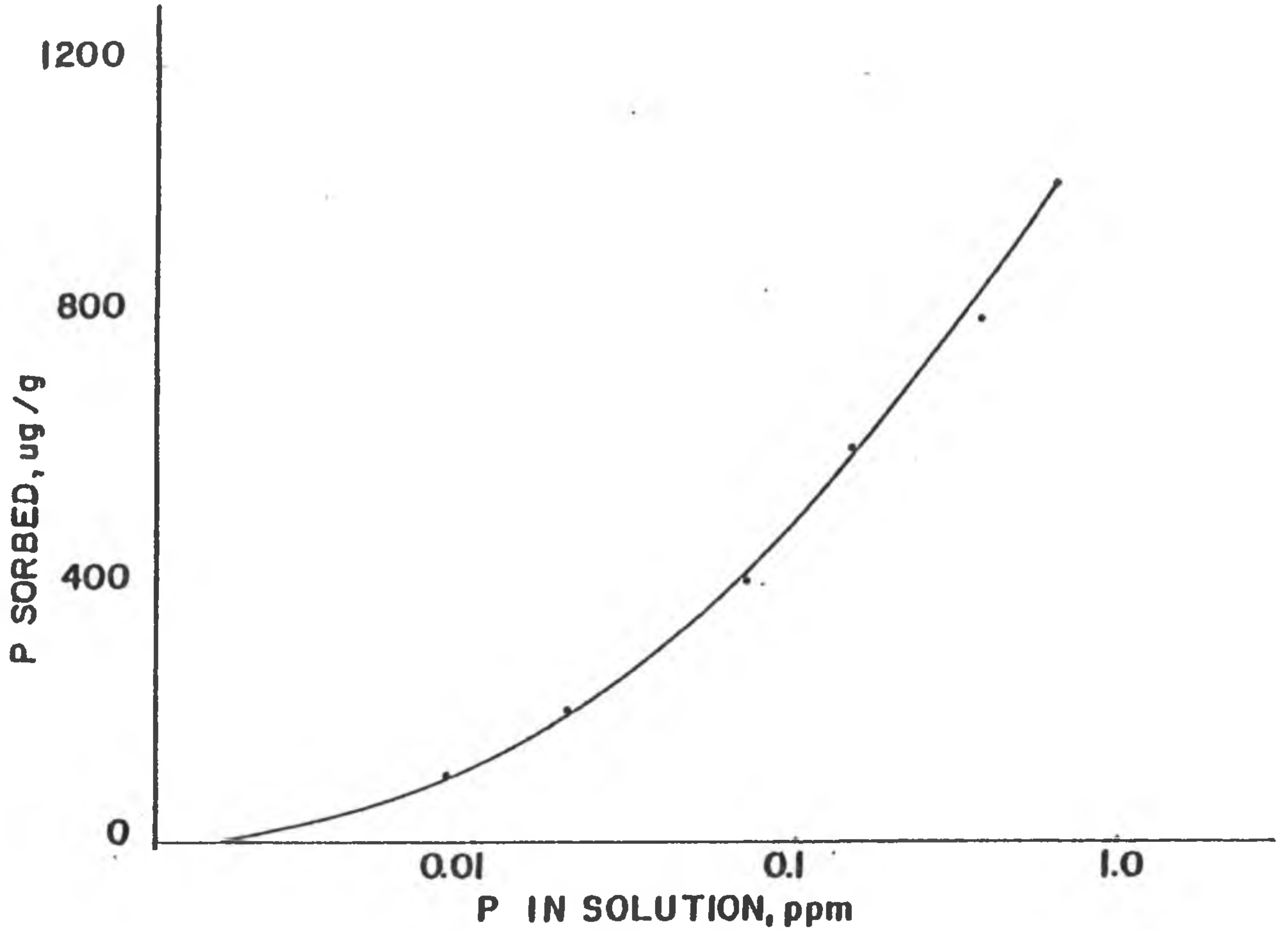


Figure B.4. P adsorption curve for the Halii soil

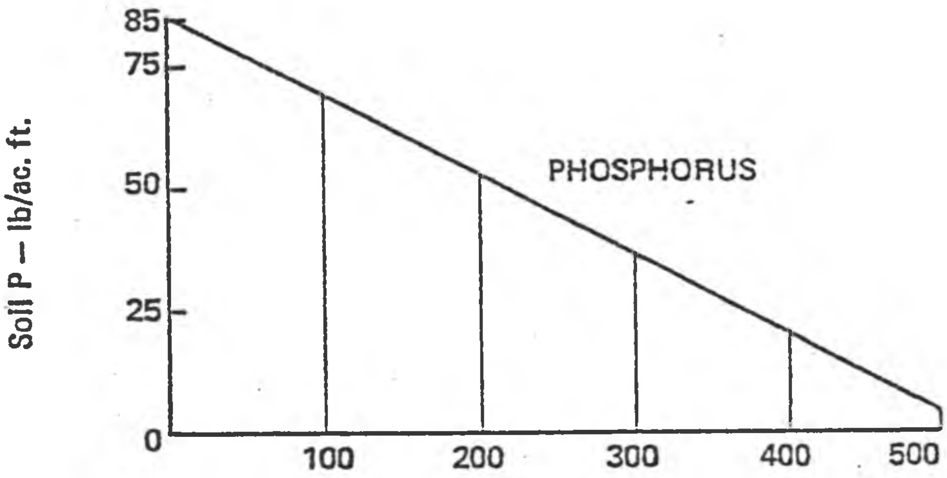


Figure B.5. Soil analysis and P fertilizer recommendations. Agronomy Chart No. 68-1, HSPA Experiment Station.

LITERATURE CITED

Alben, A. O. and H. Boggs. 1936. Zinc content of soils in relation to pecan rosette. Soil Sci. 41:563-566.

Aldrich, N. L. 1960. Crookneck in pineapples is not hard to control. Queensland Agr. Jour. 86:97-98.

Alley, M. M., D. C. Martens, M. G. Schnappinger, Jr. and G. W. Hawkins. 1972. Field calibration of soil tests for available zinc. Soil Sci. Soc. Amer. Proc. 36:621-624.

Anon. 1963. HSPA Experiment Station Ann. Report, 23-24.

Arain, M. S. 1976. Influence of phosphate fertilization on zinc adsorption by soils and the labile zinc pool. Ph.D. Dissertation, Univ. of Hawaii, Manoa.

Barnette, R. M., J. P. Camp, J. D. Warner and O. E. Gall. 1936. Use of zinc sulfate under corn and other field crops. Fla. Agr. Exp. Sta. Bull. 293:3.

Bauer, A. 1971. Considerations in the development of soil tests for Zn. Comm. Soil Sci. and Plant Analysis. 2(3):161-193.

Bingham, F. T. 1963. Relation between phosphorus and micronutrients in plants. Soil Sci. Soc. Amer. Proc. 27:389-391.

