ZINC LEVELS IN SOILS AS RELATED TO ZINC UPTAKE AND YIELD OF PHASEOLUS VULGARIS

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This is to certify that the

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ABSTRACT

ZINC LEVELS IN SOILS AS RELATED TO ZINC UPTAKE AND YIELD OF *PHASEOLUS VULGARIS*

by James Ray Melton

Experiments were conducted to survey the zinc status of various Michigan soils, to study the effect of zinc fertilization on yield and zinc uptake by pea beans, to correlate various zinc soil tests with yield by pea beans, and to study the effect of lime applications on yield and zinc uptake by pea beans. Field, greenhouse, and laboratory studies were initiated in order to fulfill these objectives.

Measurements of total (12.0 *N* hydrochloric acid) and extractable (0.1 *N* hydrochloric acid) zinc did not appear to separate those soils on which yield responses to zinc had been obtained from those on which no responses had been obtained.

On all soils, highest yields were obtained when the zinc concentration in plants was between 25 and 34 parts per million. Yields were depressed by zinc toxicity when plant zinc concentration was greater than 50 parts per million.

On the basis of both greenhouse and field studies, a 0.1 *N* hydrochloric acid extraction procedure was found to

be a good soil test for plant available zinc in Michigan. It should be desirable, however, to initiate further field studies to further evaluate the 0.01 M disodium ethylenediaminetetraacetate + 1.0 M ammonium carbonate extractant as a zinc soil test.

Generally, yields were increased when zinc fertilizers were applied after liming soils which tested pH 6.3 or below. It is quite probable that zinc deficiency could be induced by liming certain Michigan soils.

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By

James Ray Melton

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To My

Wife

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INTRODUCTION

The essentiality of zinc (Zn) for growth of the fungus *Aspergillis niger* was first shown by Raulin (1869), and later confirmed by Bertrand and Javillier (1911). Brechley (1914) described Zn deficiency in higher plants, but Zn toxicity was considered more important at that time.

In the higher plants, Mazé (1915) reported that Zn was essential for the growth of corn. The need for Zn in higher plants was not universally accepted, however, until Sommer and Lipmann (1926) demonstrated the essentiality of Zn for sunflower, broad beans, kidney beans, and barley. Bonner and Varner (1965) recently reported that Zn is also essential for many species of algae and for many nonphotosynthetic organisms.

Zinc deficiency in *Phaseolus vulgaris* var. Sanilac (pea beans) has been identified in Michigan (Ellis et al., 1964a). Many pea beans (approximately 1/2 million acres) are grown on soils which test above pH 7.0 in the lake-plain area of Eastern Central Michigan. Heavy rates of phosphorus (P) applied to preceding sugar beet crops are believed to accentuate Zn deficiency symptoms.

Zinc fertilizers that have been effective for pea beans include the sulfate, chloride, carbonate, nitrate, oxide, oxysulfate, and phosphate salts of Zn, and Zn-containing materials such as blast furnace slag, stripping acid residues, and frits. Polyaminocarboxylic acid chelates and organic extracts such as polyflavanoids have been successfully used as organic carriers of Zn. Zinc sulfate was found to be one of the most effective and economical sources of Zn in Michigan (Brinkerhoff et al., 1966 and 1967; Judy et al., 1965).

Michigan experiments concerned with the effectiveness of various kinds of Zn fertilizers for plant growth, the depressing effect of high P levels on plant uptake of Zn, and the increase in uptake of Zn by plants as temperature was increased have previously been reported (Judy, 1965; Brinkerhoff et al., 1966 and 1967; and Ellis et al., 1964). However, the relation between the amounts of Zn extracted from Michigan soils by various methods and the yield and Zn uptake by plants have not been adequately established. Consequently, the investigations reported herein were conducted to:

1. Survey the Zn status of various Michigan soils.
2. Study the effect of Zn fertilization on yield and Zn uptake by pea beans.
3. Correlate various Zn soil tests with yield of pea beans.
4. Study the effect of lime applications on yield and Zn uptake by pea beans.

REVIEW OF LITERATURE

Most soils contain micronutrients in sufficient quantities to sustain normal plant growth. Deficiencies occur on some soils, however, because of crop removal, leaching, chemical fixation, erosion, or an initial lack of primary minerals which contain these nutrients.

Role of Zinc in Plants

A concentration of approximately 20 ppm Zn in plant tops appears to be optimal for normal plant growth and metabolism (Bonner and Varner, 1965). Zinc deficiency symptoms usually develop when Zn content is below 15 to 20 ppm (Hiatt and Massey, 1958; Nelson, 1956; Viets et al., 1954). Rosetting of fruit trees, mottle leaf of citrus, little leaf of beans (Stiles, 1946), white bud of corn (Barnette et al., 1936, Stiles, 1946), and fern leaf of potato (Boawn and Leggett, 1963) are typical of the types of Zn deficiency symptoms that have been reported.

The primary role of Zn in the plant is as a catalyst (Schutte, 1964). Zinc is located in the prosthetic group of carbonic anhydrase (Day and Franklin, 1946) and is associated with aldolase activity in subterranean clover (Quinlan-Watson, 1953). The activity of NADase decreases in fungi as Zn concentration is increased (Nason and Erans, 1951). Hagi and Vallee (1960) suggested that Zn might act as a bridge between protein and pyridine nucleotide in yeast alcohol dehydrogenase.

Zinc may be involved in chlorophyll synthesis and rate of transpiration (Schutte, 1964). Chester and Robinson (1951) postulated that Zn may be involved in the activity of the auxin β-indole acetic acid (IAA). Tsui (1948) and Nason et al. (1951) also believed that Zn was related to auxin synthesis as deficient plants were low in the IAA precursors tryptophan and tryptophan synthetase.

Zinc is essential for seed production in many plants, and is a component of glycylglycine dipeptidase and dihydropeptidase, enzymes involved in protein metabolism (Seatz and Jurinak, 1957). Smaller quantities of free amino N, amide N, and inorganic P compounds were found in plants which contained adequate Zn (Possingham, 1954; Reed, 1946).

Several morphological and physiological changes were found in plants when the level of metabolically active Zn was inadequate (Seatz and Jurinak, 1957). Among these changes were: 1) palisade cells of leaves were abnormally large and were transversely rather than columnarly divided, 2) number of chloroplasts were reduced, 3) starch grains were absent, 4) oil droplets formed in chloroplasts, and 5) phenolic materials and calcium oxalate crystals accumulated in leaves. Visual deficiency symptoms in plant tops are interveinal chlorosis, necrosis of lower leaves, and shortening of internodes. Deficiency of zinc in roots was indicated by abnormal shape and large amounts of fats and tannins but no starch (Seatz and Jurinak, 1957).

Some examples of plant response to Zn were: 1) the top:root ratio was greater in plants adequately supplied with Zn (Millikan, 1963), 2) zinc was not translocated in or from older tissue (Shaw et al., 1954), 3) upper leaves of corn contained more Zn in both normal and deficient plants than in lower leaves (Viets et al., 1953), 4) zinc was located mostly in and around the primary veins in the corn leaf blade (Sayre, 1952), 5) meristamatic tissue of pineapple contained the largest concentrations of Zn (Lyman and Dean, 1942), 6) zinc requirement of vegetative parts of peas and beans was much lower than during seed production (Reed, 1942), and 7) an equivalency of Zn and other bases was found throughout snap bean plants near early bloom stage (Seatz et al., 1956).

Zinc In Soil

In most soils, more Zn is found in the A_1 horizon than in any of the lower horizons. Total content of Zn varies greatly between soil groups (Mitchell, 1964). The total Zn content of soils varies from 10 to 300 ppm, and only part of this Zn is available for plant growth (Swaine, 1955). In the U. S., Zn deficiencies have been reported in 31 states

(Berger, 1962). Soils with adequate available Zn contained more than 10 ppm available Zn, and deficient soils contained less than 2 ppm Zn available for plant growth as determined by the *Aspergillus niger* extraction (Bould et al., 1963).

Zinc is commonly found in the primary minerals biotite, hornblende, magnetite, and the ferromagnesian group (Bould, 1963). Smithsonite, willemite, Zn blende, and calamine, which are primary Zn-containing minerals, occur in the soil in minute quantities. More available Zn is found in acid soils derived from granite than in calcareous soils derived from limestone (Thorne et al., 1942).

