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The effects of zinc and phosphorus treatments on five different plant species were investigated in a greenhouse experiment. A second greenhouse experiment extended these investigations in sweet corn over a broad range of phosphorus treatments with and without adequate zinc nutrition to study phosphorus induced zinc deficiency. The plant responses measured in each experiment were yield, content and uptake of zinc, phosphorus, iron and manganese.

The susceptibility of the five plant species to zinc deficiency ranged from very severe in sweet corn and bush beans, moderately to slightly severe in potatoes and tomatoes and tolerant in wheat.

The soils used throughout these experiments were both phosphorus and zinc deficient. Phosphorus deficiency was the most limiting factor to plant growth and zinc deficiency could not be observed in susceptible species until phosphorus needs were met. In no instance

did phosphorus application interfere with zinc uptake and in fact, higher levels of applied phosphorus increased the total uptake of zinc. Zinc deficiency nevertheless resulted because the supply of available zinc in these soils was inadequate to meet plant needs.

Phosphorus content was greatly elevated in susceptible species when zinc deficiency symptoms were observed. Iron and manganese contents were greatly elevated in zinc deficient sweet corn whereas an increased content of these elements occurred only in the most severely zinc deficient bush beans and not at all in other species.

Zinc-Phosphorus Relationships in Five Plant Species

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INTRODUCTION

Adequate zinc nutrition of plants is dependent on several factors other than the ability of the soil to supply zinc. Among these are the poorly understood physiological conditions such as phosphorus induced zinc deficiency and interactions between the essential metal cations. A number of investigators have suggested that excess phosphorus can induce a zinc deficiency by interfering with the uptake, translocation or utilization of zinc. Limited evidence suggests that zinc deficient plants may also contain an exceedingly high content of heavy metals, particularly manganese and iron. These elements may be at such high levels that they can be toxic to plants directly or can create severe nutrient imbalances which may be confused with zinc deficiency.

Plant species are known to vary in their susceptibility to zinc deficiency and nutrient balance although a careful study of species differences has not been made under uniform conditions. For instance, it is not known if phosphorus induced zinc deficiency is a real phenomenon in all plant species or if it is restricted only to certain species. The same can be said for the occurrence of high levels of heavy metal nutrients and the interactions involving these nutrients in zinc deficient plants. In this study, comparisons between five species were made in an attempt to answer these questions.

LITERATURE REVIEW

Many papers have reported the occurrence of zinc deficiencies in plants all over the world (American Zinc Institute, 1963). There are three factors about zinc deficiency that are still unresolved in the present literature. First, the inducement of zinc deficiency by phosphorus fertilization is an area of great disagreement. Many workers support the concept of phosphorus induced zinc deficiency while other workers reject this same concept. Secondly, the nature of heavy metal nutrient balances and interactions in zinc deficient plants and their effect on plant symptoms has not been considered to any great extent. Finally, the influence of different plant species on susceptibility to zinc deficiency and species effect on the previously mentioned factors has received virtually no attention.

Phosphorus Induced Zinc Deficiency

In his review on zinc deficiencies in plants, Thorne (1957) stated that in some instances phosphorus fertilizers have induced zinc deficiencies and in other instances they have not done so. The earliest observations of phosphorus induced zinc deficiency assumed that a reaction in the soil between zinc and phosphate accounted for zinc deficiency. Jones *et al.* (1936) tested the reaction of zinc sulfate with superphosphate in the soil. They observed that the soluble zinc decreased as more superphosphate was added. Jamison (1943a) found that the previous experiments by Jones _et_ _al_. used exceptionally large quantities of materials to facilitate the detection of zinc. As new methods of detection had been developed, Jamison was able to apply materials at rates comparable to field conditions. He found that zinc solubility was more related to soil pH than the quantity of phosphates in the soil. In fact he reported (1943b) that on seven of 12 soils, zinc solubility increased as more superphosphate was added. Only on two soils was zinc solubility decreased because of excessive superphosphate. Peech (1941) had also observed the dependence of zinc solubility on soil pH. His experiments were conducted up to a pH of eight and he found that zinc solubility declined sharply from pH 4 to pH 6.5. He used three soils containing varying amounts of phosphorus but the plots of extractable zinc of each soil paralleled one another. Bingham and Garber (1960) found that increasing amounts of different phosphatic fertilizers increased zinc solubility in the soil. Boawn _et_ _al_. (1954) suggested that it was unlikely for zinc to become a limiting nutrient while free precipitates of zinc phosphate existed in the soil.

The primary factor affecting the solubility of zinc has been considered to be soil pH. The amount of available phosphorus is also dependent on soil pH. Workers in South Africa have studied the effects of liming on phosphorus induced zinc deficiency. De Villiers and Laker (1966) found that liming stimulated phosphorus uptake but zinc deficiency occurred that curtailed plant growth. Laker (1967a) determined that although lime stimulated phosphorus uptake, it reduced the uptake of applied zinc by almost 50 percent. The greatest amounts of available phosphorus occur in a pH range of six to seven (Buckman and Brady, 1965). Woltz _et al._ (1953) reported that primary and secondary zinc phosphates formed at low pH's were more soluble than tertiary phosphates formed at higher pH's. Loth (1938) found that the concentration of zinc in the soil solution was minimum at pH 6.5.

Attention in more recent work has been focused on phosphorus inducement of zinc deficiencies within the plant. Many workers have observed exceptionally high levels of phosphorus concentrated in the tissues of zinc deficient plants. Hay (1966) observed that phosphorus concentration was elevated significantly in zinc-deficient sweet corn. Stukenholtz _et al._ (1966) and Termen _et al._ (1966) observed the same in field corn as did Boawn and Leggett (1964) in Russet Burbank potatoes, Nossaman and Travis (1966) in grain sorghum and Bingham and Martin (1956) in citrus. Other workers however, have observed that phosphorus content was unaffected by zinc deficiency. Viets _et al._ (1954) found this to be the case in beans. Seatz _et al._ (1959) found that the application of 1000 pounds of P_2O_5 per acre had no effect on zinc response although P content increased significantly.

Attempts to correlate phosphorus and zinc content have also shown contradictory results. Rogers and Wu (1948) could find no correlation between phosphorus and zinc in oat plants. Hay (1966) however, found that phosphorus and zinc were antagonistic on each other in sweet corn. Ellis et al. (1964) found a similar negative correlation between the concentration of these two elements in beans and corn. Laker (1967b) observed that phosphorus application stimulated uptake of native soil zinc but the increase in plant growth was so much greater than the net effect was a reduction in zinc concentrations in maize. Data by Boawn et al. (1954) does not support the idea that phosphorus inhibits zinc absorption by bean plants. Millikan (1963) attempted to relate P: Zn ratios in subterranean clover to the incidence of zinc deficiency but he found that the critical ratio was especially dependent on plant age.

Millikan (1940) obtained data that showed that the requirement for zinc by wheat increased as the rate of superphosphate application was increased. This observation was based on plant analysis data which showed a high degree of correlation between the concentration of these elements. This information would indicate some physiological dependence of zinc and phosphorus on each other. Further imbalances of these two elements would lead to serious physiological disturbance in zinc-phosphorus nutrition as suggested by Leggett and Boawn (1963). Sharma et al. (1968) found that phosphorus had little effect on zinc absorption by corn and tomato roots, but that there was a physiological inhibition of zinc translocation from roots to tops.

Viets et al. (1953) reported that the zinc concentration in zinc deficient corn plants could be higher than that found in normal plants and Boawn and Leggett (1964) found the same situation in Russet Burbank potatoes. These observations have been explained as being a "Steenbjerg effect". Steenbjerg (1951) studied yield curves and plant analyses ranging from extreme deficiency to normal growth and luxury consumption. He found in situations of extreme poverty of the limiting nutrient, that the nutrient tended to be more concentrated in the plant tissue of deficient plants before normal growth occurred. After the plant's needs were met for this element, additional application caused it to accumulate in the plant's tissue. In his attempt to determine the critical concentration of plant nutrients, Ulrich (1952) was confronted with deficient plants having higher concentrations of the limiting element than normal plants. He cited some work with radiozinc which showed the concentration of this element in the nodes of deficient corn plants and a failure of internode growth. Because of disportionate growth of similar plant parts, the zinc analysis of deficient plants was greater than if a normal pattern of growth had occurred.

Neither Steenbjerg (1951) nor Ulrich (1952) extended their studies to include the relationship of the deficient element to the rest of the nutrient complement of the plant. Moore et al. (1957) worked with interactions among copper, iron and molybdenum in lettuce grown in nutrient solutions. They found that when copper and iron levels in the nutrient solution were low, copper content was greater in deficient plants. But when the level of iron was increased, a plot of copper concentration versus yield was more linear. Thus the plot at low iron levels allowed two yield points for the same copper concentration whereas at a higher iron level this was not possible. The authors believed that the imbalance of copper and iron supply in the nutrient solution caused a toxic condition within the plants that could be corrected by increasing the levels of copper and iron in the nutrient solution.

Heavy Metal Nutrition

Iron and manganese balances in plants have been studied without the consideration of the effects of zinc on their nutritional relationships. The metabolic functions of iron and manganese have been demonstrated to be interrelated by Somers and Shive (1942). The biological effectiveness of the one was determined by the proportionate presence of the other. The uptake of these two elements was thought to be fairly well understood. Maas et al. (1968) found that the rate of manganese absorption increased rapidly with decreasing hydrogen ion concentration until there was a precipitation of this element at about pH 7. Problems in iron uptake and nutrition have been related to the level of phosphorus being supplied to the plants. Franco and Loomis (1947) reported that moderate amounts of KH_2PO_4 in nutrient solution caused a mild iron chlorosis in seedlings. This problem could be avoided by omitting phosphorus from the nutrient solution for 2-4 days. Biddulph and Woodbridge (1952) found that solutions containing both phosphorus and iron developed a precipitate of these two elements and thus reduced their availability to the plants. Rediske and Biddulph (1953) observed that maximum iron uptake occurred when phosphorus and iron were equimolar in the nutrient solution. They further added that phosphorus induced chlorosis was not due to a blockage of iron uptake by phosphorus but rather to the blockage of the use of iron in the plant.

Recent work on iron and manganese nutrition has included zinc as a variable. Smith and Specht (1957) found that copper, zinc and manganese all interfered with iron metabolism in citrus. Hewitt (1953) however, found that iron deficiency in sugar beets was not accentuated by manganese. Lingle and Holmberg (1957) studied the effects of zinc and manganese sprays on sweet corn. Manganese spray increased zinc uptake while zinc spray decreased manganese uptake. Dingus (1968) also observed that zinc prevented manganese injury to corn by reducing manganese uptake. Lindsay et al. (1963) observed an iron-zinc antagonism of each element on the other.

Lingle *et al*. (1963) were only able to observe that zinc depressed iron uptake.

In the nutritional relationships in deficient plants, it is important to separate the effects of essential heavy metals. Jackson *et al*. (1967) reported extremely high iron concentrations in zinc deficient sweet corn. The concentration of iron in those plants was 3-4 times greater than the plants grown with adequate zinc. Dilution could not explain these results because total uptake was also greater in the deficient plants. Similarly, Rosell and Ulrich (1964) observed that both iron and manganese levels in sugar beet plants increased very rapidly as zinc became deficient. Phosphorus levels were also greatly elevated in the zinc deficient plants. Clark (1969) studied the effects of different nutrient deficiencies on the level of other nutrients in corn. He observed that zinc deficiencies increased phosphorus, iron and boron content while iron deficiencies increased zinc and manganese in deficient plants. Hay (1966) advanced the hypothesis that one of the symptoms of a zinc deficient plant was the occurrence of greatly elevated iron content. Further investigation into Hay's data revealed a parallel relationship between both iron and manganese content. Hay's hypothesis therefore could be extended to include elevated manganese content as well as iron to be a symptom of a zinc deficient plant.

Differences Among Plant Species

A wide variety of plant species are affected by zinc deficiency (Thorne, 1957). Yet the response of different plant species ranges from the very sensitive to insensitive. Millikan (1961) determined a coefficient of utilization of micronutrients which was simply the grams of dry matter production divided by the micrograms of nutrient absorbed. He found that insensitive plant species had a higher coefficient of utilization for zinc than did sensitive species. Lo and Reisenauer (1968) determined the zinc needs of alfalfa, an insensitive plant, to be much reduced compared to other species.

The effect of plant species on phosphorus and zinc nutrition has been shown to vary between different genetic lines of the same species. Halim et al. (1968) found that different genetic lines of corn would accumulate different levels of phosphorus and zinc. Dunphy et al. (1966) and Paulsen and Rotimi (1968) found varying responses between different lines of soybeans to phosphorus fertilization. The latter workers found that "Chief" soybeans grew normally in solutions containing high levels of phosphorus whereas "Lincoln" soybeans were stunted. Zinc was found to be translocated to the tops of "Chief" but movement in "Lincoln" was restricted. Brown and Leggett (1967) showed that the sensitivity of ten bean varieties varied from slight to severe when all were grown under uniform field conditions. Later work by Boawn and Brown (1968) with a susceptible and tolerant variety of bean showed that each had the same phosphorus-zinc nutritional needs in nutrient solution work. Millikan (1963) also determined that phosphorus-zinc needs varied between three varieties of subterranean clover. One variety of subterranean clover was not as susceptible to zinc deficiency when large amounts of phosphorus were supplied as the other two varieties.

Brown and Tiffin (1962) did a study comparing the phosphorus, zinc, iron relationships in 14 plant species. Five species showed no deficiency symptoms, seven developed zinc deficiency and two developed iron deficiency. Added phosphorus accentuated zinc and iron deficiency but phosphorus plus zinc caused iron deficiency in corn and millet. In this study, two varieties of soybeans showed entirely different responses to zinc. PI soybeans developed iron chlorosis with and without added zinc. HA soybeans developed neither iron chlorosis nor zinc deficiency. Thus they concluded that micronutrient deficiencies were related to a particular plant's ability to absorb nutrients from the soil.

Objectives

Reviewing the literature has produced many contrary statements about zinc deficiencies in plants. The early work showed that factors beyond those within the soil contributed to the inducement of zinc deficiency. However, the many conclusions reached have been supported by data obtained from different plant species, but the nutrient composition of the many species varies considerably (Morrison, 1959). Whether or not phosphorus induces zinc deficiency is one of the primary sources of confusion in most studies. Equally confusing has been the imbalances noted in heavy metal content of zinc deficient plants. No thorough attempt has been made to answer what effect the level of zinc nutrition has on the response and the nutrient balances in various plant species. To answer these important questions, greenhouse experiments were initiated in the spring of 1968 to study the responses of five plant species grown in soils known to be zinc deficient.

EXPERIMENTAL METHODS

Soils

The soils used throughout these experiments were obtained from sites where zinc deficiency had previously been observed in field experiments. Sifton soil was collected in the field and air dried prior to screening. Screening through a three-quarter inch iron mesh grate was necessary to remove both stones and plant residues. The screened soils were placed in barrels lined with a double plastic barrier and stored. All subsequent soils obtained were stored in barrels in a similar fashion to prevent contamination. Shano soil for experiment I was shipped in from the Irrigation Research Station, Prosser, Washington. It arrived ready for storage. A second quantity of Shano soil for experiment III was collected from a field site at Othello, Washington on the Irrigation Research Station. This soil had to be air dried before storage.

Soil tests were run on these soils by the Oregon State University Soil Testing Laboratory. A supplemental zinc test using DTPA-TEA extractant according to the procedures of Lindsay and Norvell (1970) was also run on these soils. Fertilizer applications were made on the basis of these soil test results shown in Table 1.

Table 1. Chemical analysis of experimental soils.

Soil	Soil pH	P ppm	K me/100g	Ca me/100g	Mg me/100g	OM %	CEC me/100g	Zn ppm HCl	Zn ppm DTPA
Sifton	5.7	9.3	0.37	4.3	0.7			.40	.26
Shano (I)	7.5	3.6	0.34	9.5	3.6			.58	.62
Shano (III)	8.2	3.4	0.26	14.1	2.5	0.11	11.4	1.60	.16

The original pH of the Sifton soil was 5.7. For some of the treatments in these experiments, the Sifton soil was limed to a pH of 6.5. To determine the amount of lime to apply, increments of $Ca(OH)_2$ were added to one pound samples of soil at rates equivalent to 0, 2, 4, 6, 8 and 10 tons of calcium carbonate per two million pounds of soil. A 1:1 soil to water mixture was prepared and allowed to incubate at room temperature for three days before pH's were read. A plot of the pH reading versus lime application showed that a five-ton application of calcium carbonate per two million pounds of soil would raise the pH to 6.5.

The actual liming was done on 30 pound units of air dried soil. $Ca(OH)_2$ was mixed with the soil and placed in large plastic bags. The limed soil was brought to field capacity with distilled water and incubated five days prior to potting.

Experimental Design

Both experiments I and III were factorially designed with all treatments replicated four times. Experiment I utilized four variables which included three soils, five plant species, three levels of phosphorus and two levels of zinc. Experiment III used five levels of phosphorus and two levels of zinc as variables. Pots were assigned to blocks on greenhouse benches according to replication and plant species. Three greenhouse benches, four feet wide by 17 feet long, were used to grow 360 pots in experiment I and one bench was used for 40 pots in experiment III. To minimize border and other greenhouse effects, blocks were randomly assigned to consecutive cross boards on the benches. The pots within blocks were likewise randomly assigned and rerandomized weekly during the first three weeks of growth. Further rerandomization after four weeks was curtailed to avoid damaging plants in the rerandomization process.

Greenhouse Procedures

Soils were potted in green plastic pots 7-1/2 inches in diameter and 6-1/2 inches deep. One hole had been drilled in the bottoms and previously fitted with a short Tygon tube to channel drainage water into a cup. All pots were washed, rinsed, acid rinsed and finally rinsed in distilled water prior to use. For experiment I, five pounds of air dried soil were added to each pot and fertilizer applications were based on this weight. The exception in experiment I was when seven pounds of Shano soil were used to grow tomatoes. Seven pounds of Shano soil were used throughout experiment III.

Fertilizer treatments for experiment I are listed as follows:

Element	Rate	Source
Nitrogen	100 ppm N	NH_4NO_3
Potassium	100 ppm K	K_2SO_4
Magnesium (Sifton only)	10 ppm Mg	$MgSO_4$
Phosphorus		
P_0	0 ppm P	H_3PO_4 (85%)
P_1	100 ppm P	H_3PO_4
P_2	200 ppm P	H_3PO_4
Zinc		
Zn_0	0 ppm Zn	$ZnSO_4 \cdot 7H_2O$
Zn_1	3 ppm Zn	$ZnSO_4 \cdot 7H_2O$

Non-variable elements were made up into solutions so that a 20 ml volume contained the correct amount of nutrients to be added to each pot. The solution was pipetted on the surface and allowed to dry before it was mixed throughout the upper half of the pot.