____________ and J. P. Martin. 1956. Effects of soil phosphorus on growth and minor element nutrition of citrus. Soil Sci. Soc. Amer. Proc. 20:382-384.

____________ and M. J. Garber. 1960. Solubility and availability of micronutrients in relation to phosphorus fertilization. Soil Sci. Soc. Amer. Proc. 24:209-213.

Boawn, L. C., F. G. Viets, Jr., and C. L. Crawford. 1954. Effect of phosphate fertilizers on zinc nutrition of field beans. Soil Sci. 78:1-7.

____________, ________________ and ______________. 1957. Plant utilization of zinc from various types of zinc compounds and fertilizer materials. Soil Sci. 83:219-227.

____________ and G. E. Leggett. 1964. Phosphorus and zinc concentrations in Russet Burbank potato tissue in relation to development of zinc deficiency symptoms. Soil Sci. Soc. Amer. Proc. 28:229-232.

____________ and J. C. Brown. 1968. Further evidence for a P-Zn imbalance in plants. Soil Sci. Soc. Amer. Proc. 32:94-97.

Bowen, J. 1972. Differential zinc absorption in sugarcane clones. Abstract in Amer. Soc. Pl. Physiologists Western Section, Univ. of Oregon, p. 16, June 15-17.

Bray, R. H. 1948. Requirements for successful soil tests. Soil Sci. 66:83-89.