According to Bould (1963), Zn is adsorbed as a divalent cation on clays or complexed by organic matter after release from the minerals. Elgabaly (1950) stated that Zn may enter the inner layer of the electrical double layer of a micelle where it cannot be exchanged for neutral inorganic salts such as ammonium acetate. Elgabaly and Jenny (1943) postulated that Zn clay has a mosaic surface capable of independent cation and anion exchange, and that non-replaceable Zn is inside empty oxygen and hydroxyl octahedra of the brucite layer of the montmorillonite clay crystal. However, Nelson and Melsted (1955) stated that Zn was not fixed on cation exchange positions and was not adsorbed as a complex ion in the electrical double layer in Illinois soils.

Bingham et al. (1964) postulated that Zn is precipitated as $Zn(OH)_2$ in the clay systems, and Bernheim and Quintin

(1950) reported that the bi-zincate ion, $ZnO_2^{=}$, became more prevalent as the base concentration increased. DeMumbrum and Jackson (1956) found that Zn reacted with the octahedral hydroxide in layer silicates but did not react with kaolinite. Jurinak and Thorne (1955) proposed that both chemical and strong clay absorption complexes and Zn hydroxide were formed in soils.

Carboxyl and phenolic groups in soil organic matter have been shown to be involved in chelation (Broadbent et al., 1952; Himes et al., 1963). According to Himes and Barber (1957), removal of organic matter from soil by oxidation with hydrogen peroxide destroyed Zn-chelating ability of these carboxyl and phenolic groups. Zinc saturation of peat fractions resulted in numerous shifts in the double bond region of the infrared spectrum, indicating a chelation with N=O and C=O groups (DeMumbrum and Jackson, 1956). Randhawa and Broadbent (1965) found that humic acid complexed very little Zn at pH values less than 3.6, but complexing ability increased rapidly with an increasing hydroxyl ion concentration up to pH 8.5. Miller and Ohlrogge (1958) discovered that water-soluble chelating agents in organic materials complexed more Zn at higher pH values. Ark (1936) reported that steam sterilization of Zn deficient soils released sufficient Zn to correct the deficiency, thus implying fixation by microbial action. Mortensen (1963) concluded that surface adsorption, chelation, ion exchange, and peptidization were involved in complexing of Zn by soil organic matter.

According to Hibbard (1940a), removal of organic matter from soils by ashing or H_2O_2 treatment did not affect the solubility of soil Zn. Hodgson et al. (1966) found that organic matter complexed 28 to 99 percent of the Zn in the soil solution; however, they found only a small proportion of total Zn in the soil complexed by soil organic matter. Geering and Hodgson (1966) showed that addition of citrate to a carbonate-saturated water system drastically increased Zn movement.

Factors Affecting Zinc Availability

Soil Zn may be classified as water-soluble, replaceable, and nonreplaceable (Jones et al. 1936). In addition to organic matter and clay, such factors as replaceable bases, carbonates, phosphates, type of nutrient on clay, and soil temperature influence Zn distribution within these three fractions.

Phosphorus

Bingham et al. (1958 and 1960) related soil type to P-induced Zn deficiency; high levels of residual or fertilizer P were required before yields were reduced on some soils. A reduction in both P and Zn uptake was found in kidney beans, corn, and tomatoes when P was applied to limed soils (Burleson et al., 1961; Ward et al., 1963). This reduction in uptake seldom occurred on unlimed soils. Millikan (1963) proposed that depression in plant growth was due to a high P concentration rather than a low Zn concentration. Boawn and Leggett (1963 and 1964) suggested that Zn deficiencies were more closely associated with high P:Zn ratios than with low concentrations of soil Zn. The critical P:Zn ratio was 400:1 for Russet Burbank potatoes (Boawn et al., 1964) and 300:1 for corn (Watanabe et al., 1965). Some researchers (Ward et al., 1963; Burleson et al., 1961; Stukenholtz et al., 1966) suggested a P-Zn antagonism within the root, but Bingham (et al., 1963) concluded that a reaction outside the root contributed to this antagonism.

Boawn et al. (1954) stated that the amount of extractable P in the soil was not related to appearance of Zn deficiency symptoms in field beans. Seatz et al. (1959) showed that up to 436 pounds of applied P per acre had no effect on Zn response. Zinc uptake by citrus increased as more P was applied (Bingham, 1963) and soluble Zn was increased by additions of 900 pounds of K, H, NH_4, and Ca phosphates (Bingham et al., 1960). Nelson et al. (1965) found that wheat showed no Zn deficiency symptoms or yield depression at several levels of applied P when grown on a soil testing pH 7.4.

Nitrogen

Many crops have shown an increased uptake of soil Zn after nitrogen application (Ellis et al., 1964; Nelson et al., 1962). This enhancement of uptake was attributed to the acidification effect of the nitrogen fertilizer (Boawn et al., 1960). Zinc uptake by subterranean clover, however, was reduced by nitrogen application (Ozanne, 1955), and this affect was attributed to formation of Zn-protein complexes in the root.

Other Nutrients

Magnesium has been shown to increase Zn uptake by bean plants (Seatz, 1960), and a mutual substitution effect between Zn and Mg has been proposed (Barrows et al., 1960; Merrill et al., 1953). Other nutrient-relationship studies showed that a high K:Ca ratio in a calcareous soil resulted in Zn deficiency symptoms while a low K:Ca ratio resulted in Fe deficiency symptoms (Greenwood et al., 1951). Also, Jurinak and Thorne (1955) showed that Na and K increased Zn solubility, but Ca decreased Zn solubility in soils. Ward et al. (1963) reported that K level in the soil was a very important factor governing P-induced Zn deficiency.

Soil Reaction

Camp (1945) found the best utilization of Zn from soils at pH values of 6.0 to 6.5. Shaw and Dean (1951) observed that non-chelated Zn was practically unextractable at pH 7.0 to 8.5 (dithizone extraction). Jurinak and Thorne (1955) showed Zn solubility in Na and K bentonite systems to be lowest between pH 5.5 and 6.7, but increased at higher pH values. However, Zn solubility in a Ca bentonite system did not increase at higher pH values; in fact, minimal solubility was found at pH 7.6. The authors suggested that these effects were due to differential solubility of alkali zincates and of calcium zincate.

Carbonates

The success by Nelson et al. (1959) in evaluating Zn status of soils suggests that $CaCO_3$ content, as well as soil pH, may help to determine Zn availability in soils. Rogers et al. (1948) postulated that liming reduced Zn uptake in plants by increasing the pH.

Jurinak and Bauer (1956) found that 10 percent of the adsorption sites on calcite were occupied by Zn when the aqueous Zn^{++} equilibrium concentration was 0.90 x 10^{-6} M at 25.1° C. The relative degree of affinity for Zn was found to be: magnesite > dolomite > calcite. Endothermic heats of adsorption and very large positive entropies of adsorption indicate that aqueous Zn^{++} is dehydrated when adsorbed by dolomite and magnesite. Compatability of Zn^{++} with the $MgCO_3$ crystal lattice was thought to be a possible reason for the stronger Zn interaction with dolomite and magnesite than with calcite.

Type of Nutrient on Clay

Pretreatment of clays with Ca, K, and Cu solutions resulted in Zn adsorption in the order: K-clay > Ca-clay > Cu-clay (Mangaroo et al., 1965). Ammonium acetate could replace Zn added to a H-saturated soil system but could only partially replace Zn added to a Ca-saturated soil system. When Zn was applied to a Ca-saturated soil system, the amount of Zn extracted with NH_4OAc decreased with time (Nelson et al., 1955).

Temperature

Ellis et al. (1964) showed that yield, Zn concentration in plant tissue, and Zn uptake by corn decreased when soil temperature decreased from 75° F to 55° F. Also, Martin et al. (1965) found that low soil temperature accentuated P-induced Zn deficiency.

Procedures for Extracting Zinc From Soils

The average Zn concentration in the lithosphere is estimated to be about 80 ppm. Viets et al. (1953) found that total Zn in a loam soil averaged 66 ppm to a depth of 3 feet. They calculated that this soil contained 400 pounds per acre total Zn which is approximately 2,000 times the annual needs of an agronomic crop. Since much of this total Zn is not available to the plant, methods of determining both total Zn and plant available Zn were needed.

Extraction of Total Zinc

Wahhab and Bbatti (1959) digested several West Pakistan soils in 72 percent perchloric acid, and then extracted with 1.0 N HCl. Amounts of total Zn extracted were between a trace and 15.0 ppm with sands, and from 17.5 to 87.5 ppm with the sandy loams and clays.

Nair and Mehta (1958) who analyzed 58 soils from Western India, reported total Zn values ranging from 49.5 to 80.6 ppm, as determined by the HNO_3-HF method of Holmes (1943).