Phosphorus and zinc variables were made into appropriate solutions so that the proper amount of each element could be dispersed in a 10 ml volume. Approximately one-half the soil was removed and phosphorus and zinc were applied to the middle of the soil mass. Phosphorus was applied in a circular band and zinc applied to the center. The soil was replaced and planting was begun.

Experiment III used a different basis to determine the amount of fertilizer treatments to apply. Applications were based on banding fertilizers in rows spaced 36 inches apart and taking a six inch segment of that fertilizer band. This substantially increased the amount of fertilizer material added per pot but it would be a closer replication of actual field conditions. The treatments used in experiment III are listed as follows:

Element	Rate pounds per acre	Source
Nitrogen	50 N	NH_4NO_3
Potassium	30 K	K_2SO_4
Phosphorus		
P_0	0 P_2O_5	$Ca(H_2PO_4)_2$
P_1	60 P_2O_5	$Ca(H_2PO_4)_2$
P_2	120 P_2O_5	$Ca(H_2PO_4)_2$
P_3	240 P_2O_5	$Ca(H_2PO_4)_2$
P_4	480 P_2O_5	$Ca(H_2PO_4)_2$
Zinc		
Zn_0	0 Zn	$ZnSO_4 \cdot 7H_2O$
Zn_1	3 Zn	$ZnSO_4 \cdot 7H_2O$

Nitrogen and potassium were applied as in experiment I; however, a second application of nitrogen was applied after five weeks growth bringing the total nitrogen application to 100 pounds of N per acre. Phosphorus was added as dry, reagent grade $Ca(H_2PO_4)_2$ to the middle of the soil mass. Zinc was added as a solution similar to the method of experiment I.

Planting began immediately after the soils had been treated with both blanket and variable fertilizer treatments. All species were planted on May 2, 1968 except tomatoes which were started in greenhouse flats on August 24, 1968. Nine kernels of sweet corn (Zea mays saccharata) var. "Jubilee" were planted and thinned to to three plants per pot. Seven seeds of bush beans (Phaseolus vulgaris) var. "Sanilac" were planted and thinned to three plants per pot. Twenty-five seeds of wheat (Triticum aestivum) var. "Pitic 62", a Mexican dwarf wheat, were planted but not thinned. Potato (Solanum tuberosum) var. "Russet" buds were scopped out with a mellon ball cutter to insure uniform pieces. These were treated with "Captan" and allowed to suberize for a day prior to planting. Four buds were planted and later thinned to two plants per pot. Tomatoes (Lycopersicon esculentum) var. "Willamette" were started in greenhouse flats in sterilized Sifton soil. Four plants were transplanted and later thinned to two plants per pot.

The soils were brought to field capacity with distilled water after planting. All subsequent watering was done with distilled water; however, excessive watering was avoided although cups were provided to catch drainage water which was returned to the pot. Watering was done daily and twice daily as dictated by plant needs.

The greenhouse temperature was kept at 80-85°F during the days and 50°F at night. Supplemental lighting was provided to maintain a 16 hour period of daylight. Lighting was timed to bracket the normal daylight hours. The supplemental lighting was provided by fluorescent lighting which included one "Gro-Lux" tube for every two "daylight" and "subdued daylight" tubes. A distance of six to twelve inches was maintained between the lights and plant tops at all times.

Plant Analysis

Plants were harvested at about six weeks of age and their fresh weights were recorded. Leaves were separated from stems in bush bean, potato and tomato samples and bagged separately. All plant materials were then dried at 75^{o}C in a forced air dryer after which dry weights were obtained before grinding. Grinding plant samples was done mainly in an "Osterizer" unit using stainless steel blades. It was necessary to grind stems in a "Wiley" mill which also had all stainless steel parts. The ground samples were stored in paper envelopes before the chemical analysis was begun.

One gram samples were weighed out, digested with HNO_3 and $HClO_4$ and brought to 100 ml volumes. Zn, Fe and Mn were determined directly on these digests by means of a "Perkin Elmer 303" atomic absorption spectrophotometer. After appropriate dilutions, Ca and Mg were also determined by atomic absorption. K in experiment I was determined by flame photometric techniques and in experiment III by atomic absorption methods. Phosphorus was determined by the molybdevanadophosphoric acid colorimetric method by Jackson (1958).

The statistical analysis of variance was carried out according to the procedures outlined in Experimental Methods for Extension Workers (1966) and Statistics for Scientists and Engineers (Wine, 1964). Multiple comparison correlation coefficients were obtained using Oregon State University statistical analysis library program *STEP (1968). Simple linear regression analysis was done by using Oregon State University statistical analysis library program *SIMLIN (1969).

RESULTS AND DISCUSSION

Experiment I

This experiment was established to distinguish any differences in the responses of five plant species to different levels of zinc nutrition. The confounding effects of different soils and different levels of phosphorus nutrition were also included in this experiment. In addition, the effect of liming was also studied where the Sifton soil was limed from pH 5.7 to 6.5

Plant Symptoms and Yield Response of the Five Plant Species

Sweet Corn. Zinc deficiency symptoms were observed when plants were grown on the limed and calcareous soils with added phosphorus but no zinc. The most apparent symptom was a failure of internodes to grow after about five to seven days following emergence, and this caused the zinc deficient plants to be thick and have a stunted appearance. White stripes developed on the third and fourth leaves between the leaf midrib and edges at about 10-14 days; however, most of the plants grew out of the leaf symptoms before harvest at six weeks. Plants receiving zinc on the calcareous Shano soil had no zinc deficiency symptoms, but they appeared light green in color indicating a possible incipient iron chlorosis. Zinc deficient plants grown on the same soil were dark green in the unaffected leaf areas indicating that iron chlorosis was not a problem in these plants. All plants grown at the P_0 rate had thin stalks and narrow leaves regardless of the soil or level of zinc application. The growth response to applied P was positive evidence that all three soils were phosphorus deficient.

The yield data in Table 2 shows that there were highly significant differences in yield caused by phosphorus, zinc and soils. P applications increased total plant yields on all soils tested regardless of the level of zinc nutrition. However P applications induced zinc deficiency symptoms in plants grown at the Zn_0 level on the limed and calcareous soils but did not depress total yields. Yields were increased by applied zinc only after P had been applied to the limed and calcareous soils; there was no measurable yield response to zinc on the acid Sifton soil.

Zinc deficiency symptoms occurred in sweet corn as expected. First, zinc deficiency symptoms were noted only after a phosphorus application and secondly, liming was necessary to bring out deficiency symptoms on the acid soil. In no instance did phosphorus induced zinc deficiency symptoms depress total plant yield. In fact, yields were further increased at the P_2 rate instead of being reduced by a worsening of deficiency symptoms as had been expected.

<u>Bush Beans</u>. Zinc deficiency symptoms were observed on all three soils after phosphorus had been applied without added zinc. The

Table 2. The effects of P and Zn on sweet corn yield and phosphorus and zinc composition.

	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc	
Treatment	DM/pot	%	mg/pot	ppm	μg/pot	DM/pot	%	mg/pot	ppm	μg/pot	DM/pot	%	mg/pot	ppm	μg/pot
P_0Zn_0	3.1	.09	2.8	15	46.1	5.8	.16	9.3	13	72.6	3.8	.08	3.2	16	63.1
P_0Zn_1	3.4	.09	3.2	24	83.0	6.0	.16	9.6	16	94.5	3.6	.08	2.9	23	81.5
P_1Zn_0	12.8	.09	11.5	8	102.3	7.4	.16	11.8	8	61.9	7.0	.49	33.3	8	58.2
P_1Zn_1	12.6	.09	10.9	14	167.7	14.3	.11	15.3	8	121.0	20.3	.22	45.0	8	171.2
P_2Zn_0	15.1	.09	13.2	7	105.2	8.9	.18	15.6	8	72.3	10.7	.51	54.3	8	82.0
P_2Zn_1	16.1	.09	14.9	10	160.8	15.0	.11	16.6	8	131.4	21.8	.26	55.4	8	179.2

Least significant difference	.05	.01
Yield (grams of dry matter/pot)	1.6	2.1
Phosphorus (%)	.04	.06
Phosphorus (mg/pot)	3.7	4.9
Zinc (ppm)	3	4
Zinc (μg/pot)	33.2	44.1

apparent deficiency symptoms were stunted growth and yellowing of the lower leaves. The leaf veins remained green in the lower leaves and the middle leaves were speckled with small, brown spots; however, the youngest leaves at the top were unaffected. Plants grown on the acid Sifton soil were zinc deficient but their symptoms were the least severe. Bean plants grown with added zinc on the Shano soil were light green in color but when zinc was deficient, the unaffected leaf areas were dark green.

Table 3 shows the yield data for bush beans and the significant responses to phosphorus, zinc and soils. Phosphorus applications increased yields on all three soils regardless of the zinc status of the plants. Zinc increased yields only after phosphorus had been applied although the response to zinc was least on the acid soil. Liming the Sifton soil had no beneficial effect on bush beans because it not only increased the severity of zinc deficiency symptoms, but total yield remained less even after zinc was applied.

Wheat. No visible zinc deficiency symptoms were observed in the plants grown on any of the treatments in this experiment. Wheat grown on Shano soil was lighter green in color indicating a possible mild iron deficiency but these symptoms occurred both with and without added zinc.

Yield data in Table 4 shows no response to zinc application on either the acid or limed Sifton soils. Yields appeared to be increased

Table 3. The effects of P and Zn onbush beans yield and phosphorus and zinc composition.

	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc	
Treatment	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot
P_0Zn_0	1.7	.14	2.4	18	31.2	1.8	.16	2.9	12	21.6	2.4	.12	3.0	13	32.2
P_0Zn_1	1.8	.16	2.9	32	58.2	1.7	.18	3.1	16	28.4	2.3	.10	2.3	16	37.8
P_1Zn_0	5.4	.19	10.4	11	56.0	3.4	.31	11.0	8	26.8	3.0	1.19	35.8	8	25.3
P_1Zn_1	6.8	.18	12.4	17	119.2	5.6	.20	11.2	11	62.8	8.7	.43	37.1	10	87.6
P_2Zn_0	6.4	.22	13.8	11	65.3	4.7	.39	18.2	7	35.0	4.8	1.30	61.4	8	38.4
P_2Zn_1	8.1	.19	15.4	17	135.8	6.2	.25	15.6	10	62.1	7.8	.52	40.1	11	85.1

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	1.4	1.8
Phosphorus (%)	.08	.11
Phosphorus (mg/pot)	4.5	5.9
Zinc (ppm)	3	4
Zinc (µg/pot)	17.8	23.6

Table 4. The effects of P and Zn on wheat yield and phosphorus and zinc composition.

Treatment	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc	
	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot
P_0Zn_0	3.2	.25	7.9	16	52	4.1	.25	10.5	15	60	2.8	.12	3.4	18	51
P_0Zn_1	2.8	.24	6.7	21	60	4.4	.31	13.6	21	91	2.7	.12	3.2	28	76
P_1Zn_0	5.2	.54	28.5	16	82	6.5	.43	27.8	13	86	6.0	.54	31.4	10	56
P_1Zn_1	5.1	.48	24.6	20	101	6.4	.42	27.2	17	108	7.6	.50	38.0	15	115
P_2Zn_0	5.3	.56	29.9	16	82	6.8	.46	31.1	13	88	7.1	.57	40.3	9	64
P_2Zn_1	5.3	.55	29.2	20	105	6.8	.48	32.9	18	124	7.7	.60	46.3	17	134

Least significant differences	.05	.01
Yield (gram of dry matter/pot)	0.7	1.0
Phosphorus (%)	.06	.08
Phosphorus (mg/pot)	4.0	5.2
Zinc (ppm)	3	5
Zinc (µg/pot)	22	29

by zinc after phosphorus had been applied to the calcareous Shano soil, but no visible zinc deficiency symptoms were observed. There was a highly significant response to phosphorus application and a significant response to liming which increased yields. But neither of these treatments could induce zinc deficiency symptoms in wheat grown on these soils.

Potatoes. Symptoms of mild zinc deficiency were observed in plants grown on the limed Sifton soil, while more severe symptoms were observed in the plants grown on the Shano soil. Affected plants were shorter and had large, irregularly shaped leaves. All plants grown at the P_0 level showed purpling on the underside of their leaves that was indicative of phosphorus deficiency. No iron deficiency symptoms could be identified even on the Shano soil which previously had grown lighter green plants in trials with other species.

Yield data for potatoes in Table 5 shows that there was no response to zinc fertilization on either the acid or limed Sifton soils. Potatoes grown on the calcareous Shano soil responded significantly to zinc fertilization after phosphorus had been applied. Phosphorus applications increased yields regardless of the zinc level supplied either from the soil or fertilizer treatment. Liming decreased the yield of potatoes on Sifton soil particularly after phosphorus was applied. This reduction in yield could not be related to the level of zinc nutrition because the yields on the limed soil were nearly

Table 5. The effects of P and Zn on potato yield and phosphorus and zinc composition.

	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc	
Treatment	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot	DM/pot	%	mg/pot	ppm	µg/pot
P_0Zn_0	4.1	.16	6.3	20	85	4.2	.16	6.6	14	61	3.7	.15	5.4	11	40
P_0Zn_1	3.8	.14	5.6	30	113	3.0	.17	5.0	20	56	3.6	.14	5.4	12	48
P_1Zn_0	6.8	.19	12.8	14	93	5.4	.22	11.8	12	66	4.1	.85	34.4	8	33
P_1Zn_1	6.0	.20	11.8	24	137	5.0	.21	10.8	14	70	6.2	.43	26.5	10	64
P_2Zn_0	7.2	.20	14.0	16	111	5.4	.23	12.7	10	54	5.0	1.11	55.0	8	41
P_2Zn_1	7.4	.19	13.7	19	137	4.8	.25	11.5	12	57	7.2	.55	39.1	10	74

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	1.2	1.6
Phosphorus (%)	.10	.14
Phosphorus (mg/pot)	5.8	7.7
Zinc (ppm)	6	9
Zinc (µg/pot)	17	22

identical at both levels of zinc application.

Tomatoes. In a preliminary experiment tomatoes could not be grown without the inclusion of a blanket treatment of 10 ppm P on all soils. Because tomatoes were found to have extremely high demands for phosphorus, the rates of application were doubled from the treatments applied on the other species. The plants grown on the acid Sifton soil exhibited no symptoms attributable to zinc deficiency, but phosphorus deficiency severely limited growth at the P_0 rate. A severe purpling on the underside of the leaves was noted on all plants grown on the acid Sifton soil. This symptom, often attributed to phosphorus deficiency, was not related to a phosphorus response on this soil, and was absent in plants grown on the other two soils when P was added. Tomato plants grown on the limed and calcareous soils had an abnormal appearance which could not be related to any of the treatments. The greater severity occurred in the plants on Shano soil which developed longer internodes with leaves clustered at stem tips. Plants receiving zinc had a more bushy appearance but the coloration and structure of the leaves was unchanged. Zinc deficiency sometimes results in leaf rosettes at the stem tips, but this generally occurs in trees and not vegetable crops.

The yield data for tomatoes in Table 6 indicates a highly significant growth response to phosphorus and liming. No significant response to zinc could be detected other than at the P_0 rate on the Shano

Table 6. The effects of P and Zn on tomato yield and phosphorus and zinc composition.

Treatment	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc		Yield grams,	Phosphorus		Zinc	
	DM/pot	%	mg/pot	ppm	µg./pot	DM/pot	%	mg/pot	ppm	µg./pot	DM/pot	%	mg/pot	ppm	µg./pot
P_0Zn_0	0.5	.08	.4	34	15.7	1.8	.16	2.8	15	26.0	8.0	.18	14.0	3	27.8
P_0Zn_1	0.3	.08	.2	38	11.9	1.9	.15	2.8	15	27.2	12.7	.12	14.6	5	61.2
P_1Zn_0	13.4	.17	21.8	7	95.0	18.2	.22	40.0	3	45.5	20.3	.66	132.5	2	47.6
P_1Zn_1	13.2	.17	22.1	14	171.9	16.8	.25	39.2	3	64.1	21.4	.49	103.3	4	76.0
P_2Zn_0	14.8	.20	28.1	8	112.2	17.3	.29	49.5	4	50.8	19.8	.68	131.4	3	50.8
P_2Zn_1	14.6	.21	29.8	12	161.4	18.1	.24	47.0	4	72.3	19.0	.60	112.8	4	84.6

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	3.6	4.7
Phosphorus (%)	.06	.08
Phosphorus (mg/pot)	6.0	8.0
Zinc (ppm)	6	8
Zinc (µg/pot)	25.7	34.2

soil. Normally, zinc responses are much more striking especially where P is applied.

Phosphorus Content and Uptake by Five Plant Species

Sweet Corn. All the soils used in experiment I were extremely deficient in available phosphorus. The thin, weak appearance of plants grown at the P_0 level and the growth response caused by the addition of the first rate of P confirmed the phosphorus deficiency. Table 2 shows that phosphorus uptake was most limited in plants grown at the P_0 level regardless of zinc status. Phosphorus content in the plants grown on the acid Sifton soil were identical for all the P treatments but total phosphorus uptake increased at the higher P rates. Therefore, the identical phosphorus contents were a consequence of the dilution effects caused by increased growth. Zinc had no influence on phosphorus contents or uptake in plants grown on the acid soil, but then no zinc deficiency symptoms or growth responses were evident on this soil. Limed Sifton soil had a greater availability of native soil phosphorus as shown by the higher phosphorus content and greater uptake at the P_0 level. The consequences of zinc deficiency are seen at the P_1 and P_2 rates where phosphorus content is significantly greater in the zinc deficient plants. Total phosphorus uptake did not vary significantly between deficient and normal plants at each rate of applied

P. Therefore, phosphorus accumulated in zinc deficient plants and was ineffective in causing additional growth without added zinc. The plants grown on the Shano soil illustrate this point further. Applied P was readily available for uptake but accumulated in zinc deficient plants until it was twice as concentrated as phosphorus in normal plants. Whether the increased content of phosphorus in zinc deficient plants is related only to the level of P application or is actually elevated by zinc deficiency cannot be ascertained from these results.