Brown, A. L., B. A. Krantz and P. E. Martin. 1962. Plant uptake and fate of soil applied zinc. Soil Sci. Soc. Amer. Proc. 26: 167-170.

____________, ____________ and J. L. Eddings. 1970. Zinc-phosphorus interactions as measured by plant response and soil analysis. Soil Sci. 110:415-420.

____________, J. Quick and J. L. Eddings. 1971. A comparison of analytical methods for soil zinc. Soil Sci. Soc. Amer. Proc. 35:105-107.

Burleson, C. A., A. D. Dacus and C. J. Gerard. 1961. The effect of phosphorus fertilization in the zinc nutrition of several irrigated crops. Soil Sci. Soc. Amer. Proc. 25:365-368.

____________ and N. R. Page. 1967. Phosphorus and zinc interactions in flax. Soil Sci. Soc. Amer. Proc. 31:510-513.

Carroll, M. D. and J. F. Loneragan. 1968b. Response of plant species to concentrations of zinc in solution. I. Growth and zinc content of plants. Aust. J. Agr. Res. 19:859-868.

____________ and ____________. 1969. Response of plant species to concentrations of zinc in solution. II. Rates of zinc absorption and their relation to growth. Aust. J. Agr. Res. 20:457-463.

Cate, R. B. and L. A. Nelson. 1965. A rapid method of correlation of soil test analysis with plant response data. Int. Soil Testing, Tech. Bull. 1.

Chesters, G. G. C. and G. W. Rolinson. 1951. The role of zinc in plant metabolism. Biol. Rev. Cambridge Phil. Soc. 26:239-252.

Clements, H. F. 1959. Recent development in crop logging of sugarcane. Proc. 10th Congr. ISSCT. 522-529.

____________ and S. Moriguchi. 1945. The crop-log for use in sugarcane production. Rept. Univ. Hawaii Agr. Expt. Sta., for the biennium ending June 1944, 34-40.

Cox, F. R. and A. L. Kamprath. 1972. Micronutrient soil tests. In J. J. Mortvedt, P. M. Giordano and W. L. Lindsay (eds.)"Micronutrients in Agriculture", p. 289-317. Soil Sci. Soc. Am., Madison, Wisconsin.

Dubach, P. and N. C. Mehta. 1963. The chemistry of soil humic substances. Soils Fert. 26:293-300.

Dwivedi, R. S., N. S. Randhawa and R. L. Bansal. 1975. Phosphorus-zinc interaction. I. Sites of immobilization of zinc in maize at a high level of phosphorus. Plant and Soil. 43:639-648.

Elgabaly, M. M. 1950. Mechanism of zinc fixation by colloidal clays and related minerals. Soil Sci. 69:167-174.

_____________ and H. Jenny. 1943. Cation and anion interchange with zinc montmorillonite clays. J. Phys. Chem. 47:339-408.

Ellis, B. J. and B. D. Knezek. 1972. Adsorption reactions of micronutrients in soils. In J. J. Mortvedt, P. M. Giordano and W. L. Lindsay (eds.), "Micronutrients in Agriculture", p. 59-78. Soil Sci. Soc. Am., Madison, Wisconsin.

Ellis, R., Jr., J. F. Davis and D. L. Thurlow. 1964. Zinc availability in calcareous Michigan soils as influenced by phosphorus level and temperature. Soil Sci. Soc. Amer. Proc. 28:83-86.

Evans, H. 1959. Elements other than nitrogen, potassium and phosphorus in the mineral nutrition of sugarcane. Proc. 10th Congr. ISSCT. 473-508.

Evans, C. E., J. I. Wear, B. F. Hajek and J. T. Cope, Jr. 1974. The relationship of soil zinc removed by three extractants to zinc uptake by corn and sorghum in medium-to fine-textured soils. Comm. in Soil Science and Plant analysis. 5(2):105-113.

Fox, R. L. and E. J. Kamprath. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Amer. Proc. 34:902-907.

Fudge, B. R. 1940. Citrus nutrition studies. Fla. Agr. Expt. Sta. Ann. Rept. 1944. 198.