Holmes (1943) extracted from 11 to 140 ppm total Zn from soils throughout the United States. Southwestern soils contained 18 to 135 ppm, Central soils contained 40 to 130 ppm, Southeastern soils contained 11 to 147 ppm (only 2 New Hampshire soils studied) and Northwestern soils contained 66 to 105 ppm total Zn. Total Zn was fairly uniform between most profiles studied, especially those from the Central United States.

Alben and Bogg (1936) reported that soils utilized for pecan orchards in Texas and Louisiana had from 18 to 252 ppm total Zn, with an average of about 60 ppm total Zn in the topsoil (determined by fusion of soil with potassium pryo-sulfate and disintegrated in hot HCl). Only about one-half as much total Zn was extracted from soils at 0 to 6 inches as was extracted from soils at a depth of 12 to 72 inches in the soil profile.

Sherman and McHargue (1942) extracted from 80 to 513 ppm total Zn from Kentucky soils with a mixture of hydro-fluoric and perchloric acids. Total Zn content of these same soils was 78 to 502 ppm as determined by Na_2CO_3-K_2CO_3 fusion. Takazaua and Sherman (1947) found no correlation between total Zn determined by the mixed Na_2CO_3-K_2CO_3 fusion and plant available Zn.

According to Woltz et al. (1953), the total Zn content of twenty agricultural soils of New Jersey varied from 10 to 225 ppm. Zinc content of Appalachian soils averaged 100 ppm while that of Coastal Plain soils averaged 41 ppm. Heavy-textured soils generally contained more total Zn than light-textured soils.

Total Zn in 42 surface soils from Southern and Central Wisconsin varied from 4 ppm in a peat soil to 109 ppm in a silt loam. The average total Zn content of approximately 60 ppm agrees closely with reported data from other soils throughout the United States (Stewart and Berger, 1965).

Extraction of Available Zinc

Total Zn determinations have not adequately evaluated the level of plant available Zn in soils. Therefore, scientists have investigated soil extractions with micro-organisms such as *Aspergillus niger*, weak extracting agents like water, ammonium acetate, and magnesium sulfate, or stronger extracting agents such as HCl, dithizone, and EDTA to devise a suitable procedure for measuring plant available Zn in soils. Many soil testing laboratories have based their Zn-application recommendations on quantity of Zn extracted by some chemical reagent and other considerations such as pH, carbonate content, kind of crop, humus content, or soluble P.

Burd and Martin (1923) percolated water through soils (previously moistened approximately to field capacity) in filtration tubes and determined the quantity of certain macronutrients in the leachate. Hibbard (1940), utilizing a similar experiment, concluded that pure water has almost no solvent power for soil Zn. However, he extracted less Zn with water from soils previously giving evidence of Zn deficiency, the range being from 0 to 21 ppb (parts per billion).

A dithizone (diphenylthiocarbazone) method for measurement of small quantities of Zn was developed by Hibbard (1937). Epstein and Stout (1951) used dithizone to extract Zn from dilute clay suspensions. Shaw and Dean (1951) modified the extraction procedure by directly extracting Zn from soil samples with a two-phase system of aqueous NH_4OAc and carbon tetrachloride (CCl_4) containing dithizone. Of the 52 soils studied by Shaw and Dean, less Zn was generally extracted by dithizone from soils deficient in Zn for plant growth than from soils sufficient in Zn for plant growth. There was from 0.5 to 17.0 ppm Zn extracted, with most soils releasing from 0.3 to 3.0 ppm Zn. These values are similar to those that other workers (Stewart et al., 1965; Massey, 1957) reported when using the same dithizone extraction procedure (Wisconsin and Kentucky soils). Massey (1957) found a good correlation between Zn uptake by corn plants and dithizone extraction.

Wear and Sommer (1948) found a good correlation between the occurrence of Zn deficiency symptoms and quantity of Zn extracted with 0.1 N HCl or 0.04 N acetic acid (HOAc) from acid soils of Alabama. On Zn deficient soils, 0.05 to 0.09 ppm Zn was extracted with 0.1 N HCl and 0.00 to 0.50 ppm Zn was extracted with 0.04 N NH_4OAc. However, on soils with sufficient Zn, 1.20 to 4.70 ppm Zn was extracted with 0.1 N HCl and 0.05 to 3.50 ppm Zn was removed by 0.04 N NH_4OAc.

Hibbard (1940) found that either HCl or H_2SO_4, in concentrations as dilute as 0.01 N, extracted much more Zn than that present in the soil solutions. Other investigators (Nelson et al., 1959; Hoover, 1966) found that quantities of Zn extracted from soils with 0.1 N HCl did not correlate well with crop response, especially on highly calcareous soil. However, Nelson et al. (1959) found a high correlation between plant deficiency symptoms and 0.1 N HCl extractable Zn in calcareous soils if the "titratable alkalinity" was taken into consideration. Stewart and Berger's (1965) data from 0.07 to 13.70 ppm Zn extracted from Wisconsin soils with 0.1 N HCl agreed closely with the 0.9 to 12.0 ppm extracted by Nelson et al. (1959).

The additional Zn extracted by 0.1 N HCl, as compared to that extracted with dithizone, was suggested by Martens et al. (1966) to be held by organo-clay complexes. They concluded that the Zn held in these complexes was less available to plants than that extracted by dithizone.

Zinc extracted from Texas soils with 0.1 M copper sulfate ($CuSO_4$) and 0.1 N HCl was significantly correlated with

Zn content of sorghum leaves (Hoover, 1966). Zinc levels in soils used in this study varied from 0.3 to 17.8 ppm Zn.

Trierweiler and Lindsay (1966), using an ammonium carbonate $(NH_4)CO_3$ - EDTA extraction, found a good correlation between extractable Zn and plant response on Colorado soils. Hoover (1966) found that extraction of Zn with 1 percent EDTA was significantly correlated with Zn content of sorghum leaves from plants grown on Texas soils.

Of the numerous solvents used by Hibbard (1940) for extracting Zn from soils, a saturated water solution of carbon dioxide (CO_2) and 0.5 N KCl plus 0.04 N HOAc was selected. He later used 0.05 N KCl adjusted to pH 3.2 with HOAc. In general, only 1 to 5 ppm Zn was extracted from California soils by this procedure; however, up to 32.7 ppm Zn was removed from one soil at the 0-2 inch depth (Hibbard 1940a). Lyman and Dean (1942) found Zn extracted by CO_2 saturated water was highly correlated with soil pH but not with Zn uptake by pineapple plants. Koter et al. (1965) found that the quantity of Zn extracted with 1.0 N KCl correlated well with the quantity of Zn taken up by wheat, oats, and rye plants.

A good correlation was found between Zn deficiency exhibited by pineapple plants and soil Zn soluble in NH_4OAc (HOAc brought to a pH of 4.6 with NH_4OAc). The Hawaiian soils contained from 0.5 to 3.5 ppm extractable Zn.

Stewart and Berger (1965) found a higher correlation between Zn uptake by plants and Zn extracted from the soil by 2.0 N $MgCl_2$ than with 0.1 N HCl or NH_4OAc-dithizone combinations. Surface samples from 42 locations in South and Central Wisconsin were used in this study; extractable Zn in these soils varied from 0.60 to 3.98 ppm.

Martens et al. (1966) reported highly significant relationships between Zn uptake by corn plants and Zn extracted from the soil by each of the following methods: 0.2 M $MgSO_4$, dithizone, Aspergillis niger, and total Zn. Organic carbon content was also highly significantly correlated with Zn uptake by corn plants. These workers felt that 0.2 M $MgSO_4$ was the most satisfactory extractant.

Vlasyak and Zimina (1954) reported that the lowest amount of available Zn in Russian soils was 18.5 to 24.1 ppm in the cultivated podzols, and that the highest amount was 87 to 140 ppm in the Solonetz and Solonchak soils. This observation suggests that either available Zn levels in Russian soils are much higher than those in the United States soils or that they are actually determining total Zn.

Nair and Mehta (1958) found 1.79 to 4.57 ppm dithizone-extractable Zn in 58 soils of Western India. These values agree closely with those found in United States soils using the same extractant.

Ravikovitch et al. (1968) used 7 different methods to extract Zn from 15 calcareous soils of Israel. Ammonium nitrate (1.0 N), 1.0 N KCl, and 0.01 M disodium ethylenediamine di (O-hydroxyphenyl acetic acid) in 1.0 N NH_4OAc gave the most significant multiple correlation coefficients with Zn uptake by six crops.