Bush Beans. Phosphorus was too deficient in all three soils to meet the plant needs at the P_0 level. The total uptake and content of phosphorus in these plants was restricted as shown in Table 3. Phosphorus content did not deviate widely in the plants grown on the acid Sifton soil and the level of zinc application appeared to have no effect on either phosphorus content or uptake even though mild zinc deficiency symptoms were present. Phosphorus composition in bush bean plants grown on the limed Sifton and calcareous Shano soil was markedly influenced by zinc deficiency. At the P_1 rate, phosphorus content was greater in zinc deficient plants although total uptake was equal between deficient and normal plants. However, at the P_2 rate, not only was phosphorus content elevated in zinc deficient plants, but total uptake was significantly increased too. The greatest increases in phosphorus content and uptake occurred in the zinc deficient plants grown on Shano soil where phosphorus content exceeded one percent in these severely affected plants but an increase in total uptake occurred only at the P_2 rate. This greater uptake was related directly to the availability of phosphorus which at the P_1 level was insufficient to allow accentuation of phosphorus uptake in the zinc deficient plant.

Soil pH did not affect the uptake of phosphorus greatly between the limed and acid Sifton soils although generally total uptake was greater on the limed soil. However, the severity of zinc deficiency was much greater in the plants grown on the limed soil. This indicates that some factor other than available phosphorus caused the increased severity of zinc deficiency in these plants and that this factor was related to soil pH.

Wheat. Wheat plants also responded to phosphorus applications on all three soils. Table 4 shows that phosphorus content and uptake were related to availability of this nutrient on each soil. This is particularly illustrated on the Shano soil where phosphorus contents were the highest because applied P was most available on this soil according to the total uptake. Similarly, the growth response to zinc, as slight as it was, proportionately increased the amount of phosphorus uptake enough to offset any dilution effects. Zinc had no effect on the phosphorus composition in wheat grown on either the acid or limed Sifton soils. Liming did increase wheat growth but not phosphorus uptake. Hence there was a net dilution effect caused by the growth response at the more favorable soil pH.

Potatoes. Phosphorus deficiency was evident in potatoes by limited growth and purpling on the underside of potato leaves. Addition of P corrected both these symptoms on all three soils. The data in Table 5 show that phosphorus content and uptake at the P_0 level were the least regardless of the rate of zinc application. Phosphorus content and uptake in potatoes grown on the acid and limed Sifton soils were not influenced by the rate of zinc application but then no severe zinc deficiency symptoms or growth responses to zinc were observed in those plants either. Plants grown on the Shano soil responded to zinc fertilization and phosphorus content and total uptake showed the effects of this response. Total phosphorus uptake in zinc deficient plants exceeded the uptake in normal plants and when this was coupled with limited growth in these same plants, phosphorus contents were doubled. The greater phosphorus uptake in zinc deficient potatoes is evidence that a lack of zinc directly influences the uptake of this element. But it must be pointed out that this does not occur until there is enough available phosphorus in the soil to allow this accumulation.

Tomatoes. As previously stated, the rates of P application were doubled; plus, there was a blanket application of 10 ppm P on all soils. However, phosphorus uptake on the acid Sifton soil was considerably more limited than on either of the other two soils. Liming the acid Sifton soil resulted in greater plant growth and phosphorus uptake. The low soil pH of the acid soil seems to be the factor detrimental to tomato growth because of this obvious response to liming. Applied zinc had no effect on phosphorus in tomatoes on either the acid or limed Sifton soils, but plants grown on the Shano soil were affected. There was visual evidence of zinc deficiency symptoms in tomatoes on this soil although there were no yield responses to zinc. Phosphorus content and uptake were elevated significantly in the plants suspected of being zinc deficient. Thus it appears that zinc deficient tomato plants tended to accumulate more phosphorus than normal plants and that zinc application tended to reduce phosphorus uptake.

Zinc Content and Uptake by Different Plant Species

Tables 2 through 6 show the zinc content and uptake for the various treatments in sweet corn, bush beans, wheat, potatoes and tomatoes respectively. There was a great deal of similarity among these data so that a species by species discussion is not warranted. The most significant finding in these results was that in no instance did the application of phosphorus fertilizers depress the total uptake of zinc in any plant species. Zinc uptake was related only to the level of available zinc in the soil and the growth response induced by phosphorus and zinc fertilization. Although zinc uptake increased following an application of zinc, the content of this micronutrient varied according to the susceptibility of each plant species to zinc deficiency.

Thus in sweet corn, there was an obvious "Steenbjerg effect" where equal zinc content was measured in both zinc deficient and normal plants. The failure of zinc content to increase following zinc fertilization results from the diluting effect of increased, normal plant growth on absorbed zinc. Therefore the zinc contents measured in these plants indicate that the rate of zinc application is just adequate to restore normal plant growth. In species other than sweet corn, the growth response to zinc was less and therefore there were significant increases in zinc content after zinc applications that were related only to the increased availability of this element.

Phosphorus applications did not depress zinc uptake in any of the plant species grown in experiment I. This is a significant finding because one of the explanations of phosphorus induced zinc deficiency has been that this element interfered with zinc uptake. In fact, the contrary was found; phosphorus applications generally increased zinc uptake although the greatest increases occurred between the P_0 and P_1 rates. It is true that there was a significant growth response between these rates and that zinc uptake would be expected to increase. Never-the less, zinc deficiency symptoms were induced although there had been an actual increase in total zinc uptake. This implies that the incidence of phosphorus induced zinc deficiency occurred after phosphorus needs were met and the levels of native soil zinc became the most limiting factor for plant growth.

Liming the acid Sifton soil depressed the level of zinc uptake in susceptible plant species. The differences in zinc uptake after liming were significant when phosphorus was applied at either the P_1 or P_2 rates because this avoided the confounding effects of phosphorus deficiency. Zinc contents were always elevated in the acid Sifton soil for two reasons. First, there was a greater availability of this element in this soil and secondly, yields were usually depressed on this soil. Bush beans and potatoes were exceptions to the second factor but the greater availability of zinc overrode the effect of yield depression on zinc uptake. The depressed level of zinc uptake in the susceptible species grown on the limed soil coincides with the appearance of zinc deficiency symptoms at the Zn_0 level.

Iron and Manganese Content and Uptake by Different Plant Species

Sweet Corn. The level of zinc nutrition markedly influenced the content of iron and manganese in sweet corn as shown in Table 7. Plants grown at the P_0 level generally were unaffected but phosphorus deficiency overrode any effect on these heavy metals that zinc might have. As phosphorus deficiencies were corrected and zinc was withheld from the fertilizer treatments, the content of iron increased significantly within the plants on all three soils. However, the greatest increases in iron content occurred in the most severely affected plants which were found on the limed Sifton and calcareous Shano soils.

Table 7. The effects of P and Zn on sweet corn yield and iron and manganese composition.

	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese	
Treatment	DM/pot	ppm	μg/pot	ppm	μg/pot	DM/pot	ppm	μg/pot	ppm	μg/pot	DM/pot	ppm	μg/pot	ppm	μg/pot
P_0Zn_0	3.1	83	257	110	343	5.8	87	488	33	142	3.8	55	210	43	166
P_0Zn_1	3.4	89	300	105	356	6.0	89	530	40	206	3.6	68	240	46	161
P_1Zn_0	12.8	136	1735	69	880	7.4	300	2164	58	424	7.0	180	1242	112	779
P_1Zn_1	12.6	80	999	64	792	14.3	110	1574	26	367	20.3	64	1289	34	680
P_2Zn_0	15.1	148	2232	65	983	8.9	319	2839	60	530	10.7	151	1589	96	1004
P_2Zn_1	16.1	85	1370	78	983	15.0	146	2180	35	527	21.8	58	1256	28	620

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	1.6	2.1
Iron (ppm)	38	50
Iron (μg/pot)	348	463
Manganese (ppm)	15	20
Manganese (μg/pot)	139	185

Additions of zinc depressed the level of iron content significantly but some elevation remained in the plants on the limed soil. It is important to note that although the level of iron was more elevated in the zinc sufficient plants on this soil, it nevertheless was one-half the level measured in the zinc deficient plants.

Total iron uptake was increased significantly after P applications. There was an obvious response to phosphorus that increased plant growth and therefore increased the need for iron. But growth needs alone are inadequate to explain why zinc deficient plants absorbed equal or greater amounts of iron than normal plants which yielded two to three times as much plant material. The incidence of zinc deficiency is the only factor consistent with increased iron uptake as well as the elevated level of iron content in these affected plants. Even though visible zinc deficiencies were not observed on the acid Sifton soils, increased iron content and uptake in plants receiving no supplemental zinc is consistent with the deficiency of this element in the fertilizer treatment. Perhaps an incipient zinc deficiency occurred in those plants that was only expressed by its effect on heavy metal composition.

Liming did not depress the total uptake of iron in sweet corn; however, a more vigorous growth occurred following liming which enhanced nutrient uptake in normal plants receiving supplemental zinc. Yet in the zinc deficient plants, iron contents were generally doubled.

This was related directly to the incidence of zinc deficiency in those plants.

Manganese content and uptake followed the same trends as iron but there were important exceptions. First, manganese content and uptake were significantly increased only in those plants that exhibited visible zinc deficiency symptoms. This is especially evident on the limed Sifton and Shano soils at the P_1 and P_2 rates. Manganese uptake was likewise elevated in those same zinc deficient plants on both soils but the greater uptake occurred on the Shano soil. The second exception was a comparison of the magnitude of the increase in manganese content and its relationship to iron contents in zinc deficient plants on each soil. In plants receiving phosphorus but no supplemental zinc on the acid Sifton soil, there was a 50 percent increase in iron content but no significant changes in manganese content were measured in these same plants although manganese was probably most available in this soil because of the low pH. On the limed Sifton soil where there were visible zinc deficiency symptoms in plants grown at the P_1 and P_2 rates, iron contents increased nearly 200 percent while manganese increased about 100 percent over the levels in plants receiving zinc. Liming did depress the level of available manganese but nevertheless, zinc deficiencies accentuated a greater uptake of this element. On the Shano soil there was a 200 percent increase in iron content but the levels measured were one-half of that occurring in the corresponding plants on the limed soil. However, manganese contents increased 200 percent in zinc deficient plants on Shano soil and only 100 percent on the limed soil. Although the pH of Shano soil was greater than that of the limed soil which would further depress the availability of manganese, it appears that manganese was more actively accumulated in zinc deficient plants on this soil than it was on other soils. Because iron was less available in Shano soil, manganese was more actively affected by zinc deficiencies.

Bush Beans. Table 8 shows the responses of iron and manganese in bush beans to the various soil and fertilizer treatments. There was no evidence of accentuated iron or manganese content in plants grown on the acid Sifton soil although mild zinc deficiency symptoms and yield reductions occurred. Similarly there was no effect on heavy metal content in bush beans grown on the limed soil even though zinc deficiency symptoms were more severe and yields were greatly reduced. Liming did significantly reduce manganese content but that was likely a pH response. Iron and manganese contents were greatly elevated in the zinc deficient plants induced by the P_1 rate when zinc was not included in the treatment on Shano soil. Iron levels were not further affected beyond this first increase noted at the P_1 rate. However, manganese content further increased at the P_2 rate and this was directly related to the increased rate of phosphorus application.

Table 8. The effects of P and Zn on bush bean yield and iron and manganese composition.

Treatment	SIFTON Yield grams, DM/pot	SIFTON Iron ppm	SIFTON Iron µg/pot	SIFTON Manganese ppm	SIFTON Manganese µg/pot	SIFTON-LIMED Yield grams, DM/pot	SIFTON-LIMED Iron ppm	SIFTON-LIMED Iron µg/pot	SIFTON-LIMED Manganese ppm	SIFTON-LIMED Manganese µg/pot	SHANO Yield grams, DM/pot	SHANO Iron ppm	SHANO Iron µg/pot	SHANO Manganese ppm	SHANO Manganese µg/pot
P_0Zn_0	1.7	161	271	292	496	1.8	138	243	74	130	2.4	206	474	85	205
P_0Zn_1	1.8	135	245	266	482	1.7	123	208	65	111	2.3	126	288	63	144
P_1Zn_0	5.4	128	706	265	1415	3.4	140	482	136	489	3.0	204	622	118	356
P_1Zn_1	6.8	181	830	239	1626	5.6	128	708	91	506	8.7	132	1144	69	590
P_2Zn_0	6.4	135	850	287	1792	4.7	147	689	148	688	4.8	201	946	149	712
P_2Zn_1	8.1	131	1068	257	2071	6.2	131	822	139	902	7.8	133	1042	77	605

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	1.4	1.8
Iron (ppm)	49	66
Iron (µg/pot)	254	337
Manganese (ppm)	36	48
Manganese (µg/pot)	314	418

Total iron and manganese uptake in bush beans grown on the acid and limed soils were directly related to the growth responses and not to the incidence of zinc deficiencies. The total uptake of these elements was affected on the Shano soil by zinc deficiencies although total uptake did not significantly differ between zinc deficient and sufficient plants. Because iron and manganese contents were doubled in zinc deficient plants grown on Shano soil, it appears that heavy metal uptake was accentuated in only these most severely affected bush bean plants.

Wheat. Iron content and uptake in wheat were not affected by the level of zinc application as shown in Table 9. This same table showed a hint of increased manganese content and uptake in wheat plants grown at the P_1 and P_2 rates without added zinc on the Shano soil. But highly significant differences in manganese content occurred at the P_1 rate but not at the P_2 rate. Also there was no significant difference in total manganese uptake at either level of phosphorus application between the plants grown at each level of zinc application. Increases were noted in iron content that resulted when phosphorus deficiencies were corrected on all the soils tested but no increases in manganese content occurred except on the calcareous Shano soil. These increases in heavy metal content most probably were the result of the nutritional balances in wheat being altered when phosphorus was adequately supplied to these plants.

Potatoes. Table 10 shows that zinc had no effect on either iron

Table 9. The effects of P and Zn on wheat yield and iron and manganese composition.

	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese	
Treatment	DM/pot	ppm	μg/pot	ppm	μg/pot	DM/pot	ppm	μg/pot	ppm	μg/pot	DM/pot	ppm	μg/pot	ppm	μg/pot
P_0Zn_0	3.2	95	302	220	698	4.1	96	393	71	292	2.8	82	230	58	162
P_0Zn_1	2.8	91	258	215	606	4.4	112	488	60	265	2.7	85	232	54	146
P_1Zn_0	5.2	144	752	215	1128	6.5	115	747	62	402	6.0	106	630	82	492
P_1Zn_1	5.1	134	678	202	1029	6.4	84	584	59	378	7.6	100	756	62	471
P_2Zn_0	5.3	124	654	221	1172	6.8	115	778	71	482	7.1	104	736	81	576
P_2Zn_1	5.3	130	691	215	1148	6.8	109	731	68	462	7.7	101	779	68	519

Least significant difference	.05	.01
Yield (grams of dry matter/pot)	0.7	1.0
Iron (ppm	24	31
Iron (μg/pot)	131	174
Manganese (ppm)	12	16
Manganese (μg/pot)	113	150

Table 10. The effects of P and Zn on potato yield and iron and manganese composition.

Treatment	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese		Yield grams,	Iron		Manganese	
	DM/pot	ppm	μg./pot	ppm	μg /pot	DM/pot	ppm	μg/pot	ppm	μg/pot	DM/pot	ppm	μg./pot	ppm	μg/pot
P_0Zn_0	4.1	125	500	168	671	4.2	93	396	41	175	3.7	81	290	29	110
P_0Zn_1	3.8	114	438	187	704	3.0	144	412	43	118	3.6	73	287	22	85
P_1Zn_0	6.8	110	742	121	810	5.4	100	531	41	216	4.1	91	370	26	105
P_1Zn_1	6.0	139	779	185	1010	5.0	135	681	42	212	6.2	92	571	23	142
P_2Zn_0	7.2	107	768	135	955	5.4	100	537	49	270	5.0	84	422	30	151
P_2Zn_1	7.4	94	689	117	856	4.8	91	421	46	212	7.2	76	537	23	162

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	1.2	1.6
Iron (ppm)	35	47
Iron (μg/pot)	159	211
Manganese (ppm)	32	42
Manganese (μg/pot)	90	120

or manganese content and uptake in potatoes. There were differences in the responses of these heavy metals between the P_1 and P_2 rates at each level of zinc application but there was no consistency in these measured responses. For example, the content and uptake of iron appeared to be increased when no supplemental zinc was added at the P_2 rate. But at the P_1 rate, the opposite was true; supplemental zinc appeared to increase both iron content and total uptake. The same inconsistency was found to be true for manganese except on the Shano soil where the contents at each level of phosphorus application were consistently greater at the Zn_0 level. Manganese content and uptake were again reduced following liming of the acid Sifton soil. The growth response to applied P was again most instrumental at increasing the uptake of these heavy metal micronutrients; however, contents generally remained unaffected.

Tomatoes. Table 11 shows that iron content and uptake in tomatoes was unaffected by the level of zinc application. There were significant reductions in iron content due to phosphorus application but there was also an accompanying increase in iron uptake at the P_1 and P_2 rates. This type of response shows the dilution effect of increased plant yields as well as the increasing demands for these micronutrients caused by the growth response to phosphorus. Total iron content and manganese content were significantly reduced by liming the acid Sifton soils. This was the only instance where a plant species showed a reduction in

Table 11. The effects of P and Zn on tomato yield and iron and manganese composition.

Treatment	SIFTON					SIFTON-LIMED					SHANO				
	Yield grams, DM/pot	Iron		Manganese		Yield grams, DM/pot	Iron		Manganese		Yield grams, DM/pot	Iron		Manganese	
		ppm	μg/pot	ppm	μg/pot		ppm	μg/pot	ppm	μg/pot		ppm	μg/pot	ppm	μg/pot
P_0Zn_0	0.5	212	99	756	352	1.8	115	217	64	111	8.0	72	580	82	664
P_0Zn_1	0.3	222	70	822	267	1.9	93	171	59	111	12.7	72	894	65	808
P_1Zn_0	13.4	150	1982	368	4900	18.2	61	1096	70	1247	20.3	56	1131	67	1405
P_1Zn_1	13.2	153	1956	377	4920	16.8	46	730	63	1069	21.4	42	914	54	1343
P_2Zn_0	14.8	161	2054	387	5294	17.3	55	952	74	1264	19.8	49	937	73	1412
P_2Zn_1	14.6	159	2160	425	5878	18.1	49	893	68	1211	19.0	58	1112	75	1438

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	3.6	4.7
Iron (ppm)	50	66
Iron (μg/pot)	326	434
Manganese (ppm)	73	96
Manganese (μg/pot)	416	553

iron following a lime application. Manganese content and uptake were also reduced by liming but to a much greater extent. In fact it is probable these heavy metals may be approaching toxic levels in tomato plants grown on the acid Sifton soil.