Gall, O. E. and R. M. Barnette. 1940. Toxic limits of replaceable zinc to corn and cowpeas grown on three Florida soils. Jour. Amer. Soc. Agron. 32:23-32.

Gattani, P. D., R. L. Jain and C. P. Vinayak. 1976. Zinc-phosphorus interaction in wheat. J. Indian Soc. Soil Sci. 24(2):208-210.

Geering, H. R. and J. F. Hodgson. 1969. Micronutrient cation complexes in soil solution: III. Characterization of soil solution ligands and their complexes with Zn^{2+} and Cu^{2+}. Soil Sci. Soc. Amer. Proc. 33:54-59.

Gilbert, F. A. 1957. "Mineral Nutrition and the Balance of Life." Univ. of Oklahoma Press, Norman.

Grewal, J. S., N. S. Randhawa and D. R. Bhumbla. 1968. Correlation of soil test with response to the application of zinc to wheat. Indian Soc. of Soil Sci. Lour. 16:97-102.

Gupta, C. U., F. W. Calder and L. B. Macleod. 1971. Influence of added limestone and fertilization upon micronutrient content of forage tissue and soil. Plant and Soil. 35:249-259.

Haq, A. U. and M. H. Miller. 1972. Prediction of available soil Zn, Cu, and Mn using chemical extractants. Agron. J. 64:779-782.

Hoch, F. L. and B. L. Vallee. 1958. The metabolic role of zinc. In C. A. Lamb, O. G. Bentley and J. M. Beattie (eds.), "Trace Elements", p. 337-363. Academic Press, New York.

Hodgson, J. F. 1963. Chemistry of the micronutrient elements in soils. Adv. Agron. 15:119-159.

____________, W. L. Lindsay and J. F. Trierweiler. 1966. Micronutrient cation complexing in soil solution: II. Complexing of zinc and copper in displaced solution from calcareous soils. Soil Sci. Soc. Amer. Proc. 30:723-726.

Humbert, R. P. 1968. "The growing of sugar cane." Elsevier Publishing Company, New York.

John, M. K. 1972. Influence of soil properties and extractable zinc on zinc availability. Soil Sci. 113:222-227.

Juang, T. 1971. Soil-plant relations in the mineral nutrition of sugar cane with special reference to zinc and related elements. Ph.D. Dissertation, Univ. Hawaii, Manoa.

Jurinak, J. J. and D. W. Thorne. 1955. Zinc solubility under alkaline conditions in a zinc-bentonite system. Soil Sci. Soc. Amer. Proc. 19:446-448.

____________ and T. S. Inouye. 1962. Some aspects of zinc and copper phosphate formation in aqueous systems. Soil Sci. Soc. Amer. Proc. 26:144-147.

Kanehiro, Y. 1964. Status and availability of zinc in Hawaiian soils. Ph.D. Dissertation, Univ. Hawaii, Manoa.

__________ and G. D. Sherman. 1967. Distribution of total and 0.1N HCl-extractable zinc in Hawaiian soil profiles. Soil Sci. Soc. Amer. Proc. 31:394-399.

Kao, M. M. and T. C. Juang. 1974. Studies on chemical extraction method for soil zinc. Tawaian Sugar Research Institute. 65: 17-30.

Keefer, R. F. and R. N. Singh. 1968. The mechanism of P and Zn interaction as revealed by corn growth and composition. 9th Int. Congr. Soil Sci. Trans. (Adelaide, Aust.). 2:367-374.

Khan, A. A. and G. K. Zende. 1977. The site for Zn-P interactions in plants. Plant and Soil. 46:259-262.

Kunimitsu, K. 1969. Minor elements in a major role at Pepeekeo Sugar Company. Haw'n. Sugar Tech. 1969 Reports, 116-122.

Langin, E. J., R. C. Ward, A. R. Olsen and H. F. Rhoads. 1962. Factors responsible for poor response of corn or grain sorghum to phosphorus fertilization. II. Lime and P placement effects on P-Zn relation. Soil Sci. Soc. Amer. Proc. 26:574-578.

Lindsay, W. L. 1972. Inorganic phase equilibria of micronutrients in soils. In J. J. Mortvedt, P. M. Giordano and W. L. Lindsay (eds.), "Micronutrients in Agriculture", p. 41-57. Soil Sci. Soc. Am., Madison, Wisconsin.