EXPERIMENTAL METHODS

The levels of extractable Zn in the soils of Michigan were evaluated by obtaining samples from various depths at 65 locations which varied in pH and texture. These soils (Table 1A in the Appendix) represent 34 soil series from the udalf, orthod, aquept, baralf, aqualf, aquod, aquoll, and udoll soil suborders (see Soil Survey Staff, 1960 if definitions are desired).

Twenty of the original 65 soils which varied in extractable Zn level, soil pH, and soil texture were selected for further study in both the laboratory and in the greenhouse (Table 1). Approximately 150 pounds of soil was obtained from the Ap horizon at each of the 20 locations.

Soil Analytical Methods

The 65 soils were sampled by horizons at depths given in Table 1A and placed in paper bags, air dried, passed through a 20 mesh plastic sieve, and stored in cardboard containers. Soil pH, lime requirement, and available P, K, Ca, and Mg were determined by the Michigan State University Soil Testing Laboratory.

Soil pH

Ten grams of soil were mixed with 10 ml of water (1:1 ratio). After 15 minutes, the mixture was stirred again,

Table 1. Extractable nutrients, pH, and lime requirement of 20 Michigan soils used in greenhouse and laboratory evaluations.*

Soil Suborder and Series	Levels of Nutrients Extracted P pp2m	K pp2m	Ca pp2m	Mg pp2m	pH	Lime Requirement pp2m
Aqualf:						
Conover	63	189	4766	493	7.1	0.0
Metamora I	44	248	1604	101	6.2	4,000
Aquept:						
Breckenridge	84	118	5472	644	7.4	0.0
Charity I	79	312	8135	375	7.7	0.0
Charity II	47	432	8848	405	7.9	0.0
Hettinger	91	248	6621	966	7.5	0.0
Sims I	21	264	6336	950	7.3	0.0
Sims II	96	112	3910	375	7.6	0.0
Wisner I	47	204	6480	405	7.8	0.0
Wisner II	167	264	5760	934	7.8	0.0
Aquod:						
Brimley I	43	126	4057	433	7.5	0.0
Brimley II	135	118	3763	331	7.4	0.0
Aquoll:						
Colwood I	71	232	6336	1016	7.5	0.0
Lenawee I	63	132	5616	757	6.9	0.0
Orthod:						
Kalkaska	54	43	800	29	5.9	3,000
Karlin III	234	70	400	43	5.7	6,000
Udalf:						
Hillsdale	20	84	1752	130	6.6	0.0
Hodunk	84	183	1456	259	6.3	3,000
Locke	43	197	800	101	5.8	3,000
Miami	58	162	4490	302	7.2	0.0

*Determined by the Michigan State University Soil Testing Laboratory.

and the pH of the suspension determined using a Beckman Zeromatic glass electrode pH meter. The lime requirement of samples testing below pH 7.0 was determined by the method of Shoemaker, McClean, and Pratt (1961).

Extractable Phosphorus

Phosphorus was extracted for 1 minute from samples with Bray P-1 reagent (0.025 N HCl and 0.03 N NH_4F), using a 1:8 soil-solution ratio. Activated charcoal was used to remove organic matter from the filtrate. Phosphorus in the extract was determined by the molybdophosphoric blue method, using 1,2,4-aminonaphtholsulfonic acid as the reductant (Jackson, Method IV, p. 148, 1958).

Extractable Potassium, Calcium and Magnesium

Cations were extracted for 1 minute with 1.0 N NH_4OAc (pH 7.0) using a 1:8 soil-solution ratio. Potassium in the extract was determined by means of a Coleman Model 21 flame photometer, Ca by means of a Beckman Model DU flame spectrophotometer, and Mg by means of a Perkin Elmer Model 290 atomic absorption spectrophotometer as described by Doll and Christenson (1966).

Zinc Determinations

Total soil Zn was determined on all 65 soils by boiling 5 grams of soil in 50 ml of 12 N HCl. The suspension was boiled until approximately 5 ml of solution remained, then filtered (Whatman No. 3 filter paper) into 200 ml volumetric flasks. Zinc was determined in the resulting solution using a Perkin Elmer Model 303 atomic absorption spectrophotometer. Zinc removed by this method was nearly equal to that removed by hydrofluoric and perchloric acids (Sherman and McHargue, 1962) and to that removed by sodium carbonate fusion (Jackson, 1958).

The different procedures listed in Table 2 were compared to determine the most effective method of extracting available soil Zn. Zinc in the extracts was determined as described above.

Greenhouse Studies

Greenhouse studies, using the 20 soils listed in Table 1, were conducted to determine the effect of Zn applications and pH levels on yield and Zn uptake, and to determine the relationship between Zn extracted and plant yield and Zn uptake by pea beans. Three successive crops were grown.

The greenhouse experiment was laid out in a completely randomized design with each treatment on each soil being conducted in quadruplicate. One-gallon galvanized cans, lined with plastic bags, were used as containers. Soils were air-dried and passed through a 4-mesh stainless steel sieve; 3.5 kilograms were placed in each container.

Three levels of Zn (0, 7.5, and 15 pp2m) were established on each soil by applying $ZnSO_4$ in a circular band 2.5 inches deep and one and one-half inches from the outside of the can.

Table 2. Methods of extracting soil Zn to correlate with yields of pea beans.

Extracting Solution	Soil-Solution Ratio	Method of Extraction	Extraction Time (minutes)
0.1 N HCl	5:50	Shaking	30
0.2 N $Mg(NO_3)_2$	5:50	Shaking	60
0.2 N $MgSO_4$	5:50	Shaking	60
H_2O	40:50	Percolation	Variable*
0.2 N $Ca(NO_3)_2$	5:50	Shaking	60
0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$	10:20	Shaking	30**
1.0 N NH_4OAc	2.5:20	Shaking	60
0.4 N $MgSO_4$	27.5:150	Shaking	1440+

*Two 25-ml increments of double-distilled H_2O (total of 50 ml.) were added to 40 g. of soil, and Zn concentration in leachate determined.

**Method of Trierweiler and Lindsay (1966).

+Method of Martens et al. (1966).

On all soils testing above pH 6.5, 20 pp2m Mn were applied as $MnSO_4$.

Prior to planting, 300 pp2m N as NH_4NO_3 were applied in the fertilizer band. Fifty pp2m N from the same sources were added weekly (8 times) during the experiment. A total of 700 pp2m N were applied during the experiment.

Phosphorus was applied as monobasic calcium phosphate on each soil in an amount so that soil test P plus applied P equalled 100 pp2m, K as KCl so that the total K equalled 200 pp2m, and Mg as $MgSO_4$ so that the total Mg equalled 100 pp2m. All fertilizers applied prior to planting were mixed and banded as described above (together with the Zn and Mn fertilizers).

On September 18, 1966, 10 pea bean seeds were evenly spaced one-half inch below the soil surface at three inches from the outside of each can. The fertilizer band was located 2 inches below and 1.5 inches to the side of each seed. Four hundred milliliters of deionized water were added to each can of soil after covering the fertilizer with 2 inches of soil (the water was applied before planting the seed to prevent crusting of the soil surface). No more water was applied until after germination. No supplemental lighting was used.

After seed germination, deionized water was applied daily as needed, and the pots were brought to a constant volume of water weekly.

Plants were thinned to four per pot two weeks after emergence. When necessary, 3 foot plastic stakes were inserted into the pots to support the plants.

On November 13, 1966, stakes were removed, plant tops were cut with stainless steel razor blades, and dried at 60°C in paper bags. Plant samples were ground in a stainless steel Wiley mill.

For the second crop of pea bans, P was applied as monobasic calcium phosphate on each soil in an amount so that original soil test P plus applied P equalled 500 pp2m; all other fertilizers were reapplied to all soils at the same rates for the first pea bean crop. Supplemental artificial fluorescent lighting was used. Lime ($CaCO_3$) was uniformly mixed in certain soils with pH values less than 6.5 at approximately twice the rate recommended for field crops by the Michigan State University Soil Testing Laboratory. Beans were planted December 10, 1966 and harvested February 5, 1967.

For the third crop of pea beans, no fertilizers were added except for the weekly applications of 50 pp2m of N, and no artificial lighting was used. Any soils below pH 7.0 were heavily limed (20,000 to 28,000 pp2m) prior to the third cropping (Table 5). Beans were planted April 1, 1967 and harvested May 27, 1967.

Plants were thinned to 3 per pot in both second and third plantings.