The large LSD's between treatments calculated on both content and uptake data for iron and manganese indicates the variability measured in tomatoes. Sensitivity to the acid soil and significant reductions caused by liming as well as a certain amount of variability within blocks and treatments contributed greatly to these large LSD's. Even with large LSD's, it is apparent that most of the responses noted are dependent on the level of phosphorus application and its effect on growth. Zinc had virtually no effect on iron and manganese in tomato plants.

Evaluation of Experiment I

The occurrence of zinc deficiency among the five plant species was not common to any set of soil or fertilizer treatments. Each plant species responded individually to the treatments imposed although certain categories of sensitivity were expressed. Sweet corn and bush beans were very susceptible to zinc deficiency; potatoes and tomatoes were moderately to slightly affected, and wheat was unsusceptible. The content of zinc among these plant species was not indicative of zinc deficiency symptoms because equal zinc concentrations were measured in normal and zinc deficient plants both within the same species and among the different species. The "Steenbjerg effect" reported by Steenbjerg (1951) explains how the same level of nutrient may be measured in both deficient and sufficient plants. Ulrich (1952) stressed the importance of disportionate plant growth on inducing a "Steenbjerg effect". Such abnormal growth did occur in the susceptible plants in this experiment.

Total zinc uptake was a better index of zinc sensitivity. In wheat, the least affected species, total uptake was greater on the P_1 and P_2 treatments on the limed and calcareous soils where zinc deficiency symptoms occurred in the other plant species. Addition of supplemental zinc increased the total uptake in wheat but there was a greater increase in the susceptible species. These data indicate that although wheat was able to absorb more zinc in situations that caused zinc deficiency, when the requirement for zinc was met, the mechanism of absorption was not as active in wheat as in the other species.

Zinc deficiency greatly affected the nutrient composition among the different plant species. Phosphorus content was significantly elevated where zinc deficiencies occurred and this agrees with most of the reports in the literature. Only one paper has reported that the level of zinc nutrition did not affect the phosphorus content in zinc deficient "Red Mexican" beans (Viets _et al._, 1954). Other workers have found that genetic variability between bean varieties influences the response of phosphorus composition to zinc deficiency. Brown and Leggett (1967) determined that "Red Mexican" beans were moderately susceptible whereas "Sanilac" beans, which were grown in this experiment, were severely affected by zinc deficiency.

In no instance did the application of phosphatic fertilizers depress the total uptake of zinc in any plant species. This is contrary to one of the explanations of the cause of phosphorus induced zinc deficiency. An additional experiment was conducted to study this aspect more closely, the results of which will be discussed under experiment III.

Iron and manganese composition were significantly altered by the level of zinc nutrition in species susceptible to zinc deficiency. The content of these heavy metals increased significantly in zinc deficient plants to values three to four times greater than in normal plants. However, in no instance were levels of iron measured in excess of 1000 ppm as reported by Hay (1966). The degree of accentuation in elevated heavy metal content was species dependent with sweet corn being most affected. Brown and Tiffin (1962) reported that plant species do differ in their susceptibility to zinc deficiencies and that further differences existed among different varieties within a species. Although no variety differences were tested, species differences were measured throughout this experiment.

One significant finding in these results was that manganese composition responded to zinc deficiencies secondary to iron. Rosell and Ulrich (1964) reported that elevated iron contents preceded any increases in manganese contents caused by zinc deficiencies in sugar beets. Although their work was conducted in nutrient solutions, it nevertheless is in agreement with the results measured in this experiment.

Experiment III

This experiment was designed to study closely the role of phosphorus on inducing zinc deficiencies. To accomplish this, five rates of phosphorus were applied both with and without zinc to a crop of sweet corn on a soil known to be both phosphorus and zinc deficient. If phosphorus *per se* was responsible for the inducement of zinc deficiencies, then increasing the amount of phosphorus application would be expected to increase the severity of zinc deficiency symptoms and possibly induce zinc deficiency in plants receiving supplemental zinc. Correspondingly, the effect on heavy metal composition could be more closely studied; at this time it appears that iron and manganese contents may increase substantially where zinc deficiencies occur.

Sweet corn was chosen for this experiment because it was the only species which showed a trend towards a more active uptake of iron and manganese in experiment I. Similarly Shano soil was used because the greatest severity of zinc deficiency occurred on this soil.

Although the level of iron was low in this soil, previous work by Hay (1966) showed that iron uptake was stimulated by zinc deficiency in sweet corn on this soil. Fertilizer materials for this experiment were applied on the basis of banding in 36 inch rows. A quantity equal to a six inch segment of that fertilizer band was calculated and then applied to each pot of soil.

Plant Symptoms and Yield

No zinc deficiency symptoms were observed on plants grown either with or without supplemental zinc when no phosphorus was applied. Phosphorus applications without added zinc caused zinc deficiency to occur in the sweet corn test crop. These deficiency symptoms began after seven days growth when there was a failure of internode development which eventually resulted in extreme stunting of the plant as well as very thick stalks. Leaf deficiency symptoms began to appear on the third to fifth leaves 14 days after emergence and were typical of zinc deficiency. Leaf symptoms were characterized by a white stripe between the midrib and leaf's edge that eventually distorted the edges. The severity of zinc deficiency, as evidenced by stunting, was greatest on the plants grown at the P_1 and P_2 rates. In fact, plants in two pots at the P_1 rate and one pot at the P_2 rate failed to develop any internodes at all. Plants grown at the P_3 and P_4 rates were very thick but did develop longer internodes and had a healthier appearance. No correspondence between the severity of leaf symptoms and higher rates of phosphorus application could be ascertained although these symptoms persisted throughout the experiment. Zinc applications prevented the occurrence of these deficiency symptoms in plants receiving phosphorus; however, there was evidence of iron deficiencies in these plants. Five days after emergence the zinc sufficient plants appeared lighter green in color and had a faint yellow striping in the leaves running parallel to the midrib. But growth in these plants was rapid and did not appear to be limited by what evidently was a very mild iron deficiency.

The yield data in Table 12 indicate a large increase in yield due to the addition of supplemental phosphorus and zinc. Without supplemental zinc, the plants were zinc deficient as the first levels of phosphorus were applied and this limited yields even to a value less than measured on the check. But contrary to what was expected, applications of large amounts of phosphorus not only increased the yield but there was a marked decrease in the severity of zinc deficiency symptoms as mentioned previously.

Phosphorus Content and Uptake

Differences in phosphorus content between plants grown with and without zinc show entirely different trends. In Table 12 the data show that phosphorus content in zinc sufficient plants increased

Table 12. The effects of P and Zn on yield and phosphorus and zinc composition of sweet corn.

Treatment		Yield grams of dry matter/pot	Phosphorus		Zinc	
			%	mg/pot	ppm	μg/pot
Zn_0	P_0	2.0	.12	2.2	2	4
	P_1	1.2	.88	10.5	3	5
	P_2	1.8	1.35	25.0	4	8
	P_3	4.0	1.40	56.2	5	18
	P_4	6.5	1.38	83.5	3	22
Zn_1	P_0	2.4	.10	2.2	28	67
	P_1	27.8	.23	60.5	22	618
	P_2	22.0	.35	64.5	24	477
	P_3	27.7	.32	92.5	20	571
	P_4	32.8	.55	173.8	22	716

Least significant difference	.05	.01
Yield (grams of dry matter/pot)	11.0	14.7
Phosphorus (%)	.25	.34
Phosphorus (mg/pot)	50.2	67.2
Zinc (ppm)	8	11
Zinc (μg/pot)	237	317

directly according to the rate of phosphorus application. Zinc deficient plants however, had a large initial increase in phosphorus content but then reached a plateau at the P_2 rate. Phosphorus contents reached levels in excess of one percent in these plants and this was three times as much as in zinc sufficient plants. The differences in phosphorus uptake are great because of the large yield differences, but there was a relationship between phosphorus uptake and growth that paralleled the rate of phosphorus application.

Zinc was essential to obtain an increased growth response to applied phosphorus. Without supplemental zinc, phosphorus merely accumulated in the zinc deficient plants. It appears that phosphorus also began to accumulate in the plants grown at the P_4 rate with added zinc although a content of 0.55 percent is not considered excessive. There was no evidence that zinc reduced total phosphorus uptake although content was significantly reduced. The main effects on phosphorus content and uptake are a consequence of the amount of available phosphorus in the soil and the growth response to added zinc.

Zinc Content and Uptake

Applying zinc as part of the fertilizer band substantially increased the amount of zinc application per pot in this experiment. Not only did total zinc uptake increase, but so did the content as indicated in Table 12. No "Steenbjerg effect" on zinc content was detected because this new method of zinc application supplied more than a critical amount of zinc needed for plant growth. Without supplemental zinc, both zinc content and uptake were low; however, there was a trend towards increasing zinc uptake that was directly related to the level of phosphorus application. Correspondingly, there was a greater growth measured in these zinc deficient plants as rates of phosphorus application were increased. Thus it is difficult to assess whether increasing phosphorus uptake or zinc uptake accounted for the growth response noted. The latter suggestion seems more probable because, although phosphorus uptake was increasing, the levels in the plant were more than adequate for normal growth. Nevertheless, it is important to note that rather than suppressing total zinc uptake, high levels of phosphorus application enhanced it. Possibly this was caused by zinc impurities in $Ca(H_2PO_4)_2$ although reagent grade chemicals were used to minimize any contamination. Other workers have reported the increased availability of zinc as the level of phosphatic fertilizers were increased (Bingham and Garber, 1960). However, these phosphatic fertilizers also induce a depression in soil pH which is intimately associated with micronutrient availability. Communication with N. W. Christensen indicated a drop in pH from 7.8 to 7.0 in the $Ca(H_2PO_4)_2$ fertilizer band in Shano soil when the rate of application was 120 pounds of P_2O_5 per acre which is equal to the P_2

rate in this experiment.[1]

It is important to note that the uptake of endogenous soil zinc increased substantially by P treatments in zinc deficient sweet corn. Many workers have reported that the uptake of Zn^{65} radiotracer was depressed by phosphatic fertilizers (Burleson et al., 1961; Langin et al., 1962; and Stukenholtz et al., 1966). But there were two serious points to criticize in their reports. First, they observed little if any yield response to zinc applications, and secondly, the yield responses to phosphorus were slight. Jackson et al. (1967) conducted experiments on sweet corn where there were yield responses to both applied phosphorus and zinc. Their data indicated that phosphorus applications depressed total zinc uptake when zinc was applied although zinc deficiency symptoms were not reinduced. But when phosphorus was applied without added zinc, there was an increase in total zinc uptake even though the plants were zinc deficient. The observations of Jackson et al. correspond closely to the observations reported here; however, there was too much variability in the data reporting total zinc uptake to confirm any depression in applied zinc uptake.

Iron and Manganese Content and Uptake

Table 13 shows both iron and manganese content and uptake in

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[1] Christensen, N. W. Research Assistant, Oregon State University, Soils Department. Personal communications.

Table 13. The effects of P and Zn on yield and iron and manganese composition of sweet corn.

Treatment		Yield grams of dry matter/pot	Iron		Manganese	
			ppm	µg/pot	ppm	µg/pot
Zn_0	P_0	2.0	82	162	102	205
	P_1	1.2	115	148	362	390
	P_2	1.8	120	218	352	608
	P_3	4.0	125	514	195	533
	P_4	6.5	75	496	142	882
Zn_1	P_0	2.4	78	189	68	140
	P_1	27.8	60	1696	52	1448
	P_2	22.0	68	1470	62	1277
	P_3	27.7	65	1747	58	1893
	P_4	32.8	62	1978	80	2512

Least significant differences	.05	.01
Yield (grams of dry matter/pot)	11.0	14.7
Iron (ppm)	30	40
Iron (µg/pot)	726	971
Manganese (ppm)	87	117
Manganese (µg/pot)	724	969

experiment III. Low iron contents measured in zinc sufficient plants confirms that a mild iron deficiency existed in these plants. There were significant increases in iron and manganese contents in the zinc deficient plants at the P_1 and P_2 rates, but sharp reductions in the content of these elements occurred at the higher rates of phosphorus application although total uptake was not depressed. At first it was assumed that iron and manganese were precipitated by the additional phosphates and made unavailable to the plants. But this explanation seems inadequate for two reasons. First, the total uptake of these elements was not reduced, and secondly, there was no similar reduction in the zinc sufficient plants. The reduction of iron and manganese contents coincide best with the increasing zinc uptake in the zinc deficient plants. Perhaps the best explanation is that the increasing amount of zinc in the deficient plants at the high P rates was sufficient to reduce both iron and manganese content in the plant. The total uptake of both elements nevertheless continued to increase at the higher rates of phosphorus application as a consequence of increased plant growth. The increases in total iron uptake are not as large as those for manganese, but this reflects the greater deficiency of the former element.

There are few reports in the literature about the effect of zinc deficiency on micronutrient balance. Hay (1966) reported iron content in excess of 1000 ppm and 500 ppm in zinc deficient plants grown on

Sifton and Shano soils respectively. But he did not use phosphorus rates in excess of the P_2 rate used in this experiment. Although the high iron levels measured by Hay were not duplicated in experiment III, there was a significant increase in iron content in the zinc deficient plants.

Potassium, Calcium and Magnesium

The content and total uptake of these elements in the plants from both experiments I and III are given in the Appendix. The contents of these elements were not affected by zinc deficiency symptoms to any extent that could not be explained by a dilution effect. That dilution effect was caused by the growth response to zinc in those species susceptible to zinc deficiency symptoms within the limits imposed in these experiments. One further observation concerning these elements is that in no case did zinc application depress the total uptake of any one of these nutrients.

Interactions in Experiment I

The factorial design used in experiment I allowed for testing of interactions between the variables involved. Four variables were used, two of which were quantitative and two which were qualitative. Zinc and phosphorus variables were quantitative because they were distinct, incremental additions to each pot. However, soils and plant species were qualitative variables because each soil and plant species was unique. To simplify the interpretations of data, statistical analyses were determined separately for each plant species to eliminate the additional interactions from this variable. A brief survey of the data indicated that there were major differences in the responses of each plant species. What was of interest was a comparison of similarities and direction of interactions among the different plant species.

Interpretation of interactions must start with the most complicated, the three factor interaction of soil x P x Zn in the case of experiment I. A significant interaction at this highest level will bias the significance at a lower level. Thus a significant response to either soils, P or Zn or any combination of two of these factors is no more than an estimate of their effect when all three factors are involved in the highest order interaction. Further analyses of variance were conducted separately on the plant data obtained on each soil to clarify the significance of P and Zn interactions, but this restricts the breadth of any implication concerning these factors. Although these additional analyses were computed with the intent to clarify the contribution of each soil, the primary interpretations will be made including soils as a variable to enable the broadest consideration to all the variables.

Plant Yields

Interactions measured on plant yields of all species are shown in Table 14. Sweet corn and bush beans were the only species to show an interaction at the highest level but only in sweet corn was it highly significant. This means that the yields of these two species were affected by a response that was dependent on the combination of variables, not the single variables alone. Because of the qualitative nature of soils involved in these analyses, the independent contribution of each soil alone was studied in separate analyses of variance and these results are presented in Tables 19, 20 and 21 for selected plant species and responses. It is apparent in those tables that zinc applications had little or no effect on yields in sweet corn, bush beans or tomatoes grown on the acid Sifton soils whereas there were significant increases in yield on the other soils. A response to P x Zn interactions was not always measured if there was a significant response to zinc but when it did occur, there had always been a significant response to zinc. The nature of a P x Zn interaction on yield response is illustrated for sweet corn on limed Sifton soil.

	Zn_0	Zn_1
P_0	5.8 g	6.0 g
P_1	7.4 g	14.3 g

The response to P and Zn individually can be measured, but the sum

Table 14. The interactions of zinc, phosphorus and soils on the yield of different plant species.

	Plant Species				
Factor	Sweet corn	Bush beans	Wheat	Potatoes	Tomatoes
Soils	**	**	**	**	**
Phosphorus	++	++	++	++	++
Zinc	++	++	NS	NS	NS
Soil x P	**	NS	**	*	**
Soil x Zn	**	**	*	**	NS
P x Zn	++	++	NS	++	NS
Soil x P x Zn	**	*	NS	NS	NS

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

NS Not significant

of the contribution to each factor alone is significantly less than the response measured when both are applied together. In this case, Zn_1 increased the yield 0.2 g and P_1 increased it 1.6 g. The sum of the increase due to these two factors alone is 1.8 g and yet the actual measured response is 8.5 g. This is a highly significant positive interaction.

The significance of the individual factors in Table 14 are important to mention. First, there were significant yield differences within species on each soil which would be expected because of their qualitative character. Secondly, all plant species responded significantly to phosphorus applications. Third, responses to zinc were limited to highly susceptible species, although when less susceptible species did respond to zinc, the response was usually limited to the Shano soil and hence a great deal of significance was lost in the total analysis. Finally, P x Zn interactions were generally confined to the same species responding to zinc alone, but potatoes were the exception. Because the magnitude of the P x Zn interaction can be large, this may override the less significant response to zinc alone. Interactions involving soils with P or Zn alone will not be discussed because the responses involving soils are confounded by the individual expression of zinc deficiency symptoms on each soil.

Phosphorus Content and Uptake

The effects of interactions on phosphorus content and uptake in all the plant species are shown in Table 15. There were more species whose phosphorus compositions were significantly affected by a soil x P x Zn interaction than whose yields were affected. Much of this significance can be explained because the less susceptible species experienced deviations in nutrient composition before measurable yield responses occurred. In all the plant species except wheat, zinc applications depressed the content of phosphorus in the plants. Total phosphorus uptake was also depressed in these species except in sweet corn where the large growth response to zinc had an overriding effect on total uptake.

The response to phosphorus alone was to increase both phosphorus content and uptake. This is of course related to an increasing availability following phosphorus application. P x Zn interactions however, acted to depress both the content and total uptake of this element. This interaction was usually more evident on total phosphorus uptake at the P_2 rate than at the P_1 rate because the growth response to the former rate indicated that this nutrient was still limiting plant growth at the P_1 rate. The following example from the data for bush beans grown on Shano soil illustrates a negative interaction on both phosphorus content and uptake.

Table 15. The interactions of zinc, phosphorus and soils on phosphorus content and uptake in different plant species.