____________ and W. A. Norvell. 1969. Development of a DTPA micronutrient soil test. Agron. Abstr. pp. 84.

Loneragan, J. F. 1951. The effect of applied phosphate on the uptake of zinc by flax. Aust. J. Sci. Res. B4:108-114.

Lott, W. L. 1938. Relation of hydrogen ion concentration to the availability of zinc in soil. Soil Sci. Soc. Amer. Proc. 3:115-121.

Lyman, C. and L. A. Dean. 1942. Zinc deficiency of pineapple in relation to soil and plant composition. Soil Sci. 54:315-324.

Maclean, A. J. 1974. Effects of soil properties and amendments on the availability of zinc in soils. Canadian J. of Soil Sci. 54(4):369-378.

Malavolta, E. and H. P. Haag. 1962. On the Mineral Nutrition of some Tropical Crops. Int. Potash Inst. (ed.), Berne, Swetzerland.

Mangaroo, A. S., F. L. Himes and E. O. Mclean. 1965. The adsorption of zinc by some soils after various pre-extraction treatments. Soil Sci. Soc. Amer. Proc. 29:242-246.

Manskaya, S. M. and T. V. Drozdova. 1968. Geochemistry of Organic Substances. Pergamon Press, New York.

Marinho, M. L. and K. Igue. 1972. Factors affecting zinc absorption by corn from volcanic ash soils. Agron. J. 64:3-8.

Martens, D. C. 1968. Plant availability of extractable boron, copper, and zinc as related to selected soil properties. Soil Sci. 106:23-28.

Massey, H. F. 1957. Relation between dithizone extractable zinc in the soil and zinc uptake by corn plants. Soil Sci. 83:123-129.

Maze, P. 1914. Influence respective des elements de la solution minerale sur le developpement du mais. Ann. Inst. Pasteur. 28:1-5.

Melton, J. R., B. G. Ellis and E. C. Doll. 1970. Zinc, phosphorus and lime interactions with yield and zinc uptake by Phaseolus Vulgaris. Soil Sci. Soc. Amer. Proc. 34:91-93.

Meuer, E. J., A. E. Ludwick and W. R. Kussow. 1971. Effect of lime and phosphorus on zinc uptake from four soils of Brazil. Soil Science and Plant Analysis. 2(5):321-327.

Meyer, J. H. 1976. Soil analysis as a guide to predicting zinc deficiency in sugarbelt soils. South African Sugar Technologists' Association Proc. 50:135-140.

Motooka, P. S. 1962. The use of 0.1N HCl extractable zinc in assessing available and fixed zinc in Hawaiian soils. M.S. Thesis, Univ. Hawaii, Manoa.

Nason, A., N. O. Kaplan and S. P. Colowick. 1951. Changes in enzymatic constitution in zinc deficient Neurospora. J. Biol. Chem. 188:397-406.

Nelson, J. L., L. C. Boawn and F. G. Viets, Jr. 1959. A method for assessing zinc status of soils using acid-extractable zinc and "titratable alkalinity" values. Soil Sci. 88:275-283.

Norvell, W. A. and W. L. Lindsay. 1969. Reaction of EDTA complexes of Fe, Zn, Mn and Cu with soils. Soil Sci. Soc. Amer. Proc. 34:405-407.

Olsen, S. R. 1972. Micronutrient interactions. In J. J. Mortvedt, P. M. Giordano and W. L. Lindsay, (eds.), "Micronutrients in Agriculture", p. 243-264. Soil Sci. Soc. Am., Madison, Wisconsin.

Pauli, A. W. R., R. Ellis, Jr. and H. C. Moser. 1968. Zinc uptake and translocation as influenced by phosphorus and calcium carbonate. Agron. J. 60:394-396.

Pescador, P., Jr. 1963. Assessment of extracting solutions for their estimation of "available zinc" in Hawaiian soils. M.S. Thesis, Univ. Hawaii, Manoa.

Prasad, K. G. and H. Sinha. 1968. Zinc status of Bihar soils. J. Indian Soc. Soil Sci. 17:267-274.