Plant Analytical Methods

One gram of dry ground plant sample was ashed in a muffle furnace at 500° C for 4 hours. Five ml of 2 N HCl was slowly added to the plant ash until effervescence ceased, and the resulting suspension was filtered (Whatman No. 3 filter paper) into 50 ml. volumetric flasks for Zn determination as described above.

Field Studies

Field experiments to determine the response of pea beans to applied Zn were conducted at 20 locations from 1964 to 1967 inclusive. Varieties used, soil types, and fertilizer treatments have previously been reported (Judy et al., 1965; Brinkerhoff et al., 1966 and 1967; Vinande et al., 1968). Yields from these experiments were correlated with levels of extractable soil Zn (0.1 N HCl), and the results are reported herein.

Statistical Procedures

Statistical analyses were conducted using a Controlled Data Corporation (CDC) 3600 computer. Yield and Zn concentration and uptake data were analyzed by means of the analysis of variance; significant differences between treatments were determined by using Tukey's HSD values (Federer, 1955). The HSD values give a more rigorous test of significance than do the more commonly used LSD values. Multiple regression coefficients were determined by means of standard computer programs utilizing the method of least squares.

RESULTS AND DISCUSSION

Total and Extractable Zinc in Sixty-five Michigan Soils

Total and extractable (0.1 N HCl) Zn were determined in 65 soils in order to evaluate Zn distribution in Michigan soils. These soils were from 35 series, and represented 8 soil suborders. Adjusted average values, together with the range in values, for total and extractable Zn and soil pH at various depths are given in Table 3 for each suborder; data for each soil are given in Table 1A in the Appendix. Adjusted averages were computed because the depth of sampling was not constant at all locations.

Total Zn varied greatly between the different soil suborders; average total Zn in the aquoll (humic gley) suborder was more than twice that in the orthod (podzol)--possibly because of the greater content of organic matter and clay of soils in the aquoll suborder. However, differences in total Zn within a given suborder tended to be greater than average differences between suborders, as indicated by the ranges given in Table 3.

Total Zn was as high or higher in the surface layer than at lower depths in all suborders, and these findings were similar to those of Thorne (1942). No consistent differences

Table 3. Total and extractable Zn and pH at various depths in 65 Michigan soils which include 35 soil series from 8 soil suborders.

Soil Suborder	Number of Soil Series	Number of Locations	Approx. Depth	PPM Total Zn Range	PPM Total Zn Average	PPM Extractable Zn Range	PPM Extractable Zn Average	pH Range	pH Average
Aqualf	3	7	0-10	28-63	48	2.2-8.0	5.3	6.2-7.9	7.3
			10-20	22-67	42	0.4-5.3	2.1	6.2-8.0	7.3
			20-30	21-62	41	0.3-6.9	2.6	6.4-8.1	7.4
			30-40	22-75	48	0.3-6.6	2.3	6.5-8.1	7.7
Aquept	8	24	0-10	22-65	43	0.8-18.2	5.6	5.9-7.9	7.6
			10-20	20-61	36	0.3-8.1	2.3	6.6-8.1	7.7
			20-30	9-56	35	0.3-8.6	1.5	7.0-8.3	7.9
			30-40	23-71	34	0.2-9.1	1.1	6.5-8.3	8.0
Aquoll	4	12	0-10	36-84	61	2.0-10.8	6.0	6.4-7.8	7.1
			10-20	28-85	54	1.7-19.6	5.7	6.5-8.0	7.4
			20-30	33-74	47	0.4-11.9	3.9	7.2-7.9	7.7
			30-40	33-88	48	0.5-7.4	1.8	7.2-8.3	7.9
Aquod	1	2	0-10	35-47	41	2.8-2.9	2.9	7.5-7.7	7.6
			10-20	28-34	31	0.3-0.9	0.6	7.7-8.0	7.9
			20-30	25-42	34	0.7-0.8	0.8	7.8-8.2	8.0
			30-40	37-43	40	0.2-0.4	0.3	8.1-8.2	8.1
Boralf	4	4	0-10	34-92	59	0.8-19.3	6.8	5.5-8.0	6.1
			10-20	46-60	54	0.1-7.0	3.9	5.4-8.0	6.6
			20-30	40-69	51	0.4-8.0	2.9	5.7-7.8	7.7
			30-40	32-60	46	0.3-0.4	0.4	7.6-8.3	8.0
Orthod	6	8	0-10	18-42	28	1.9-6.5	3.4	5.5-7.4	5.7
			10-20	16-32	26	1.2-3.7	1.9	5.4-7.2	6.0
			20-30	6-55	21	0.8-4.5	1.6	5.3-7.8	6.4
			30-40	6-43	18	0.5-1.4	0.9	5.5-8.6	6.7
Udalf	7	7	0-10	17-58	32	1.7-6.0	3.3	6.1-7.6	6.7
			10-20	18-55	32	1.0-5.3	2.3	5.6-8.1	6.6
			20-30	16-70	33	0.2-2.5	2.4	5.6-8.1	6.8
			30-40	5-59	32	0.5-21.0	1.8	5.6-8.3	7.0
Udoll	1	1	0-10	---	45	---	3.5	---	5.6
			10-20	---	46	---	1.4	---	4.9
			20-30	---	29	---	1.1	---	4.7
			30-40	---	14	---	0.9	---	5.0

between suborders were noted with respect to the distribution of total Zn throughout the profile.

Extractable Zn was highly variable between and within soil series, both within the same suborder and between suborders. Most of the Zn responses in Michigan have been noted on soils within the aquept suborder; however, average levels of extractable Zn in this suborder did not consistently differ from that in the other suborders.

Extractable Zn always decreased with depth. About one-tenth of the total Zn was extracted with 0.1 N HCl in the surface layer, while much lower proportions of the total Zn were extracted at the lower depths. This decrease in the proportion of extractable Zn with depth may in part be due to increases in soil pH with depth, but it may also in part be due to the lower organic matter content of the lower horizons.

Soil pH increased with depth on most of the soils, with considerable variations both within and between suborders. The level of extractable Zn in the different suborders was not related to soil pH, as some of the lowest levels of extractable Zn were noted in the aquod and orthod suborders, in which the average pH values differed by about 2.0 pH units.

Soils varied greatly in total and extractable Zn, both within and between suborders and series. Measurements of total and extractable Zn, together with soil pH, did not appear to separate those soils on which yield responses had been obtained with Zn fertilizers from those on which no responses had been noted.

Yields and Zinc Content of Pea Beans in the Greenhouse

Twenty of 65 soils referred to previously were selected for more intensive greenhouse and laboratory studies because measurements of total and 0.1 N HCl extractable Zn in Michigan soils did not adequately evaluate their Zn status. Three Zn levels were established on each soil and 3 successive crops of pea beans were grown. The effectiveness of various methods of extracting soil Zn was evaluated by correlating extracted soil Zn with total dry weight of the plant tops (yields) and Zn uptake by the pea beans.

First Cropping

Yield: In general, yields of the first crop were increased by Zn application in soils testing above pH 7.1, and were either not affected or decreased on soils testing 7.1 or lower (Table 4). Marked yield decreases were noted when Zn was applied to soils testing below pH 6.3. Yields were decreased slightly when Zn was applied to the Hodunk soil (pH 6.3), but the growth of plants on this soil was stunted by residual effects of atrazine which had been applied to the soil prior to sampling.

Yields of beans were increased by Zn application on all soils in the aquept and aquod suborders except for Hettinger silty clay loam, the Colwood loam of the aquoll suborder, and

Table 4. Yield and Zn content of successive crops of pea beans grown on 20 different soils at three levels of Zn application.