	PLANT SPECIES									
	Sweet corn		Bush beans		Wheat		Potatoes		Tomatoes	
Factor	% P	mg P / pot	% P	mg P / pot	% P	mg P / pot	% P	mg P / pot	% P	mg P / pot
Soil	**	**	**	**	**	**	**	**	**	**
Phosphorus	++	++	++	++	++	++	++	++	++	++
Zinc	--	++	--	--	NS	NS	--	--	--	--
Soil x P	**	**	**	**	**	**	**	**	**	**
Soil x Zn	**	NS	**	**	NS	**	**	**	**	**
P x Zn	--	++	--	**	NS	NS	--	NS	NS	--
Soil x P x Zn	**	**	**	**	NS	NS	**	*	NS	**

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

NS Not significant

	% P		mg P/pot	
	Zn_0	Zn_1	Zn_0	Zn_1
P_0	.12	.10	3.0	2.3
P_2	1.30	.52	61.4	40.1

The greatest increases in phosphorus content and uptake occurred when zinc was deficient; however, the reductions caused by zinc were slight except where both elements were applied together.

Zinc Content and Uptake

Zinc content and uptake were unaffected by soil x P x Zn interactions in all plant species as shown in Table 16. Many of the lower order interactions such as P x Zn were significant as well as responses to single factors alone. In nearly all instances, zinc applications increased both zinc content and uptake, and in no instance were they decreased. This relates directly to the greater availability of zinc after its application. Phosphorus application depressed zinc content in plants but increased total uptake. Such a response is indicative of a growth response exceeding the rate of uptake and hence causing an actual dilution of zinc. The same growth response associated with P x Zn interactions had a similar effect on zinc content and total uptake.

Table 16. The interactions of zinc, phosphorus and soils on zinc content and uptake in different plant species.

	PLANT SPECIES									
	Sweet corn		Bush beans		Wheat		Potatoes		Tomatoes	
	ppm Zn	µg Zn / pot	ppm Zn	µg Zn / pot	ppm Zn	µg Zn / pot	ppm Zn	µg Zn / pot	ppm Zn	µg Zn / pot
Soil	**	*	**	**	**	*	**	**	**	**
Phosphorus	--	++	--	++	--	++	--	NS	--	++
Zinc	++	++	++	++	++	++	NS	++	+	++
Soil x P	**	**	**	**	**	NS	NS	NS	**	**
Soil x Zn	**	NS	**	**	*	**	**	*	NS	**
P x Zn	--	++	-	++	NS	NS	--	NS	NS	++
Soil x P x Zn	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

NS Not significant

Iron and Manganese Content and Uptake

Interactions measured on iron content and uptake are shown in Table 17 and for manganese content and uptake in Table 18. Further analyses on the total uptake of these elements according to soil for sweet corn, bush beans and tomatoes are shown in Tables 19, 20 and 21 respectively. The latter three tables show that the uptake of iron and manganese were dependent on the soil. The total uptake of these elements differed among the soils but generally, iron uptake was significantly affected on the acid and limed Sifton soils while manganese was similarly affected only on the calcareous Shano soil. Because increases or decreases in total heavy metal content were dependent on the soil, this situation reflects the availability of iron and manganese in each soil. Iron availability was observed to be low in Shano soil because of the incipient iron deficiency symptoms especially evident in sweet corn. This is not to say that manganese was likewise deficient in Sifton soils but rather that iron was the crucial element in these soils. From the previous tables showing iron and manganese data in susceptible plant species, it is apparent that the manganese composition was altered by zinc deficiencies only after iron composition had been altered.

In the plant species highly susceptible to zinc deficiency, zinc applications depressed both iron and manganese content. The total

Table 17. The interactions of zinc, phosphorus and soils on iron content and uptake in different plant species.

	PLANT SPECIES									
	Sweet corn		Bush beans		Wheat		Potatoes		Tomatoes	
	ppm Fe	µg Fe / pot	ppm Fe	µg Fe / pot	ppm Fe	µg Fe / pot	ppm Fe	µg Fe / pot	ppm Fe	µg Fe / pot
Soils	**	**	**	**	**	**	**	**	**	**
Phosphorus	++	++	NS	++	++	++	-	++	--	++
Zinc	--	--	--	++	NS	NS	NS	NS	NS	NS
Soil x P	**	**	NS	NS	**	**	NS	*	NS	**
Soil x Zn	**	*	**	NS	NS	NS	NS	NS	NS	NS
P x Zn	--	--	NS	++	NS	NS	NS	NS	NS	NS
Soil x P x Zn	*	NS	NS	NS	NS	NS	NS	NS	NS	NS

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

NS Not significant

Table 18. The interactions of zinc, phosphorus and soils on manganese content and uptake in different plant species.

	PLANT SPECIES									
	Sweet corn		Bush beans		Wheat		Potatoes		Tomatoes	
	ppm Mn	µg Mn / pot	ppm Mn	µg Mn / pot	ppm Mn	µg Mn / pot	ppm Mn	µg Mn / pot	ppm Mn	µg Mn / pot
Soils	**	**	**	**	**	**	**	**	**	**
Phosphorus	NS	++	++	++	++	++	NS	++	--	++
Zinc	--	--	--	NS	--	-	NS	NS	NS	NS
Soil x P	**	**	**	**	**	NS	**	**	**	**
Soil x Zn	**	*	NS	NS	NS	NS	NS	NS	NS	NS
P x Zn	--	NS	NS	NS	NS	NS	NS	--	NS	NS
Soil x P x Zn	**	*	NS	NS	NS	NS	NS	*	NS	NS

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

NS Not significant

Table 19. Selected analyses of variance in sweet corn for each soil used in experiment I.

	YIELD			PHOSPHORUS UPTAKE			ZINC UPTAKE			IRON UPTAKE			MANGANESE UPTAKE		
	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano
Reps								*						**	
P	++	++	++	++	++	++	++		++	++	++	++	++	++	++
Zn		++	++			++	++	++	++	--	--				--
Px Zn		++	++			++			++	--	-	-			--

++ or -- Highly significant increase or decrease
 + or - Significant increase or decrease

** Highly significant
 * Significant

Table 20. Selected analyses of variance in bush beans for each soil used in experiment I.

	YIELD			PHOSPHORUS UPTAKE			ZINC UPTAKE			IRON UPTAKE			MANGANESE UPTAKE		
	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano
Reps															
P	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
Zn	+	++	++			--	++	++	++						
Px Zn			++			--	++	++	++			++			++

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

** Highly significant
* Significant

Table 21. Selected analyses of variance in tomatoes for each soil used in experiment I.

	YIELD			PHOSPHORUS UPTAKE			ZINC UPTAKE			IRON UPTAKE			MANGANESE UPTAKE		
	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano	Sifton	Limed Sifton	Shano
Reps															
P	++	++	++	++	++	++	++	++	+	++	++	++	++	++	++
Zn			+			--	++	+	++		-				
P x Zn			+			--	++					-			

++ or -- Highly signicant increase or decrease
 + or - Significant increase or decrease

** Highly significant
 * Significant

uptake of both these heavy metals was also decreased in sweet corn which was quite significant because this could result only if the reduction in content caused by zinc was sufficient to overcome the extensive growth response to zinc. Total iron uptake in bush beans was increased after zinc applications although iron contents had been decreased. The reduction in content was insufficient to override the additional uptake due to growth. Total manganese uptake was not affected although the content of this element had been significantly reduced. The heavy metal composition in other species generally remained unaffected by zinc applications and this is evidence that deviations in both content and uptake of iron and manganese are related to the particular response of each plant species to zinc.

The changes in heavy metal composition due to phosphorus applications were dependent on both the growth response to this element and whether or not zinc had been applied where a zinc sensitive plant species was grown. Total iron and manganese uptake increased as a result of the growth response to phosphorus in all cases. However, the contents of these elements increased significantly only when zinc was lacking in the treatment. This was particularly true in both sweet corn and bush beans which were quite susceptible to zinc deficiency. In other species such as tomato, there was much variation in both content and uptake data of these heavy metals that was confounded by severe phosphorus deficiencies and soil differences. Any significance in response was clouded by the large error terms created by these large variations.

Interactions in Experiment III

Two variables were used in experiment III in a complete factorial design. Both variables were quantitative in nature, namely the incremental additions of phosphorus and zinc. The combination of these variables yields P x Zn interactions but these are not necessarily equal to P x Zn interactions measured in experiment I. Any similarities between the responses to P, Zn and P x Zn would broaden the implications that could be drawn from both experiments. The reason these P x Zn interactions are not equal is that the rate of phosphorus and zinc applications were changed as well as the chemical form by which phosphorus was applied. Further, the methods of application in experiment III were an attempt to simulate field banding practices and that alone could substantially contribute to deviations between the experiments.

Table 22 shows the significance of phosphorus, zinc and P x Zn interactions on yield and nutrient composition in experiment III. Yields were increased significantly by a P x Zn interaction over and above the highly significant responses to phosphorus and zinc individually. Yield responses to phosphorus, zinc and P x Zn interactions were very similar to those observed in experiment I where positive yield increases were also noted.

Table 22. The effect of zinc and phosphorus on the yield and nutrient composition of sweet corn in experiment III.

		Phosphorus		Zinc		Iron		Manganese	
Factor	Yield	% P	mgP/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Phosphorus	++	++	++	NS	++	**[1]	++	**[1]	++
Zinc	++	--	++	++	++	--	++	--	++
P x Zn	+	--	NS	NS	++	-	+	--	+

++ or -- Highly significant increase or decrease
+ or - Significant increase or decrease

NS Not significant

[1] Highly significant response but the change is not unidirectional.

Phosphorus content and uptake were increased after phosphorus applications; however, P x Zn interactions reduced phosphorus content significantly. Depressions in phosphorus content are contributed principally to zinc although the growth response to this same variable did increase total phosphorus uptake. Because sweet corn growth was greatly increased by zinc and P x Zn interactions on Shano soil, it is difficult to evaluate whether or not the above observations were due entirely to dilution effects. A finite amount of a plant nutrient would be diluted by increased plant growth resulting from the growth response to the correction of another factor limiting to plant growth. However, the highly elevated phosphorus content nevertheless indicates that phosphorus uptake is markedly increased in zinc deficient sweet corn. Zinc contents were unaffected by either phosphorus applications or P x Zn interactions; however, these same variables significantly increased total zinc uptake. There was no dilution effect because zinc contents were unchanged at each level of zinc application although growth was significantly affected. Phosphorus applications were expected to interfere with total zinc uptake but this was not the case at either rate of zinc application. An analysis of variance studying total zinc uptake at the Zn_0 level is shown in Table 23. This analysis indicates that total zinc uptake was significantly different because of phosphorus application. Reviewing total zinc uptake data in Table 12 shows that uptake increased directly with the level of phosphorus application. This was an unexpected result because zinc was so limiting in Shano soil. At the Zn_1 level there was sufficient zinc applied to be absorbed as a direct consequence of the increasing demands imposed by growth.

Table 23. Analysis of variance on total zinc uptake in sweet corn.

					Required F	
Source	df	SS	MS	F	5%	1%
Total	19	1396				
Blocks	3	154	51	1.68	3.49	5.95
P-treatments	4	877	219	7.21	3.26	5.41
Error	12	365	30			

$LSD_{.05} = 8$
$LSD_{.01} = 12$

Iron and manganese content and uptake responses were nearly identical to each variable and interaction. Zinc and P x Zn interactions significantly decreased heavy metal contents while actually increasing the total uptake of the two elements. This was the outcome of the large growth response to zinc and P x Zn interactions. The effects of phosphorus on heavy metal composition in this experiment are difficult to assess. Total uptake of iron and manganese increased directly with the level of phosphorus application but their content changes were affected differently. Essentially there was no change in the level of iron and manganese in plants supplied with supplemental zinc. But in zinc deficient plants, iron contents were elevated at the

P_1, P_2 and P_3 levels. Manganese contents were likewise elevated at these same levels except at the P_3 rate where there was a significant decline. There were significant declines in iron and manganese contents in zinc deficient plants at the highest levels of phosphorus application. No such declines were observed in experiment I but the levels of phosphorus application were smaller in that experiment.

The overall effect of P x Zn interactions can be defined in the following manner if the soil situation is such that both of these elements are deficient for normal plant growth. First, the check plants grown without phosphorus and zinc are extremely affected but exhibit only those symptoms characteristic of phosphorus deficiency. Phosphorus application corrects this deficiency but zinc deficiency is then entirely responsible for limiting plant growth and the plant symptoms are characteristic of that deficiency. There is usually a measurable yield increase and increase in phosphorus content and uptake when phosphorus alone is applied. Heavy metal composition of these plants is extremely upset because zinc deficiency greatly increases iron content first and then manganese content. Unlike phosphorus applications, applied zinc alone does not measurably change yields, symptoms or heavy metal composition from that noted in the check plants other than increasing zinc uptake. The symptoms of these plants correspond to those of the check plants. Applications of phosphorus and zinc together interact to increase plant yields in excess of the sum of any increases measured for each individually. Nutrient composition of these plants is affected principally by the amount of uptake which is dictated by the growth response. In addition, there appears to be no accentuation in the uptake of phosphorus, iron or manganese when both phosphorus and zinc are supplied in adequate amounts.

Effectiveness of Phosphorus and Zinc Within the Plant

Because of the many significant interactions affecting the responses of the different plant species, another method was undertaken to analyze the effects of phosphorus and zinc treatments. Multiple comparison correlation coefficients were determined on yield, phosphorus, zinc, iron and manganese content and uptake in sweet corn and bush beans. The correlation coefficients from each pair of these comparisons can be found in the Appendix. Paired combinations including yield, phosphorus uptake and zinc uptake were observed to be the most significant in bush beans and sweet corn. All further analyses were computed on bush beans from experiment I and sweet corn from experiments I and III.

An analysis of the responses to different levels of zinc application was considered important because of the effect of this element on both plant growth and composition. Computation of correlation coefficients and regression lines for yield, phosphorus uptake, and zinc uptake for both zinc deficient and sufficient plants was done for each soil used to grow bush beans and sweet corn. This procedure would allow a closer inspection of the properties of each soil used in experiment I. Plots of the regression lines are presented in the following sections for bush beans and sweet corn grown in experiment III. The results for sweet corn grown in experiment III are presented in preference to those of experiment I although all correlation coefficients and regression equations are presented in the Appendix. Inspection of the results indicated that the responses to the two levels of zinc nutrition in experiments I and III were similar; however, the data obtained in experiment III extends over a greater range of yield and nutrient uptake and for this reason it is presented.

Phosphorus and Zinc Uptake

Relationships between phosphorus and zinc uptake in sweet corn are shown in Figure 1 and for bush beans in Figures 2 and 3. Figure 1 shows that phosphorus uptake increased rapidly with only a small increase in zinc uptake at the Zn_0 level. This resulted in causing zinc deficient plants which had very high phosphorus content. After zinc was applied at the Zn_1 rate, there was a significant increase in zinc uptake associated with increased phosphorus uptake. Comparison of the slopes of each plot indicated that approximately ten times as much zinc was absorbed for every increment of phosphorus taken up after zinc was applied. Figures 2 and 3 compare the same relationships for

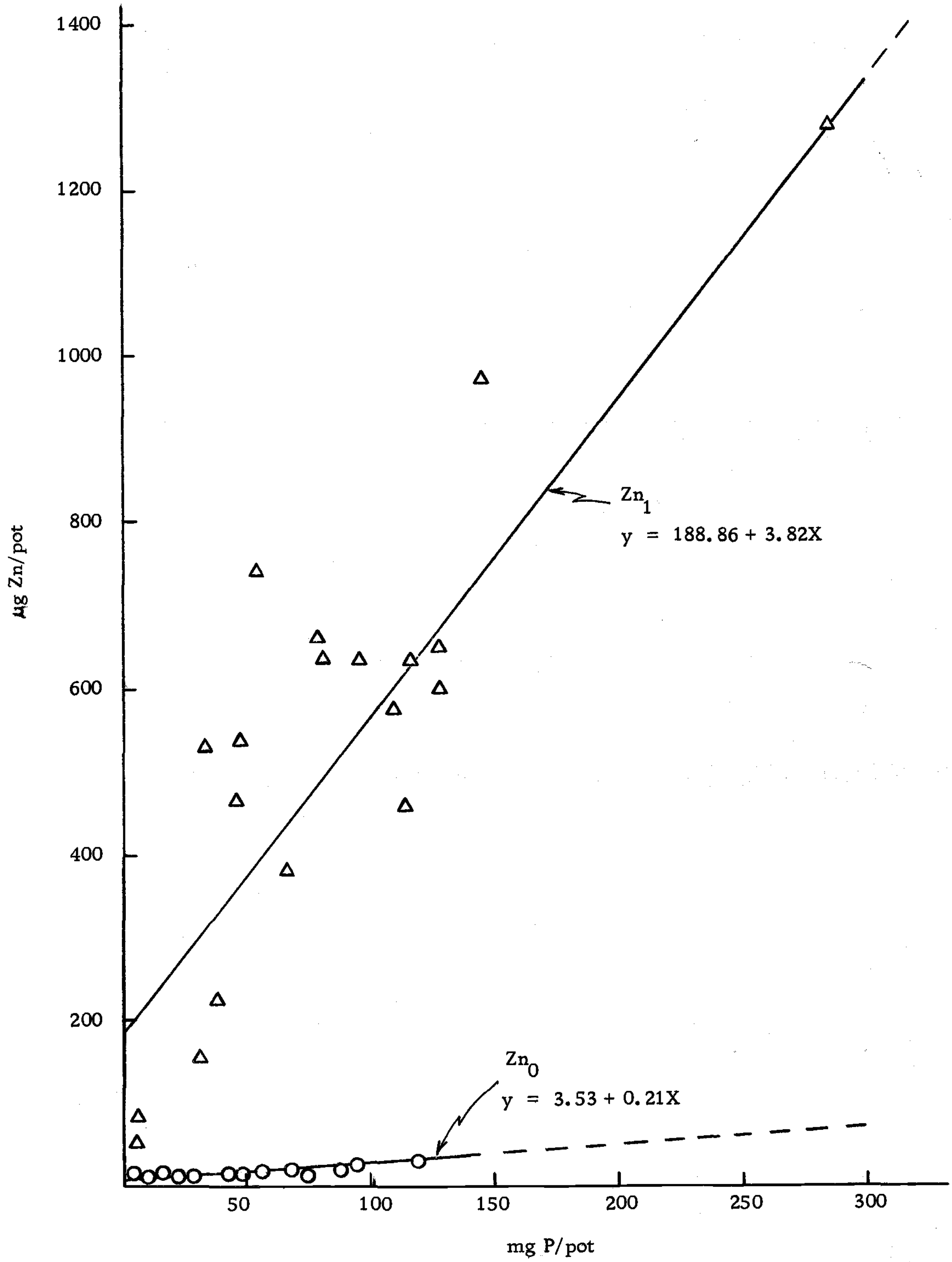

Figure 1. The relationship between phosphorus and zinc uptake by sweet corn - experiment III.