Randhawa, N. S. and F. E. Broadbent. 1965a. Soil organic matter-metal complexes: 5. Reactions of zinc with model compounds and humic acid. Soil Sci. 99:295-300.

Randhawa, N. S. and F. E. Broadbent. 1965b. Soil organic matter-metal complexes: 6. Stability constants of zinc-humic acid complexes at different pH values. Soil Sci. 99:362-366.

Reddy, G. D., V. Venkatasublaiah and J. Venkateswarlu. 1973. Zinc-phosphate interaction in maize. J. Indian Soc. Soil Sci. 21(4):433-445.

Rogers, L. H. and C. H. Wu. 1948. Zinc uptake by oats as influence by application of lime and phosphate. Agron. J. 40:563-566.

Safaya, N. M. 1976. Phosphorus-zinc interaction in relation to absorption rates of phosphorus, zinc, copper, manganese and iron in corn. Soil Sci. 40:719-722.

Schnitzer, M. and S. I. M. Skinner. 1966. Organo-metallic interactions in soils: 5. Stability constants of Cu^{++}-, Fe^{++}-, and Zn^{++}- fulvic acid. Soil Sci. 102:361-365.

Seatz, L. F., A. J. Sterges and J. C. Kramer. 1959. Crop response to zinc fertilization as influenced by lime and phosphorus application. Agron. J. 51:457-459.

Sharma, K. C., B. A. Krantz and A. L. Brown. 1968a. Interaction of P and Zn on two dwarf wheats. Agron. J. 60:329-332.

__________, __________, __________ and J. Quick. 1968b. Interaction of Zn and P in top and root of corn and tomato. Agron. J. 60:453-456.

Sharpless, R. G., E. F. Walliham and F. F. Peterson. 1969. Retention of zinc by some arid zone soil materials treated with zinc sulfate. Soil Sci. Soc. Amer. Proc. 33:901-904.

Shaw, E. and L. A. Dean. 1952. Use of dithizone as an extractant to estimate the zinc nutrient status of soils. Soil Sci. 73: 341-347.

Shoji, K. and R. M. Ota. 1958. Zinc deficiency in coffee. Haw'n. Farm Sci. 6:3.

Shook, F. 1940. Relationship between zinc and auxin in the growth of higher plants. Amer. J. Bot. 27:939-951.

Shukla, U. C. 1972. Effect of various phosphatic fertilizers on zinc availability in soils of Southern United States. Agrochimica xvi. 6:562-570.

Shuman, L. M. 1977. Adsorption of Zn by Fe and Al hydrous oxides as influenced by aging and pH. Soil Sci. 41:703-706.

Soil Conservation Service. 1973. Soil survey maps of the islands of Hawaii, Kauai and Oahu, State of Hawaii.

Soil Conservation Service. 1972. Soil Survey Investigations Report No. 1, p. 26-29.

Stanton, D. A. and R. Du T. Burger. 1967. Availability to plants of zinc sorbed by soil and hydrous oxides. Geoderma 1:13-17.

______________ and ______________. 1970. Studies on zinc in selected orange free state soils. v. Mechanics for the reactions of zinc with iron and aluminum oxides. Agrochemophysica 2:65-76.

Steinberg, R. A. 1919. A study of some factors in the chemical stimulation of growth of Aspergillus niger. Amer. J. Bot. 6:330-372.

Stenvenson, F. J. and M. S. Ardakani. 1972. Organic matter reactions involving micronutrients in soils. In J. J. Morvedt, P. M. Giordano and W. L. Lindsay (eds.), "Micronutrients in Agriculture", p. 79-114. Soil Sci. Am., Madison, Wisconsin.

Stewart, J. A. and K. C. Berger. 1965. Estimation of available zinc using magnesium chloride as extractant. Soil Sci. 100: 244-250.

Stewart, J. W. B. and M. Tahir. 1971. Estimation of available zinc in Prairie soils. Int. Symp. Soil Fert. Evaluation 1:983-991.

Stuckenholtz, D. D., R. J. Olsen, G. Gogan and R. A. Olsen. 1966. On the mechanism of phosphorus-zinc interaction in corn nutrition. Soil Sci. Soc. Amer. Proc. 30:759-763.