Soil Suborder and Series	Rate of Applied Zn pp2m	First Crop Yield g/pot	First Crop Conc. of Zn ppm	First Crop Uptake of Zn µg/pot	Second Crop Yield g/pot	Second Crop Conc. of Zn ppm	Second Crop Uptake of Zn µg/pot	Third Crop Yield g/pot	Third Crop Conc. of Zn ppm	Third Crop Uptake of Zn µg/pot
Aqualf:										
Conover*	0.0	10.4	17.5	178.7	13.0	18.0	230.7	7.4	21.2	159.7
	7.5	9.2	32.3	297.1	14.1	22.3	318.8	9.6	25.6	254.0
	15.0	9.7	51.0	491.9	12.4	30.7	378.3	10.0	24.5	243.8
Metamora I°	0.0	9.4	28.0	256.3	7.5	12.1	91.2	1.0	13.4	12.8
	7.5	8.7	60.8	526.3	9.3	30.6	256.5	4.3	20.3	84.0
	15.0	7.9	78.8	615.3	8.2	54.3	396.8	4.3	26.6	117.2
Aquept:										
Breckenridge*	0.0	7.1	14.7	105.3	12.2	9.8	116.4	5.6	11.6	66.1
	7.5	9.4	24.5	229.4	15.2	14.7	222.8	11.1	19.5	217.2
	15.0	9.5	32.3	317.6	16.3	30.2	493.5	10.0	23.0	228.7
Charity I	0.0	6.5	17.6	113.9	9.0	10.0	89.3	6.8	12.7	87.2
	7.5	7.7	18.1	139.1	9.8	10.8	105.1	10.0	19.1	191.0
	15.0	7.5	17.3	130.5	11.0	13.9	149.2	9.9	21.4	213.2
Charity II	0.0	7.2	18.0	129.2	9.2	12.5	114.4	3.0	17.0	49.3
	7.5	7.5	20.1	148.5	9.2	17.0	156.8	9.4	24.0	226.4
	15.0	8.3	24.0	198.2	13.0	17.8	230.5	9.0	27.4	246.7
Hettinger	0.0	10.1	19.1	194.0	9.2	11.9	110.4	10.1	14.7	141.5
	7.5	9.2	25.5	235.0	15.5	16.1	253.8	13.0	27.6	356.5
	15.0	10.2	32.3	216.0	16.0	19.2	311.3	12.5	28.7	361.1

continued

Table 4 -- Continued

Soil Suborder and Series	Rate of Applied Zn pp2m	First Crop Yield g/pot	First Crop Conc. of Zn ppm	First Crop Uptake of Zn µg/pot	Second Crop Yield g/pot	Second Crop Conc. of Zn ppm	Second Crop Uptake of Zn µg/pot	Third Crop Yield g/pot	Third Crop Conc. of Zn ppm	Third Crop Uptake of Zn µg/pot
Aquept:										
Sims I*	0.0	7.1	10.6	74.4	7.1	8.1	57.6	1.4	10.0	14.5
	7.5	9.2	14.1	129.3	11.7	12.0	138.0	5.4	13.0	74.0
	15.0	10.2	24.4	255.6	13.1	18.9	248.1	10.2	17.9	182.5
Sims II	0.0	6.3	12.6	79.5	7.3	8.7	63.2	9.1	13.3	122.4
	7.5	5.5	16.0	87.6	4.8	17.6	77.5	8.2	19.2	156.5
	15.0	8.7	21.6	186.7	12.3	27.4	327.4	10.5	28.0	249.0
Wisner I	0.0	7.8	13.5	105.5	5.9	9.0	52.7	5.9	13.5	82.8
	7.5	9.3	16.0	148.2	10.2	12.6	124.8	9.4	20.1	186.5
	15.0	10.2	18.3	187.3	10.6	17.5	178.1	10.4	24.5	254.9
Wisner II	0.0	4.5	17.6	82.2	3.9	7.9	31.1	6.3	14.1	94.7
	7.5	7.6	11.6	87.9	11.9	8.1	95.2	10.4	14.1	148.9
	15.0	7.6	16.6	126.3	13.9	18.9	257.2	12.7	22.0	277.6
Aquod:										
Brimley I*	0.0	4.2	8.3	34.0	5.5	8.8	47.7	3.8	20.1	81.0
	7.5	9.4	16.3	152.1	10.5	12.6	133.1	11.3	13.6	153.7
	15.0	10.6	29.1	309.7	12.6	26.8	327.6	11.9	48.5	574.2
Brimley II*	0.0	7.5	11.8	88.6	5.3	12.5	69.8	4.9	18.6	107.3
	7.5	9.2	21.9	200.5	13.2	15.6	220.6	9.0	19.3	176.3
	15.0	10.3	27.6	284.5	11.5	24.0	260.6	8.8	21.6	284.5

continued

Table 4 -- Continued

Soil Suborder and Series	Rate of Applied Zn	First Crop			Second Crop			Third Crop		
		Yield	Conc. of Zn	Uptake of Zn	Yield	Conc. of Zn	Uptake of Zn	Yield	Conc. of Zn	Uptake of Zn
	pp2m	g/pot	ppm	μg/pot	g/pot	ppm	μg/pot	g/pot	ppm	μg/pot
Aquoll:										
Colwood I*	0.0	9.0	15.4	136.2	13.3	10.4	139.7	10.5	27.4	289.7
	7.5	9.8	20.0	197.8	13.9	14.1	190.9	13.2	31.3	419.7
	15.0	11.0	32.4	355.5	15.2	23.8	359.7	14.3	33.8	467.9
Lenawee I*	0.0	9.8	15.5	151.5	14.7	14.7	216.9	8.0	16.5	130.7
	7.5	9.2	25.7	229.7	13.7	22.1	299.2	12.1	17.6	213.7
	15.0	9.7	36.0	342.2	14.7	35.8	527.6	12.4	24.3	300.9
Orthod:										
Kalkaska[o]	0.0	7.2	48.3	346.5	0.5	12.7	6.5	0.8	15.4	9.9
	7.5	3.8	145.6	548.5	0.6	19.0	7.0	0.5	26.1	13.4
	15.0	2.4	371.3	861.7	0.4	26.3	12.5	0.7	24.7	18.5
Karlin III[o]	0.0	6.4	60.0	386.6	1.5	19.8	13.5	0.7	11.7	7.5
	7.5	2.5	242.5	599.4	0.5	22.3	11.2	0.4	36.7	8.5
	15.0	1.4	343.8	523.8	0.7	52.3	34.3	0.5	20.5	8.8
Udalf:										
Hillsdale*	0.0	11.2	26.3	286.8	5.0	21.8	109.4	0.5	21.8	10.8
	7.5	10.3	36.8	381.8	6.9	55.9	375.9	1.4	11.7	17.1
	15.0	8.4	80.8	674.2	5.2	147.5	760.4	3.2	20.7	67.9

continued

Table 4 -- Continued

Soil Suborder and Series	Rate of Applied Zn pp2m	First Crop Yield g/pot	First Crop Conc. of Zn ppm	First Crop Uptake of Zn µg/pot	Second Crop Yield g/pot	Second Crop Conc. of Zn ppm	Second Crop Uptake of Zn µg/pot	Third Crop Yield g/pot	Third Crop Conc. of Zn ppm	Third Crop Uptake of Zn µg/pot
Udalf:										
Hodunk+	0.0	2.6	31.6	83.5	4.1	19.4	78.0	7.7	14.0	107.6
	7.5	2.6	90.8	245.6	10.6	23.7	245.7	9.6	21.5	205.6
	15.0	2.2	173.8	372.1	9.6	31.0	258.1	11.7	40.1	482.4
Locke°	0.0	9.0	52.3	463.8	2.1	16.0	24.6	0.8	13.4	10.0
	7.5	4.4	187.0	799.0	4.7	41.8	179.0	6.4	21.7	139.9
	15.0	2.9	323.7	921.2	8.0	42.4	335.6	5.7	32.5	184.1
Miami*	0.0	7.5	13.3	99.6	13.9	10.2	140.2	0.8	11.7	9.6
	7.5	9.8	24.3	237.8	12.9	25.8	327.2	6.1	15.3	97.0
	15.0	8.6	41.3	355.1	15.7	25.9	404.7	7.0	19.2	130.8
HSD (0.05):										
Between soils at same level of Zn.		2.2	60.8	198.8	5.1	17.1	130.7	4.1	19.8	172.3
Between Zn treatments on the same soil		1.5	40.3	131.8	3.4	11.3	86.2	2.7	13.1	114.2

*Limed prior to third planting.

°Limed prior to second and third planting.

+Limed prior to second planting.

Miami loam in the udalf suborder. Yields obtained when 7.5 pp2m Zn were applied to soils were nearly as high as those when 15.0 pp2m Zn were applied, except for Sims II clay loam in the aquept suborder and Colwood loam in the aquoll suborder.

Yields were decreased by Zn application on all soils in the aqualf, orthod, and udalf suborders except for the Miami and Conover loams. Large yield depressions were obtained when 7.5 pp2m Zn were applied to soils in the orthod suborder and to Locke loam in the udalf suborder. Further yield depressions were noted on all other soils in these 3 suborders when 15.0 pp2m Zn were applied.

<u>Zinc concentration</u>: Zinc concentration in bean tissue was increased by Zn application on all soils, except Wisner II clay loam in the aquoll suborder. The Zn concentration was possibly lower after addition of Zn because of the large yield increase (41 percent) on this Wisner soil.