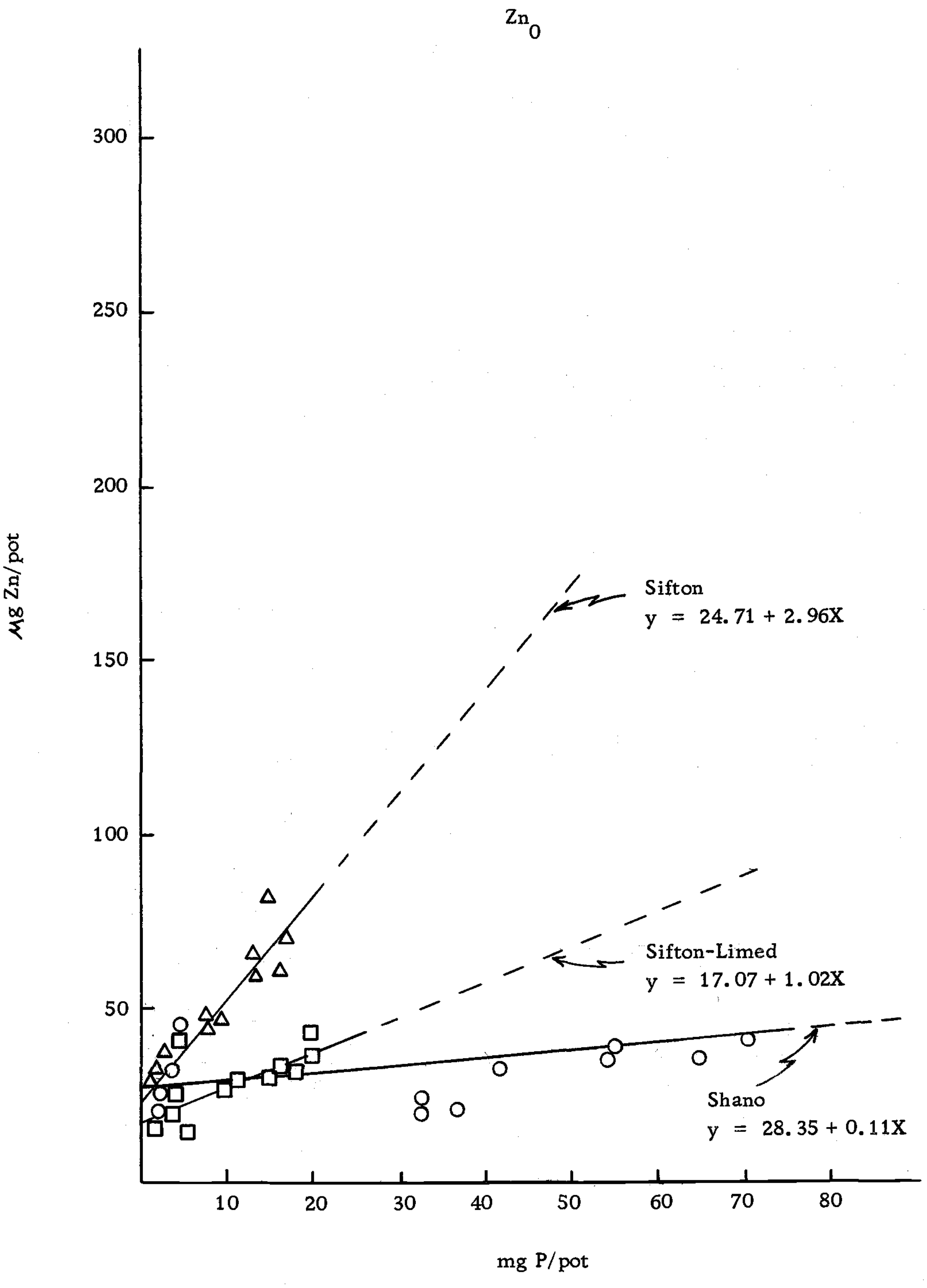

Figure 2. The relationship between phosphorus and zinc uptake by bush beans.

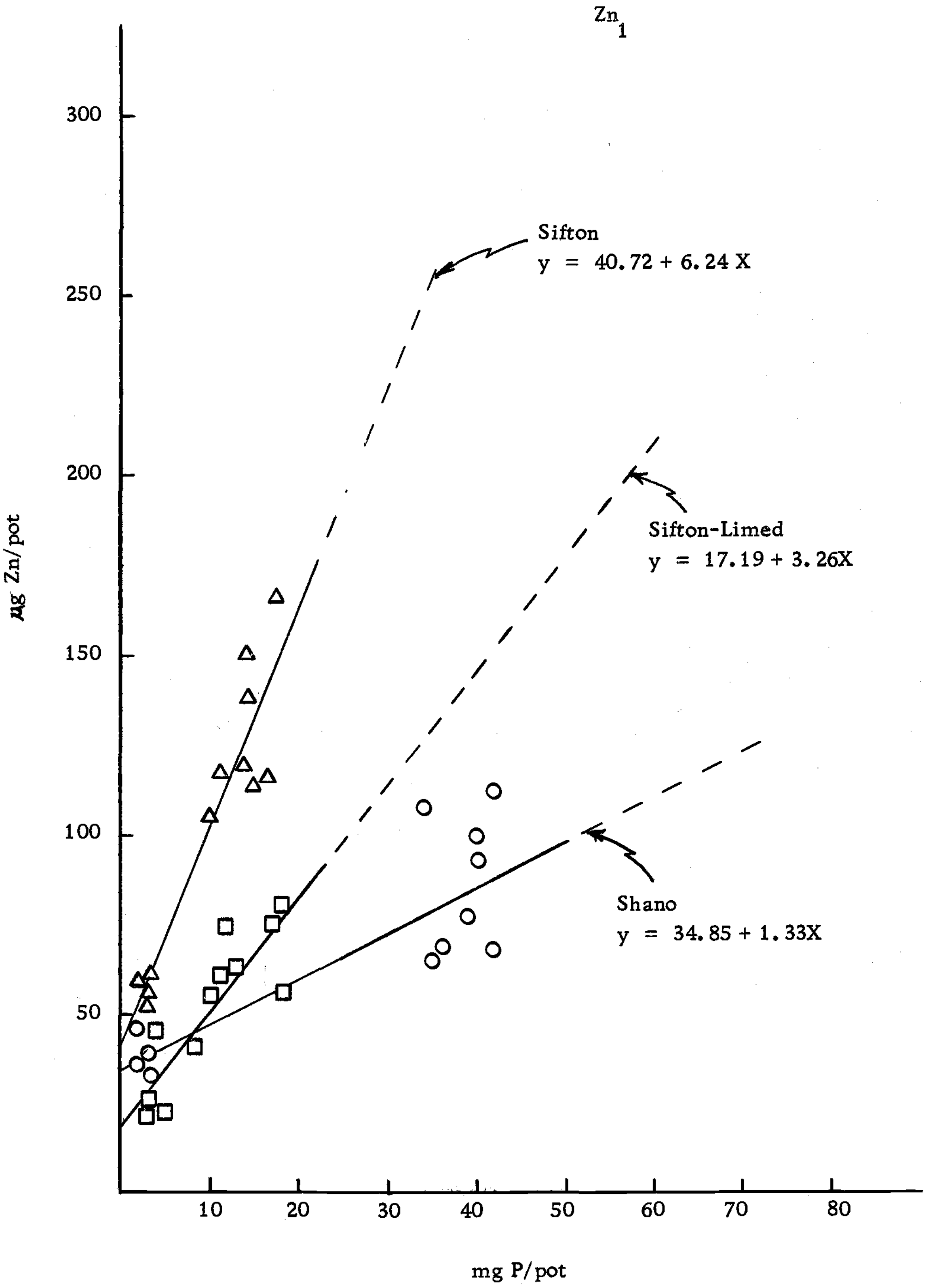

Figure 3. The relationship between phosphorus and zinc uptake by bush beans.

each soil used to grow bush beans in experiment I. Phosphorus uptake increased to a high level without any appreciable increase in zinc uptake on Shano soil which grew the most severely affected plants. On the acid Sifton soil, zinc uptake increased proportionately for every increment of phosphorus absorbed, but these plants were least affected by zinc deficiency symptoms. An intermediate response at the Zn_0 level was found in plants grown on the limed Sifton soil. Adding zinc increased zinc uptake on all soils but the relationship between soils was maintained (Figure 3). The largest increase in slope occurred on the Shano soil where there was a ten-fold increase in total zinc uptake. Plants grown on the Sifton soils showed an increase in zinc uptake but the increase was greater on the limed soil.

In the absence of applied zinc, both sweet corn and bush beans took up a large amount of phosphorus with only a small increase in total zinc uptake. This was changed markedly after zinc was applied which established a new balance between the uptake of these elements. This new balance showed that the uptake of one element was strongly related to the uptake of the other. Although the effects of growth responses have not been considered, the relationship between phosphorus and zinc further showed that phosphorus did not depress total zinc uptake because positive slopes were maintained in all three figures.

Yield and Zinc Uptake

Yield and zinc uptake regression lines for sweet corn are shown in Figure 4 and for bush beans in Figures 5 and 6. The Zn_0 regression line computed for the zinc deficient plants shows a greater increase in yield for each increment of zinc absorbed than for zinc sufficient plants. However, the maximum yield reached at the Zn_0 level is only one-fifth that reached at the Zn_1 level. Furthermore, the Zn_0 plants were abnormal in their development by having thick, stunted growth. Although zinc appeared to increase growth most effectively in the zinc deficient plants, normal growth and greater yields were obtained only with supplemental zinc applications.

Regression lines for yield and zinc uptake from each soil used to grow bush beans showed the same response as sweet corn. The greatest increase in yield per increment of zinc absorbed occurred in the zinc deficient plants; however, yields were limited and growth was abnormal in those same plants. Supplemental zinc application at the Zn_1 level increased yield and resulted in normal growth. Regression lines for Shano and limed Sifton soils were nearly identical and different from those developed for the acid Sifton soil because zinc was most available in the acid soil.

These plots show that the greatest plant yields on each soil occurred where zinc uptake was the greatest. The restricted yield of

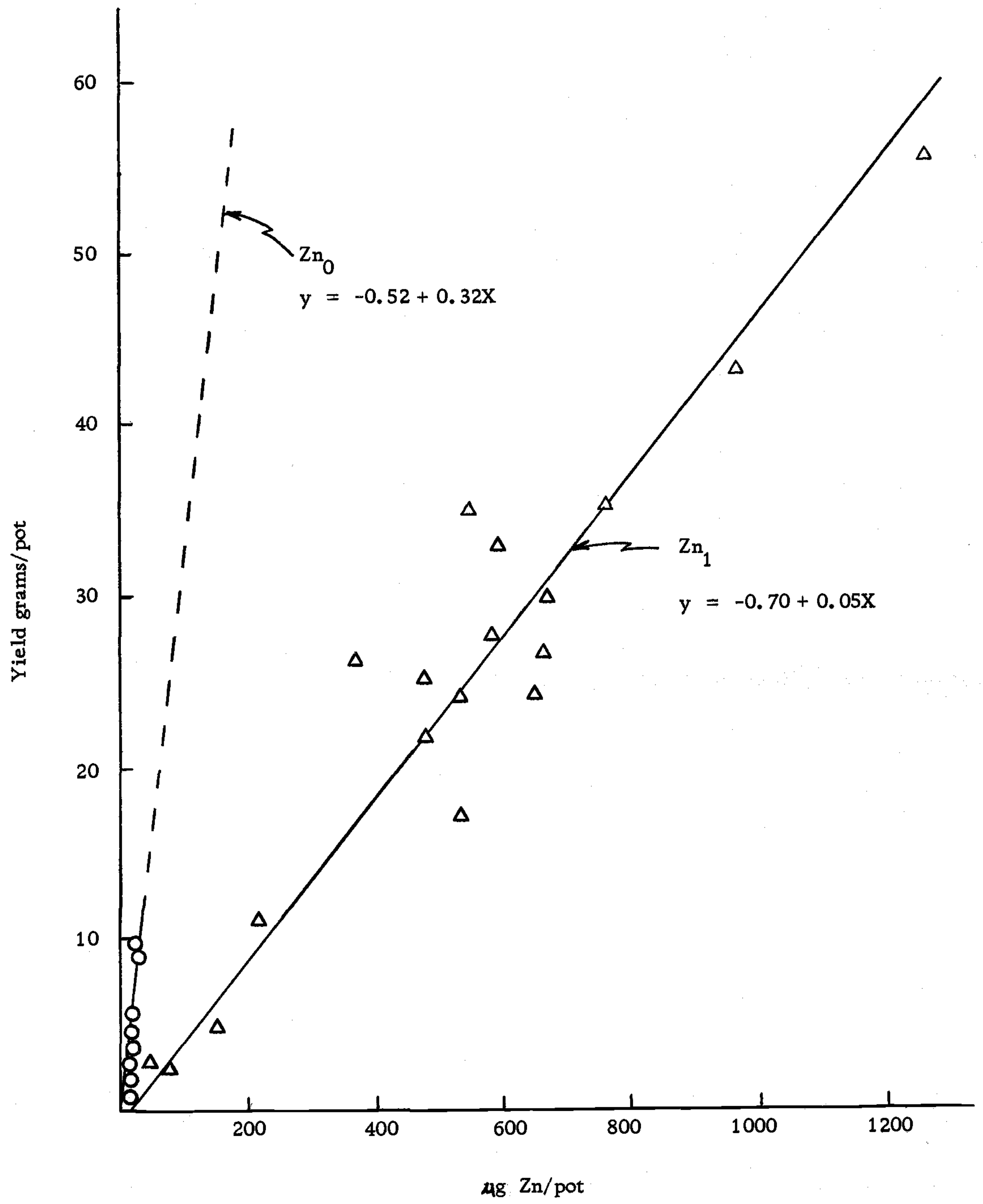

Figure 4. The relationship between yield and zinc uptake by sweet corn.

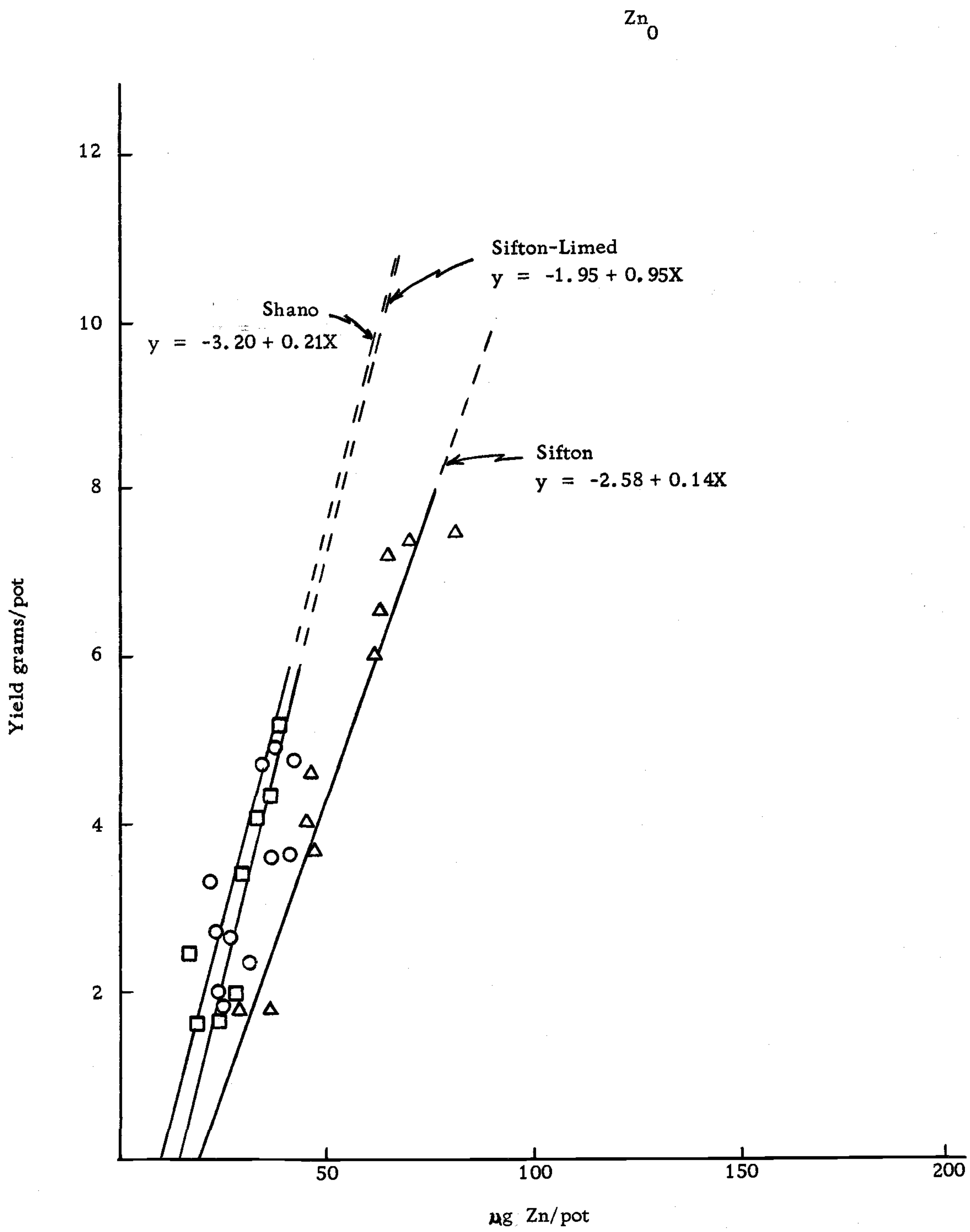

Figure 5. The relationship between yield and zinc uptake by bush beans.