Suhr, N. H. and C. O. Ingamells. 1966. Solution technique for analysis of silicates. Anal. Chem. 38(6):730-734.

Takkar, P. N., M. S. Mann, R. L. Bansal, N. S. Randhawa and H. Singh. 1976. Yield and uptake response of corn to zinc as influenced by phosphorus fertilization. Agron. J. 68:942-946.

Terman, G. L., P. M. Giordano and S. E. Allen. 1972. Relationship between dry matter yields and concentrations of Zn and P in young corn plants. Agron. J. 64:684-687.

Thorne, D. W. 1957. Zinc deficiency and its control. Adv. Agron. 9:31-65.

Trierweiler, J. F. and W. L. Lindsay. 1969. EDTA-ammonium carbonate soil test for zinc. Soil Sci. Soc. Amer. Proc. 33:49-54.

Tsui, C. 1948. The role of zinc in auxin synthesis in tomato plant. Amer. J. Bot. 35:172-179.

Tucker, T. C. and L. T. Kurtz. 1955. A comparison of several chemical methods with the bioassay procedure for extracting zinc from soils. Soil Sci. Soc. Amer. Proc. 19:477-481.

Udo, E. J., H. L. Bohn and T. C. Tucker. 1970. Zinc adsorption by calcareous soil. Soil Soc. Amer. Proc. 35:405-407.

van Overbeek, J. 1943. Plant hormones and the development of sugarcane. Gilmore's Pureto Rico Sugar Manual. p. 19-22.

_______________, D. Olivo and E. S. Vasquez. 1945. Rapid extraction method for free auxin and its application in geotropic reactions of bean and sugarcane. Bot. Gaz. 106:440-451.

Viets, F. G., Jr. 1966. Zinc deficiency in the soil-plant system. In A. S. Prasad (ed.) "Zinc metabolism", p. 90-128. Thomas, Springfield, Ill.

_______________, L. C. Boawn, C. L. Crawford and C. E. Nelson. 1953. Zinc deficiency in corn in Central Washington. Agron. J. 45:559-565.

Viro, P. J. 1955. Use of ethylene diamine tetra acetic acid in soil analysis. I. Soil Sci. 79:459-465.

Wallace, A. 1963. Role of chelating agents on the availability of nutrients to plants. Soil Sci. Soc. Amer. Proc. 27:176-179.

__________, A. A. Elgazzar, T. W. Cha and G. V. Alyander. 1974. Phosphorus level versus concentration of zinc and other elements in bush bean plants. Soil Sci. 117:347-357.

Warnock, R. E. 1970. Micronutrient uptake and mobility within corn plants (Zea mays L.) in relation to phosphorus-induced zinc deficiency. Soil Sci. Soc. Amer. Proc. 34:765-769.

Watanabe, F. S. and S. R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts. Soil Sci. 96:677-678.

_______________, W. L. Lindsay and S. R. Olsen. 1965. Nutrient balance involving phosphorus, iron and zinc. Soil Sci. Soc. Amer. Proc. 29:562-565.

Wear, J. I. 1956. Effect of soil pH and calcium on uptake of zinc by plants. Soil Sci. 81:311-315.

__________ and A. L. Sommer. 1948. Acid-extractable zinc of soils in relation to the occurrence of zinc deficiency symptoms of corn: A method of analysis. Soil Sci. Soc. Amer. Proc. 12: 143-144.

Wear, J. I. and C. E. Evans. 1968. Relationship of zinc uptake by corn and sorghum to soil zinc measured by three extractants. Soil Sci. Soc. Amer. Proc. 32:543-546.

West, E. S. 1938. Zinc-cured mottle-leaf in citrus induced by excess of phosphate. J. Counc. Sci. Ind. Res. 11:182-184.

Woltz, S., S. J. Toth and F. E. Bear. 1953. Zinc status of New Jersey soils. Soil Sci. 76:115-122.

Youngdahl, L. J., L. V. Svec, W. C. Liebhrardt and M. R. Teel. 1977. Changes in the zinc-65 distribution in corn root tissue with a phosphorus variable. Crop Science 17:66-69.