Since actual yields varied significantly on the different soils, relative rather than actual yields were used in all correlations between yields and Zn concentration in pea beans. Relative yields were calculated using the following equation:

$$\text{Relative yield} = \frac{\text{Actual Yield without Zn}}{\text{Maximum Yield with Zn}} \times 100$$

Yields were increased when Zn was applied to 12 of the soils. Highest yields were obtained when Zn concentration in the tissue was between 11 and 32 ppm; the average concentration of Zn in plants from the highest yielding treatments was 25 ppm (Figure 1).

Yields were decreased when Zn was applied to 8 of the soils. Highest yields were obtained when Zn concentration in the tissue was between 26 and 60 ppm; the average concentration of Zn in plants from the highest yielding treatments was 34 ppm. The yield depressions usually resulted from a Zn concentration greater than 50 ppm.

Zinc uptake: Zinc uptake by beans was increased by Zn application of all soils; however, no definite relationship was observed between increases in Zn uptake by the plants and increments of Zn fertilizer added to these soils. Approximately 0.2 to 3.0 percent of the Zn application of 7.5 pp2m and approximately 0.1 to 2.0 percent of the Zn application of 15.0 pp2m was recovered from the different soils by pea bean plants.

Total uptake of Zn by beans was significantly greater when grown on light-textured soils (sandy loams, loamy sands, and sands) with low pH values (below 6.7) than when grown on other soils. Soils in the former category were Metamora I, Kalkaska, Karlin III, Hillsdale, and Locke. Total uptake of Zn was not strictly related to yield.

Second Cropping

Zinc was again applied to all soils at a rate equivalent to the Zn added for the first crop. Lime was applied to the Metamora I, Kalkaska, Karlin III, Hodunk, and Locke soils

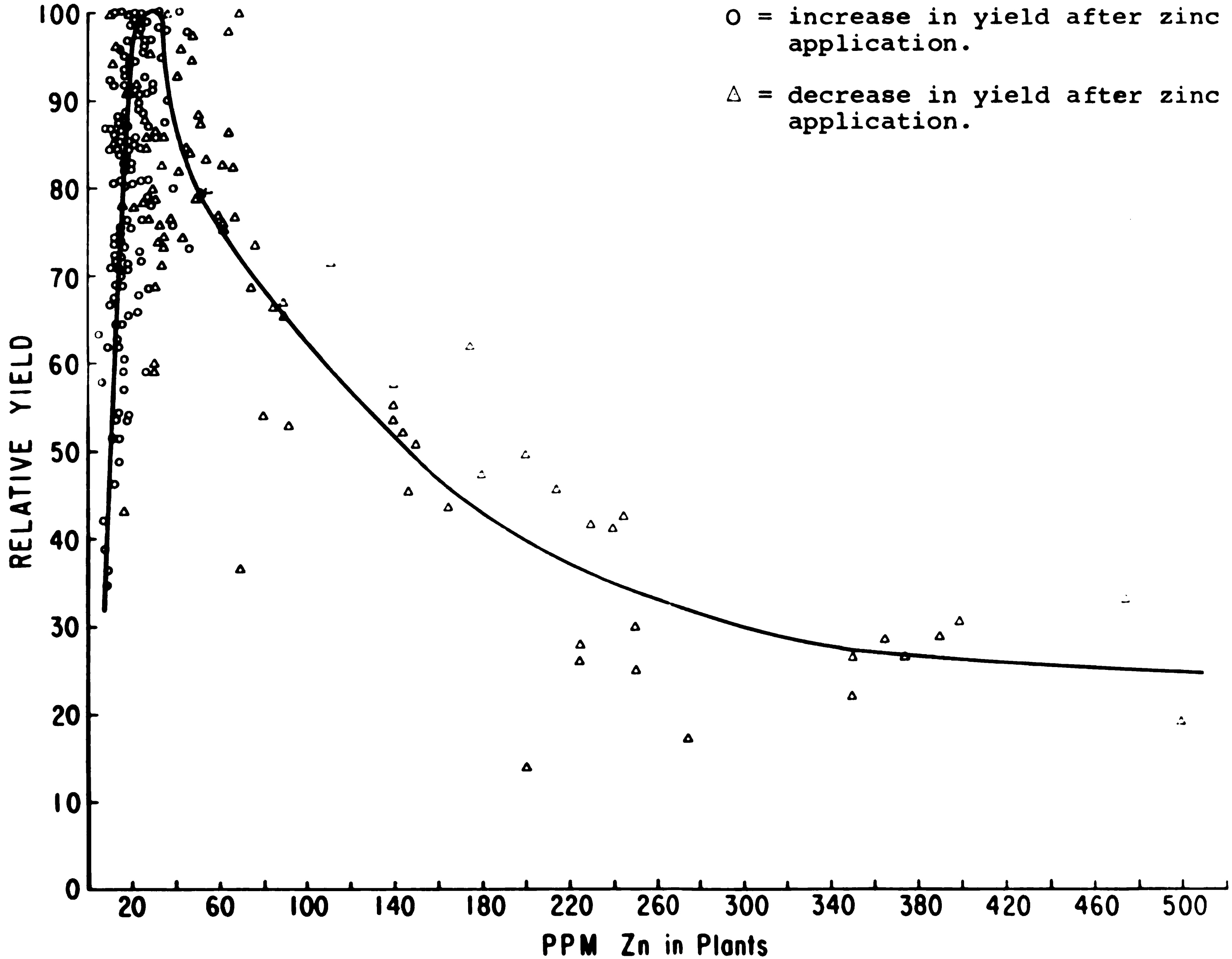

Figure 1. Relation between Zn concentration and relative yield of the first crop of pea beans grown in the greenhouse.

after yield depressions were obtained with Zn application for the previous pean bean crop (Table 5).

Yields: Responses to Zn addition with the second crop were similar to those of the first crop (Table 4). Greatest yield increases were obtained for the first increment (7.5 pp2m) of Zn fertilizer while increasing the rate of Zn application from 7.5 to 15.0 pp2m did not result in significant increases except on the Charity II soil.

After liming the Locke and Hodunk soils in the udalf suborder and the Metamora soil in the aqualf suborder (Table 6), yields were increased when Zn was applied, while in the first crop, yields on these soils were decreased when Zn was added. Increasing the rate of Zn application from 7.5 to 15.0 pp2m Zn increased yields in the Locke soil, but not on the Hodunk or Metamora soils. On the Kalkaska and Karlin soils, liming appeared to depress yields, and Zn application was not effective in increasing yields.

Zinc concentration: Zinc concentration in plant tissue was again increased by Zn addition on all soils in which yield increases were obtained for the first crop. Considering all these soils, highest yields were obtained when Zn concentration in the tissue was between 14 and 36 ppm; the average concentration of Zn in plants from the highest yielding treatments was 25 ppm.

Zinc concentration in plant tissue was also increased by Zn application on all limed soils. On these soils, highest

Table 5. Effects of greenhouse cropping and of lime application on pH values of soils.

Soil Suborder and Series	pH Before Cropping	Lime Added After 1st Crop. pp2m	pH Before 2nd Crop.	pH After 2nd Crop.	Lime Added After 2nd Crop. pp2m	pH Before 3rd Crop.	pH After 3rd Crop
Aqualf:							
Conover	7.1	0	---	5.7	28,000	7.0	7.4
Metamora I	6.2	8,000	6.6	5.3	28,000	7.0	7.0
Aquept:							
Breckenridge	7.4	0	---	6.2	24,000	7.0	7.7
Charity I	7.7	0	---	7.3	0	---	7.7
Charity II	7.9	0	---	7.4	0	---	7.8
Hettinger	7.5	0	---	7.0	0	---	7.0
Sims I	7.3	0	---	5.8	28,000	6.8	7.7
Sims II	7.6	0	---	7.2	0	---	7.5
Wisner I	7.8	0	---	7.5	0	---	7.7
Wisner II	7.8	0	---	7.5	0	---	7.7
Aquod:							
Brimley I	7.5	0	---	6.6	20,000	6.8	7.8
Brimley II	7.4	0	---	5.9	28,000	6.9	7.7

continued

Table 5 -- Continued

Soil Suborder and Series	pH Before Cropping	Lime Added After 1st Crop. pp2m	pH Before 2nd Crop.	pH After 2nd Crop.	Lime Added After 2nd Crop. pp2m	pH Before 3rd Crop.	pH After 3rd Crop.
Aquoll:							
Colwood I	7.5	0	---	5.8	24,000	7.1	7.7
Lenawee I	6.9	0	---	5.3	28,000	6.6	7.5
Orthod:							
Kalkaska	5.9	8,000	6.9	5.8	28,000	6.9	7.0
Karlin III	5.7	12,000	6.1	6.2	24,000	6.9	7.0
Udalf:							
Hillsdale	6.6	0	---	4.7	28,000	7.0	7.0
Hodunk	6.3	6,000	6.5	6.7	0	---	6.2
Locke	5.8	6,000	6.1	5.4	28,000	6.6	6.8
Miami	7.2	0	---	5.7	24,000	7.0	7.8

yields were obtained when Zn concentration in the tissue was between 20 and 42 ppm; the average concentration of Zn in plants from the highest yielding treatment was 27 ppm, approximately the same concentration as was obtained from plants on unlimed soils.