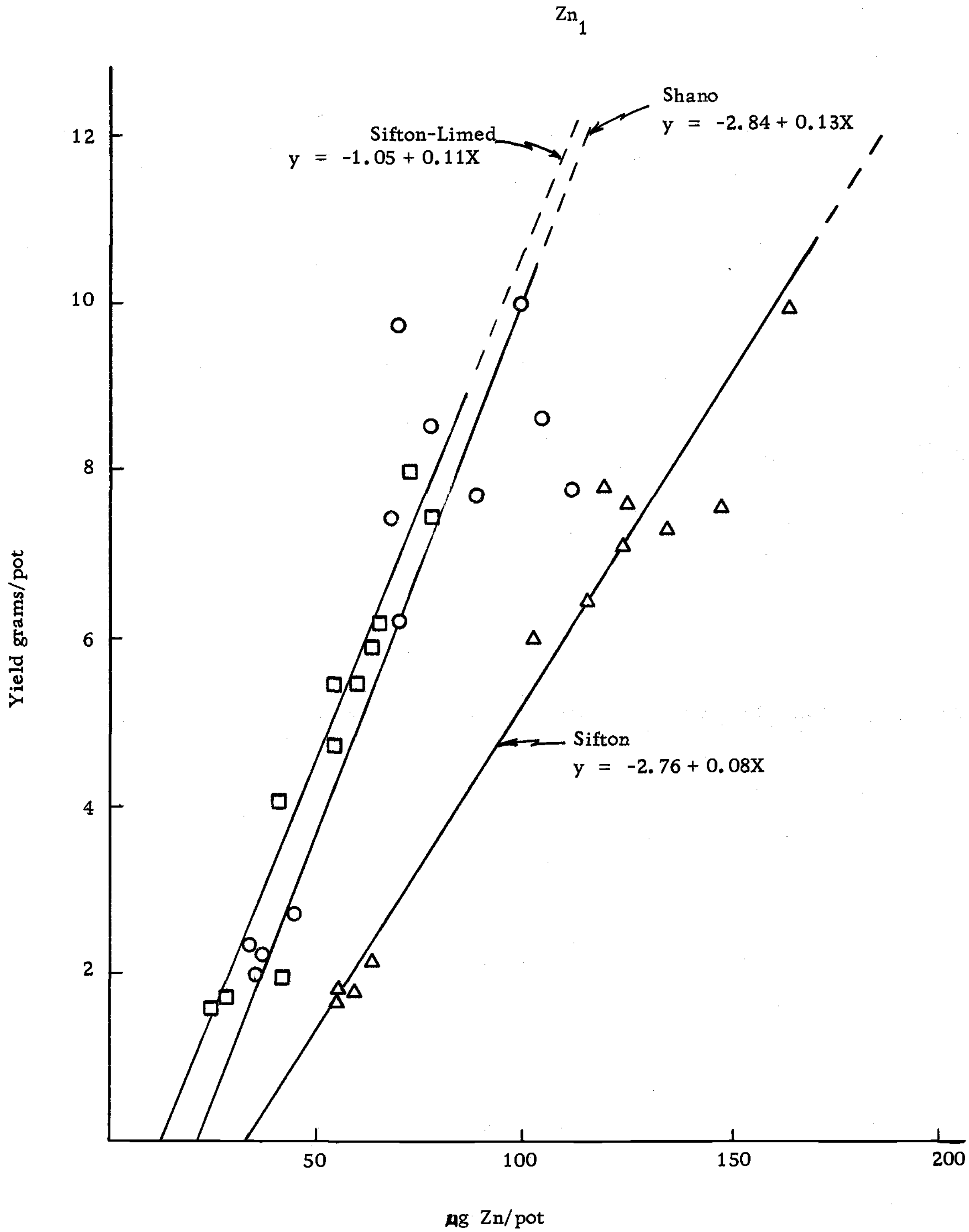

Figure 6. The relationship between yield and zinc uptake by bush beans.

sweet corn at the Zn_0 rate however, illustrates the dependence plants have on adequate zinc nutrition when grown on these soils. Plots showing bush bean yield and zinc uptake illustrate the same relationship although in Figures 5 and 6, there was not a marked difference between the minimum and maximum yield achieved on the acid Sifton soil. But it must be pointed out that total zinc uptake was greater at the Zn_0 rate on this soil than on either the limed or calcareous soils.

Yield and Phosphorus Uptake

Relationships between sweet corn yield and phosphorus uptake are shown in Figure 7 and Figures 8 and 9 show the same for bush beans. In sweet corn, yields were increased more per increment of phosphorus absorbed when zinc was applied. The same was found in bush beans; however, responses on the limed and acid Sifton soils were similar but different from that of the Shano soil. After zinc was applied, the growth response to phosphorus on the two Sifton soils became nearly alike. This indicated that the ability to supply phosphorus to plants was not altered appreciably in Sifton soil by liming whereas the ability to supply zinc was.

The response of yield to phosphorus and zinc uptake was exactly opposite. Where the smallest amount of total zinc at the Zn_0 rate was correlated with the greater yield per increment of zinc absorbed, the opposite was true for the total amount of phosphorus absorbed. A

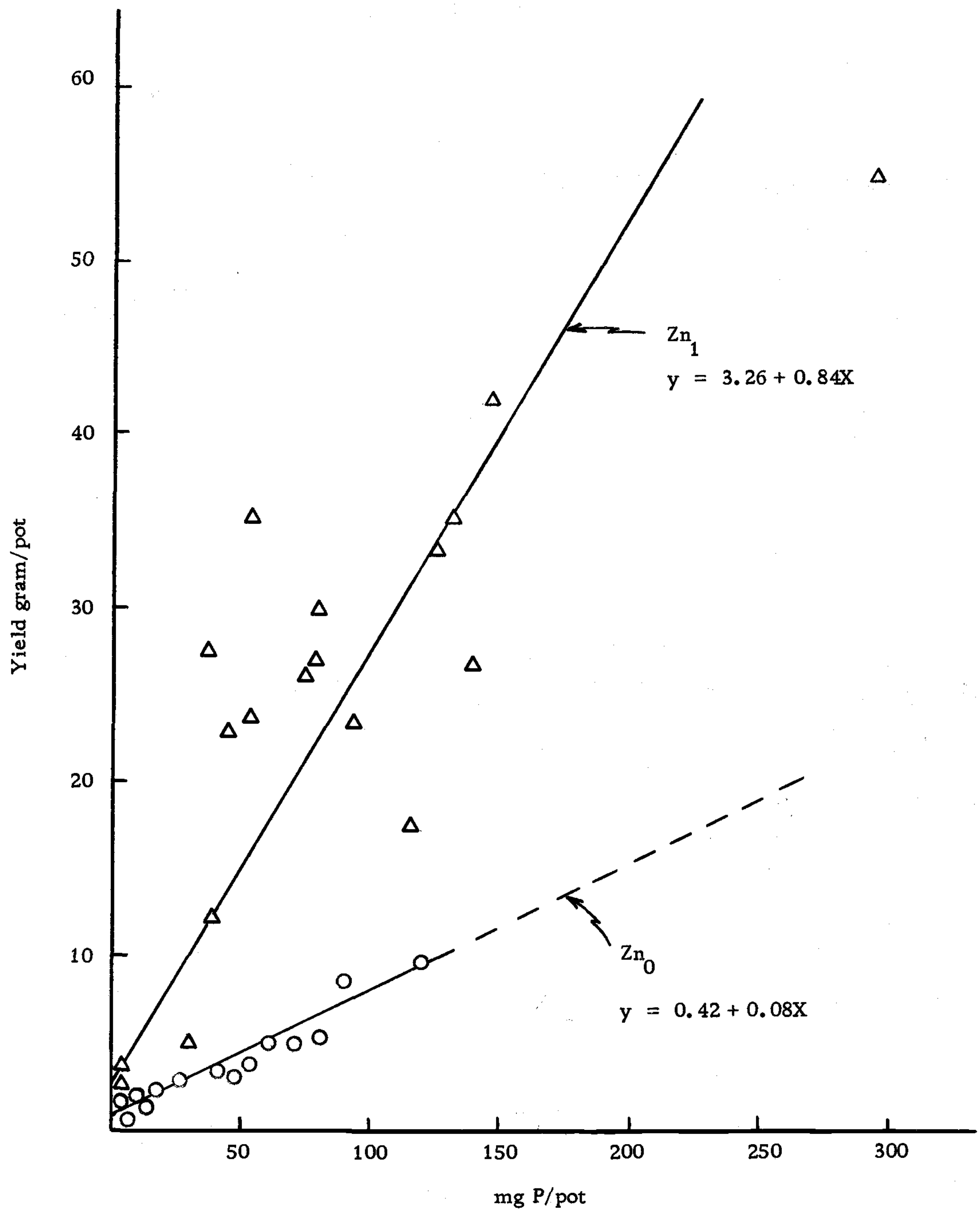

Figure 7. The relationship between yield and phosphorus uptake by sweet corn.

Zn$_0$

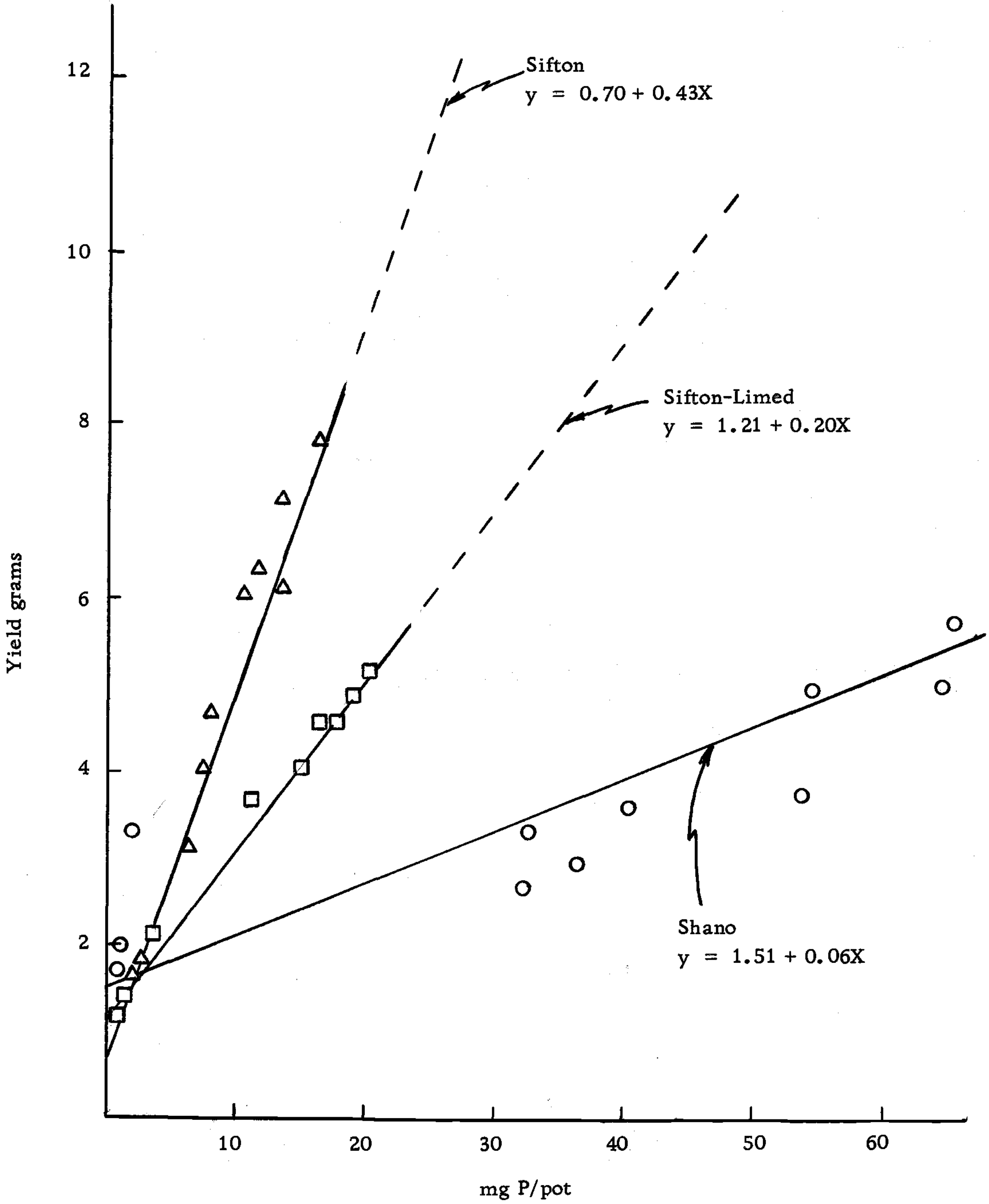

Figure 8. The relationship between yield and phosphorus uptake by bush beans.

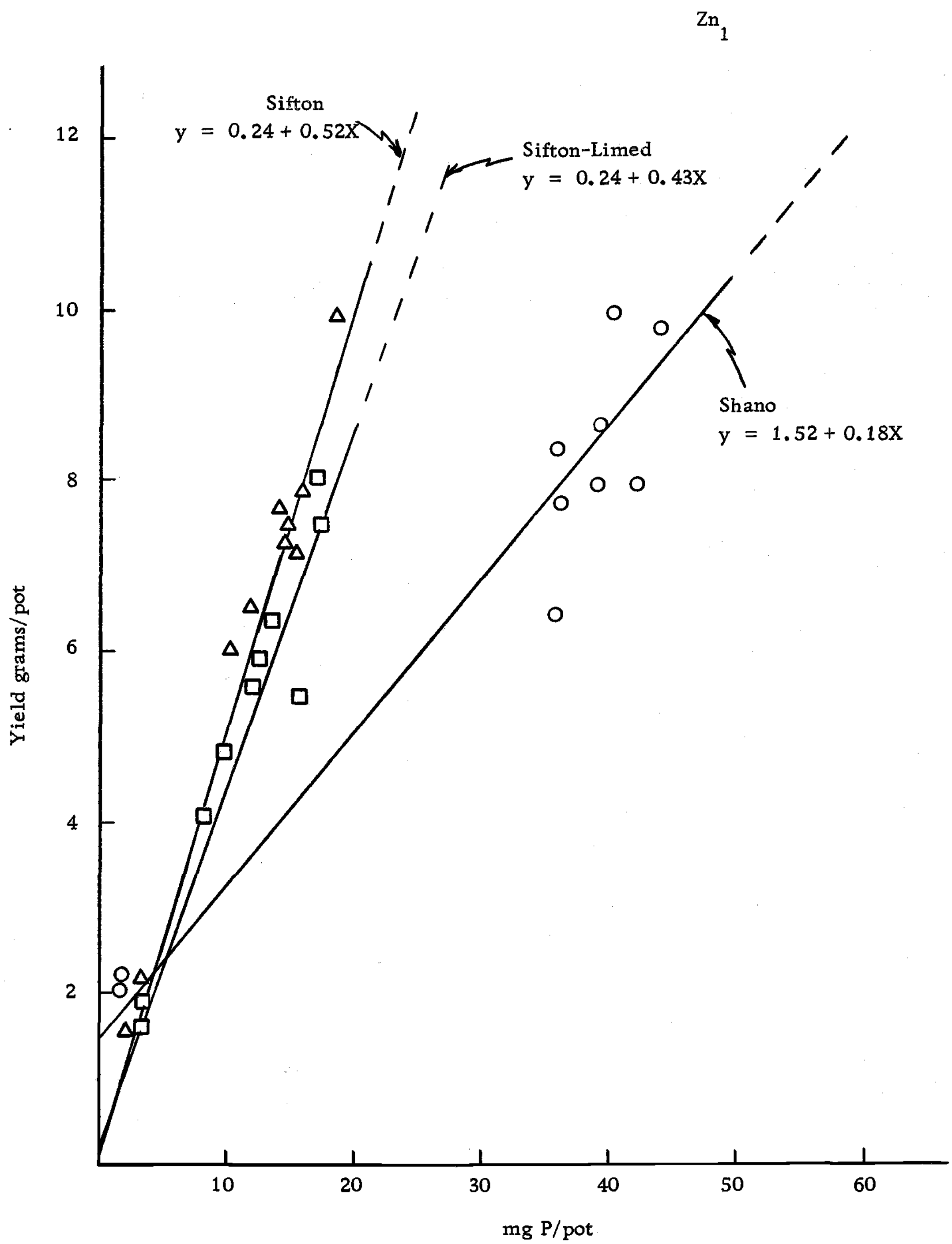

Figure 9. The relationship between yield and phosphorus uptake by bush beans.

greater increase in yield occurred for every increment of phosphorus absorbed at the Zn_1 rate because phosphorus was dependent on the level of zinc nutrition before it effectively increased plant growth. The outcome of the growth response to zinc and phosphorus applied together can be reflected in two ways. First, there is an obvious dilution effect on phosphorus. Secondly, less phosphorus may be required for normal plant growth and hence phosphorus uptake is depressed but growth is either maintained or increased.

SUMMARY AND CONCLUSIONS

Susceptibility to zinc deficiency in five plant species varied from highly susceptible to tolerant. Sweet corn and bush beans were severely affected by zinc deficiency symptoms; potatoes and tomatoes were moderately to slightly affected, and wheat was tolerant. Wherever zinc deficiencies appeared in susceptible species, the effects on nutrient composition were varied except for phosphorus responses. Phosphorus contents were always elevated in zinc deficient plants. Plots of total phosphorus uptake versus yield at both sufficient and deficient levels of zinc nutrition indicate that this element accumulates in zinc deficient plants without any appreciable growth response. In many instances, total phosphorus uptake was also greatest in zinc deficient plants except where the growth response to P x Zn interactions overrode the effect of zinc deficiency on increasing phosphorus uptake. Nevertheless, these results suggest that, given enough available phosphorus, zinc deficient plants will accumulate exceedingly high levels of this nutrient.

The relationship between phosphorus and zinc was not one of mutual antagonism as purported by several workers. Correlation regression studies presented in previous sections show that a positive relationship exists between phosphorus and zinc uptake. Applications of phosphatic fertilizers increased total zinc uptake in all instances although in many cases, zinc deficiency resulted after such applications. But it should be noted that these soils were both phosphorus and zinc deficient. If phosphorus is the nutrient most limiting plant growth, then zinc deficiency will not become apparent until the primary deficiency is corrected.

No critical level of zinc content could be determined in the various plants. In experiment I, equal zinc contents were measured in both normal and deficient sweet corn. The low zinc levels measured in tomatoes did not restrict total growth either. Plots of zinc content versus yield indicate an interesting relationship between total zinc uptake and yield. The greatest rate of yield per microgram zinc occurred where zinc was most limiting but only up to the point of maximum available zinc. When zinc was applied however, growth and total zinc uptake continued together.

Zinc deficiencies did not markedly affect iron and manganese composition in potatoes and tomatoes. Heavy metal contents were significantly increased at all degrees of zinc deficiency in sweet corn; but only in the most severely affected bush beans was the content of these micronutrients increased. However, only in sweet corn did the total uptake of these elements by zinc deficient plants exceed the total uptake in normal plants. Iron uptake was accentuated first and then followed by increased manganese uptake. Further experiments using more and higher levels of phosphorus application indicated a different response. A sharp decline in iron content occured at the P_4 rate while manganese content fell abruptly at the P_3 rate in zinc deficient plants. The only factor consistent with these reductions was a slight increase in zinc uptake which evidently had a great effect on iron and manganese balances. In addition this further pointed out that manganese responses were limited to the more severely zinc deficient plants.

This research has answered in part the objectives previously stated. First, susceptibility to zinc deficiency varies markedly among different plant species with regards to both symptoms and nutrient composition. Secondly, phosphorus per se does not induce zinc deficiency in these soils. The potential for zinc deficiency exists in these soils but is not expressed until the more limiting phosphorus situation is corrected. Finally, heavy metal balances are seriously altered by the level of zinc nutrition in certain susceptible species. Where zinc is most limiting, elevated iron content is accentuated followed by manganese. However, slight increases in total zinc uptake markedly reduce the content of both elements with manganese being depressed first.

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APPENDIX

Appendix Table 1. Calcium, magnesium and potassium content and uptake in sweet corn--experiment I.

	Sifton		Sifton-Limed		Shano	
Treatment	%	mg/pot	%	mg/pot	%	mg/pot
			Calcium			
P_0Zn_0	.78	24	.82	46	.86	33
P_0Zn_1	.78	26	.81	48	.83	30
P_1Zn_0	.42	54	.86	62	.76	53
P_1Zn_1	.45	55	.54	72	.34	69
P_2Zn_0	.41	62	.80	72	.66	68
P_2Zn_1	.36	58	.55	82	.30	66
			Magnesium			
P_0Zn_0	.37	20	.24	14	.56	22
P_0Zn_1	.24	8	.24	15	.54	22
P_1Zn_0	.20	26	.26	19	.75	41
P_1Zn_1	.20	24	.18	26	.23	56
P_2Zn_0	.16	24	.24	21	.53	55
P_2Zn_1	.15	25	.19	29	.26	56
			Potassium			
P_0Zn_0	5.2	161	4.3	299	4.2	161
P_0Zn_1	5.0	169	4.2	252	4.3	151
P_1Zn_0	2.2	280	3.6	264	3.9	272
P_1Zn_1	2.4	304	2.2	307	1.7	370
P_2Zn_0	2.0	305	3.7	325	3.1	323
P_2Zn_1	1.8	292	2.1	312	1.4	299

Appendix Table 2. Calcium, magnesium and potassium content and uptake in sweet corn--experiment III.

	Calcium		Magnesium		Potassium	
Treatment	%	mg/pot	%	mg/pot	%	mg/pot
P_0Zn_0	1.2	25	.5	10	5.4	439
P_1Zn_0	1.8	20	.7	8	5.0	290
P_2Zn_0	1.6	30	.6	10	5.4	398
P_3Zn_0	1.2	47	.5	19	6.2	1015
P_4Zn_0	.9	56	.4	28	5.2	1203
P_0Zn_1	1.4	34	.4	10	6.0	591
P_1Zn_1	.9	250	.4	98	2.2	2406
P_2Zn_1	.7	156	.4	88	2.9	2008
P_3Zn_1	.8	253	.4	106	2.4	2508
P_4Zn_1	.6	147	.4	151	2.2	2718

Appendix Table 3. Calcium, magnesium and potassium content and uptake in bush beans.

	Sifton		Sifton-Limed		Shano	
Treatment	%	mg/pot	%	mg/pot	%	mg/pot
			Calcium			
P_0Zn_0	3.0	51	3.8	66	3.3	79
P_0Zn_1	2.8	50	3.7	63	3.2	75
P_1Zn_0	2.6	138	3.8	132	3.5	106
P_1Zn_1	2.3	153	3.3	183	2.5	219
P_2Zn_0	2.5	154	3.5	164	3.0	145
P_2Zn_1	2.1	175	3.3	204	2.6	201
			Magnesium			
P_0Zn_0	.31	5	.19	3	.52	12
P_0Zn_1	.28	5	.19	3	.47	11
P_1Zn_0	.23	12	.20	7	.83	25
P_1Zn_1	.20	13	.19	10	.59	34
P_2Zn_0	.25	15	.19	9	.73	52
P_2Zn_1	.20	16	.19	12	.69	53
			Potassium			
P_0Zn_0	2.9	49	3.1	53	2.8	68
P_0Zn_1	2.9	54	3.1	53	2.5	57
P_1Zn_0	2.5	135	3.5	118	3.3	100
P_1Zn_1	2.3	156	2.8	156	1.8	154
P_2Zn_0	2.4	146	3.0	139	2.8	132
P_2Zn_1	2.3	186	2.7	162	2.1	163

Appendix Table 4. Calcium, magnesium and potassium content and uptake in wheat.

Treatment	Sifton %	Sifton mg/pot	Sifton-Limed %	Sifton-Limed mg/pot	Shano %	Shano mg/pot
			Calcium			
P_0Zn_0	.53	17	.61	25	.50	14
P_0Zn_1	.60	17	.66	30	.48	13
P_1Zn_0	.62	32	.63	41	.46	28
P_1Zn_1	.61	32	.64	40	.43	32
P_2Zn_0	.59	31	.60	41	.42	30
P_2Zn_1	.59	32	.62	42	.39	30
			Magnesium			
P_0Zn_0	.18	6	.18	7	.23	6
P_0Zn_1	.20	6	.18	8	.23	6
P_1Zn_0	.26	14	.19	12	.28	17
P_1Zn_1	.24	12	.18	11	.24	18
P_2Zn_0	.24	13	.18	13	.25	18
P_2Zn_1	.24	13	.18	12	.22	17
			Potassium			
P_0Zn_0	4.3	136	4.8	195	4.2	116
P_0Zn_1	4.4	124	4.9	215	4.2	113
P_1Zn_0	3.6	185	3.8	246	3.1	189
P_1Zn_1	3.5	178	3.6	229	2.9	218
P_2Zn_0	3.6	192	3.2	220	2.8	197
P_2Zn_1	3.6	192	3.5	234	2.6	197

Appendix Table 5. Calcium, magnesium and potassium content and uptake in potatoes.

	Sifton		Sifton-Limed		Shano	
Treatment	%	mg/pot	%	mg/pot	%	mg/pot
			Calcium			
P_0Zn_0	1.4	57	1.7	75	1.5	56
P_0Zn_1	1.4	55	1.7	51	1.5	60
P_1Zn_0	1.4	94	1.9	103	2.0	80
P_1Zn_1	1.5	90	2.0	101	1.6	98
P_2Zn_0	1.4	97	2.0	107	1.9	97
P_2Zn_1	1.3	98	2.0	92	1.5	106
			Magnesium			
P_0Zn_0	.48	19	.32	13	.84	32
P_0Zn_1	.50	19	.32	10	.85	33
P_1Zn_0	.35	24	.30	16	1.20	48
P_1Zn_1	.42	24	.31	16	.94	59
P_2Zn_0	.34	24	.31	17	.97	49
P_2Zn_1	.33	24	.31	14	.83	59
			Potassium			
P_0Zn_0	6.0	241	6.3	268	5.6	197
P_0Zn_1	6.2	234	7.2	208	5.1	198
P_1Zn_0	5.0	334	6.0	322	5.0	202
P_1Zn_1	5.9	345	6.0	302	4.3	263
P_2Zn_0	5.0	360	5.6	300	4.6	230
P_2Zn_1	5.0	362	5.9	273	3.9	282

Appendix Table 6. Calcium, magnesium and potassium content and uptake in tomatoes.

	Sifton		Sifton-Limed		Shano	
Treatment	%	mg/pot	%	mg/pot	%	mg/pot
			Calcium			
P_0Zn_0	3.5	17	4.0	72	3.4	271
P_0Zn_1	3.3	32	4.1	77	2.8	350
P_1Zn_0	2.2	256	3.0	542	2.2	449
P_1Zn_1	2.2	286	2.6	435	2.0	424
P_2Zn_0	1.9	204	2.8	476	2.0	382
P_2Zn_1	2.0	283	2.6	459	2.0	381
			Magnesium			
P_0Zn_0	1.0	5	.4	8	1.2	93
P_0Zn_1	1.0	3	.4	8	.9	109
P_1Zn_0	.4	52	.2	39	.6	129
P_1Zn_1	.4	51	.2	35	.6	120
P_2Zn_0	.4	53	.2	36	.6	121
P_2Zn_1	.4	60	.2	38	.6	117
			Potassium			
P_0Zn_0	3.2	16	4.2	76	3.6	280
P_0Zn_1	3.4	8	4.3	80	2.7	345
P_1Zn_0	2.6	339	2.0	362	2.1	430
P_1Zn_1	2.6	338	2.2	358	2.0	424
P_2Zn_0	2.5	348	2.1	358	2.3	438
P_2Zn_1	2.5	350	2.0	351	2.1	406

Appendix Table 7. Multiple comparison correlation coefficients in sweet corn (experiment I, Sifton soil).

Factor	Zinc level	% P	mg P/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Yield	Zn_0	-.286	.970	-.922	.863	.791	.951	-.932	.947
	Zn_1	.151	.985	-.797	.826	-.123	.980	-.934	.976
% P	Zn_0		-.055	.293	-.071	-.218	-.262	.100	-.358
	Zn_1		.284	-.208	.073	.296	.186	-.116	.198
mg P/pot	Zn_0			-.882	.884	.780	-.926	-.937	.904
	Zn_1			-.787	.813	-.092	.969	-.899	.980
ppm Zn	Zn_0				-.645	-.791	-.903	.898	-.877
	Zn_1				-.432	.407	-.745	.784	-.769
µg Zn/pot	Zn_0					.610	.772	-.814	.819
	Zn_1					-.002	.825	-.842	.791
ppm Fe	Zn_0						.927	-.650	.845
	Zn_1						.044	.198	-.115
µg Fe/pot	Zn_0							-.840	.942
	Zn_1							.898	.954
ppm Mn	Zn_0								-.788
	Zn_1								-.852

Appendix Table 8. Multiple comparison correlation coefficients in sweet corn (experiment I, Sifton-Limed soil).

Factor	Zinc level	% P	mg P/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Yield	Zn_0	.411	.961	-.763	.296	.525	.744	.440	.727
	Zn_1	-.856	.947	-.764	.542	.633	.916	.050	.656
% P	Zn_0		.641	-.307	-.061	.362	.462	-.195	.077
	Zn_1		-.656	.926	-.168	-.624	-.819	-.275	-.345
mg P/pot	Zn_0			-.736	.222	.541	.760	.308	.632
	Zn_1			-.533	.747	.514	.830	-.117	.757
ppm Zn	Zn_0				.340	-.635	-.733	-.442	-.623
	Zn_1				.111	-.771	-.829	-.499	-.120
µg Zn/pot	Zn_0					-.137	-.366	.044	.121
	Zn_1					-.059	.310	-.535	.833
ppm Fe	Zn_0						.940	.588	.646
	Zn_1						.883	.653	.132
µg Fe/pot	Zn_0							.597	.759
	Zn_1							.332	.486
ppm Mn	Zn_0								.925
	Zn_1								-.568

Appendix Table 9. Multiple comparison correlation coefficients in sweet corn (experiment I, Shano soil).

Factor	Zinc level	% P	mg P / pot	ppm Zn	µg Zn / pot	ppm Fe	µg Fe / pot	ppm Mn	µg Mn / pot
Yield	Zn_0	.687	.936	-.799	.618	.532	.894	.504	.870
	Zn_1	.961	.400	-.969	.894	-.343	.966	-.815	.918
% P	Zn_0		.886	-.775	.273	.943	.907	.856	.852
	Zn_1		.363	-.945	.889	-.424	.898	-.734	.932
mg P/pot	Zn_0			-.816	.566	.747	.968	.685	.924
	Zn_1			-.327	.467	.153	.505	-.386	.309
ppm Zn	Zn_0				-.065	-.696	-.844	-.699	-.836
	Zn_1				-.793	.344	-.934	.778	-.894
µg Zn/pot	Zn_0					.145	.485	.103	.454
	Zn_1					-.266	.874	-.643	.912
ppm Fe	Zn_0						.847	.947	.815
	Zn_1						-.140	.152	-.268
µg Fe/pot	Zn_0							.814	.975
	Zn_1							-.760	.917
ppm Mn	Zn_0								.852
	Zn_1								-.560

Appendix Table 10. Multiple comparison correlation coefficients in bush beans--Sifton soil.

Factor	Zinc level	% P	mg P/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Yield	Zn_0	.826	.984	-.893	.968	-.417	.949	-.421	.962
	Zn_1	.576	.976	-.923	.968	-.147	.991	-.378	.972
% P	Zn_0		.890	-.762	.807	-.414	.835	-.025	.912
	Zn_1		.733	-.637	.510	-.292	.551	.049	.690
mg P/pot	Zn_0			-.876	.945	-.352	.970	-.289	.991
	Zn_1			-.932	.932	-.187	.964	-.290	.986
ppm Zn	Zn_0				-.785	.501	-.834	.368	-.890
	Zn_1				-.831	.336	-.898	.358	-.932
µg Zn/pot	Zn_0					-.426	.904	-.444	.909
	Zn_1					-.147	.951	-.426	.913
ppm Fe	Zn_0						-.157	.596	-.316
	Zn_1						-.037	.391	-.161
µg Fe/pot	Zn_0							-.224	.966
	Zn_1							-.358	.962
ppm Mn	Zn_0								-.181
	Zn_1								-.197

Appendix Table 11. Multiple comparison correlation coefficients in bush beans--Sifton-limed soil.

Factor	Zinc level	% P	mg P/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Yield	Zn_0	.767	.899	-.616	.792	-.058	.950	.267	.746
	Zn_1	.361	.932	-.695	.942	.219	.982	.552	.731
% P	Zn_0		.954	-.751	.320	.230	.859	-.155	.244
	Zn_1		.659	-.212	.362	.149	.386	.435	.383
mg P/pot	Zn_0			-.685	.540	.145	.947	-.009	.433
	Zn_1			-.669	.868	.272	.934	.636	.754
ppm Zn	Zn_0				-.050	.192	-.586	.310	-.169
	Zn_1				-.448	-.405	-.712	-.351	-.474
µg Zn/pot	Zn_0					-.031	.723	.637	.910
	Zn_1					.120	.913	.548	.712
ppm Fe	Zn_0						.220	.188	-.127
	Zn_1						.377	.334	.330
µg Fe/pot	Zn_0							.219	.627
	Zn_1							.617	.779
ppm Mn	Zn_0								.779
	Zn_1								.963

Appendix Table 12. Multiple comparison correlation coefficients in bush beans--Shano soil.

Factor	Zinc level	% P	mg P/pot	ppm Zn	μg Zn/pot	ppm Fe	μg Fe/pot	ppm Mn	μg Mn/pot
Yield	Zn_0	.565	.842	-.636	.705	-.198	.730	.641	.929
	Zn_1	.836	.958	-.831	.828	.129	.944	.289	.940
% P	Zn_0		.898	-.837	.023	.026	.580	.843	.702
	Zn_1		.956	-.717	.781	.183	.809	.545	.893
mg P/pot	Zn_0			-.824	.327	-.011	.778	.893	.935
	Zn_1			-.805	.836	.153	.911	.451	.962
ppm Zn	Zn_0				.052	.240	-.441	-.642	-.674
	Zn_1				-.419	-.235	-.816	-.288	-.790
μg Zn/pot	Zn_0					-.130	.472	.202	.535
	Zn_1					.010	.752	.359	.823
ppm Fe	Zn_0						.504	.313	.018
	Zn_1						.433	-.014	.110
μg Fe/pot	Zn_0							.823	.849
	Zn_1							.259	.890
ppm Mn	Zn_0								.860
	Zn_1								.585

Appendix Table 13. Multiple comparison correlation coefficients in sweet corn (experiment III).

Factor	Zinc level	% P	mg P/pot	ppm Zn	µg Zn/pot	ppm Fe	µg Fe/pot	ppm Mn	µg Mn/pot
Yield	Zn_0	.310	.927	.109	.499	-.187	.816	-.468	.706
	Zn_1	.356	.841	-.387	.959	-.314	.929	-.162	.950
% P	Zn_0		.623	.439	.466	.290	.424	.329	.538
	Zn_1		.673	.022	.406	-.325	.248	.552	.515
mg P/pot	Zn_0			.287	.618	-.017	.854	-.283	.737
	Zn_1			-.212	.844	-.364	.693	.224	.924
ppm Zn	Zn_0				.892	-.315	.092	-.052	.266
	Zn_1				-.189	-.301	-.515	.650	-.380
µg Zn/pot	Zn_0					-.131	.400	-.259	.483
	Zn_1					-.426	.822	-.181	.894
ppm Fe	Zn_0						.348	.500	-.158
	Zn_1						-.566	.266	-.278
µg Fe/pot	Zn_0							-.286	.438
	Zn_1							-.133	.882
ppm Mn	Zn_0								.026
	Zn_1								.129

Appendix Table 14. Correlation coefficients and regression equations for comparisons among yield, phosphorus uptake and zinc uptake in sweet corn and bush beans.

				P uptake vs Zn uptake			Yield vs Zn uptake			Yield vs P uptake		
				y = BX + A			y = BX + A			y = BX + A		
Plant species	Exp. ident.	Soil	Zinc level	Slope	Intercept	r.	Slope	Intercept	r.	Slope	Intercept	r.
Sweet corn	I	Sifton	0	5.91	30.53	.88	0.20	-6.32	.86	1.17	-0.42	.97
			1	7.18	67.85	.80	0.15	-9.84	.81	1.10	-0.03	.98
		Sifton-Limed	0	0.86	58.76	.20	0.42	-22.0	.27	0.51	1.08	.96
			1	7.95	5.44	.74	0.21	-12.71	.54	1.29	-6.17	.95
		Shano	0	0.36	56.93	.57	0.36	-17.08	.62	0.15	2.66	.94
			1	1.96	76.60	.90	0.19	-11.82	.89	0.37	2.46	.99
	III	Shano	0	0.21	3.53	.88	0.32	- .52	.89	0.08	0.42	.93
			1	3.82	188.86	.84	0.05	- .70	.96	0.24	3.26	.84
Bush beans	I	Sifton	0	2.96	24.71	.94	0.14	- 2.58	.97	0.43	0.70	.98
			1	6.24	40.72	.93	0.08	- 2.76	.96	0.52	0.24	.98
		Sifton-Limed	0	1.02	17.07	.86	0.19	- 1.95	.86	0.20	1.21	.99
			1	3.26	17.19	.89	0.11	- 1.05	.97	0.43	0.24	.93
		Shano	0	0.11	28.35	.33	0.21	- 3.20	.70	0.06	1.51	.84
			1	1.33	34.85	.84	0.13	- 2.84	.83	0.18	1.52	.96