Zinc uptake: Zinc uptake was increased by Zn fertilization of all soils; however, no definite relationship was observed between increases in Zn uptake by the plants and increments of Zn fertilizer added. From 0.03 to 1.0 percent of the fertilizer Zn applied at 7.5 pp2m and 15.0 pp2m rates, respectively, on unlimed soils was recovered from the different soils by pea bean plants.

Zero to 1 percent of the Zn applied at 7.5 pp2m and 0.03 to 1 percent of that applied at 15.0 pp2m was recovered from the limed soils by the plants. Uptake of Zn by beans from the limed soils was much lower than that absorbed from the same soils by the first crop.

Third Cropping

Zinc fertilizer was not applied again for the third crop. Lime was applied to all soils on which pH values were below 7.0 after the second pea bean cropping; these included all soils in the aqualf, aquod, aquoll, orthod, and udalf suborders and Breckenridge and Sims I in the aquept suborder (Table 5).

Yields: Yields were increased by Zn fertilization on all unlimed soils on which similar increases were obtained for previous crops (Table 4). Greatest yield increases were again obtained for the first increment of Zn fertilizer while increasing the rate of Zn application from 7.5 to 15.0 pp2m did not result in significant yield increases.

Yields were increased by Zn addition on 11 of the 13 limed soils, but on the Kalkaska and Karlin soils, Zn fertilizers were not effective in increasing yields. Increasing the rate of Zn application from 7.5 to 15.0 pp2m did not result in significant yield increases except on the Sims I and Hillsdale soils.

Zinc concentration: Zinc concentration in bean tissue was again increased by Zn application on all unlimed soils. Highest yields were obtained from crops grown on the unlimed soils when Zn concentration in the tissue was between 19 and 28 ppm, and the average concentration of Zn in plants from the highest yielding treatments was 25 ppm.

Zinc concentration in plant tissue was also increased by Zn fertilization on all limed soils except the Hillsdale. Highest yields were obtained from crops on soils where Zn concentration in the bean tissue was between 22 and 49 ppm; the average concentration of Zn in plants from the highest yielding treatments was 25 ppm.

Zinc uptake: Zinc uptake by pea beans was increased by Zn fertilization of all soils; however, no definite relationship was observed between increases in Zn uptake by the plants and increments of Zn added to these soils.

Approximately 0.2 to 1.4 percent of residual Zn at the first increment and 0.4 to 0.7 percent of residual Zn at the second increment was recovered from the unlimed soils by the plants.

Between 0.007 and 0.8 percent of residual Zn at the first increment and 0.004 to 0.7 percent of residual Zn at the second increment was recovered from the limed soils by bean plants.

Between Crops

Yields: Yields of the second crop increased more than yields of the first crop after applying Zn to the unlimed soils (Table 4). The differences in yields may have been due to higher P rates for the second crop. Higher yields on soils with both 7.5 and 15.0 pp2m Zn applications may have also been due to higher P rates (Doll et al., 1967).

Yields were increased by Zn addition on all limed soils except those in the orthod suborder. Liming progressively increased relative yield differences obtained from soils at the 0 and at the 15.0 pp2m Zn applications for both the second and third crops. For example, yields of the first crop were only one-third as great after Zn fertilization on the Locke soils, while yields of the second and third crops were 4 times and 7 times greater, respectively, after Zn fertilization of this soil. A smaller increase in yield was obtained after applying Zn to the Hodunk soil for the third crop than after applying Zn to the second crop (lime applied before the second crop but not before the third crop).

Yields at each Zn level usually decreased when large quantities of lime were applied to soils. The actual yields between crops often decreased while relative yields increased with Zn fertilization.

Zinc concentration: Highest yields for all crops of pea beans were obtained on both limed and unlimed soils at similar levels of plant Zn concentration (approximately 25 ppm). No other definite trends in Zn concentration were found between crops on these soils.

Plant Zn concentration was decreased by applying lime to soils. Liming soils for both the second and third crop resulted in a progressive decrease of Zn concentration in the plant. For example, on the Locke soil, Zn concentration in plants decreased from 324 to 42 ppm from the first to second crops, and to 33 ppm in the third crop. A larger Zn concentration was obtained in the third crop than in the second crop of pea beans from the Hodunk soil (lime only applied for second crop). Highest yields were obtained on limed soils at similar ranges and averages of Zn concentration for both the second and third crops.

Zinc uptake: A gradual increase in Zn uptake by beans was generally obtained at each Zn treatment on unlimed soils from the first to the third crops. Similar quantities of Zn were extracted from these soils by pea bean crops (approximately 0.1 to 3.0 percent at both 7.5 and 15.0 pp2m Zn application).

Zinc uptake by beans was decreased when lime was applied. Liming soils for both the second and third crops resulted in a progressive decrease in Zn uptake by plants. For example, at 15.0 pp2m Zn application on the Locke soil, Zn uptake by beans decreased from 921 to 336 μg/pot from the first to second crops to 184 μg/pot for the third crop. A larger Zn uptake was obtained in the third crop than in the second crop from the Hodunk soil (lime only applied for second crop). Similar quantities of Zn fertilizer were extracted from these soils by bean crops (approximately a trace to 1.0 percent at both 7.5 and 15.0 pp2m Zn application).

Soil Zinc Extraction Procedures

Zinc was extracted from soils using 9 different extraction procedures (Table 6). Five of these procedures had been previously reported as suitable for determining available soil Zn. All of these procedures were adaptable to routine analyses as are used in soil testing laboratories. The amount of Zn removed from the different soils by the various extractants ranged from 11 ppb (parts per billion) with H_2O to 63 ppm with 12 $\underline{N}$ HCl.

Zinc Extracted from Soils Before Cropping

No definite relationship was noted between Zn extracted from soils by 0.1 $\underline{N}$ HCl (extractable) and that extracted by 12 $\underline{N}$ HCl (total), but much more Zn was extracted with the 12 $\underline{N}$ HCl than with 0.1 $\underline{N}$ HCl (54 times greater in the

Table 6. Amount of Zn extracted from Michigan soils by the various procedures listed in Table 2 prior to cropping.

		Extracting Solutions								
		HCl		$Ca(NO_3)_2$	$Mg(NO_3)_2$	$MgSO_4$		EDTA	NH_4OAc	
Soil Suborder and Series	pH	12.0 N ppm	0.1 N ppm	0.2 N ppm	0.2 N ppm	0.2 N ppm	0.4 N ppm	ppm	1.0 N ppm	H_2O ppm
Aqualf:										
Conover	7.1	63.2	5.3	0.43	0.19	0.39	0.90	3.51	1.17	0.019
Metamora I	6.2	27.6	2.2	1.07	0.42	0.66	1.20	2.15	0.93	0.031
Aquept:										
Breckenridge	7.4	28.4	4.3	0.47	0.18	0.27	0.78	1.40	0.75	0.018
Charity I	7.7	42.4	2.8	0.47	0.16	0.27	0.45	2.28	0.60	0.019
Charity II	7.9	40.0	0.8	0.47	0.13	0.22	0.40	2.90	0.65	0.014
Hettinger	7.5	44.4	6.0	0.46	0.18	0.27	0.78	1.50	1.00	0.021
Sims I	7.3	40.0	4.5	0.50	0.19	0.30	0.78	1.28	0.78	0.016
Sims II	7.6	31.1	4.2	0.41	0.14	0.28	0.84	1.80	0.83	0.019
Wisner I	7.8	28.0	3.7	0.40	0.16	0.30	0.62	1.47	0.83	0.014
Wisner II	7.8	42.8	0.8	0.47	0.14	0.31	0.47	1.32	0.68	0.011
Aquod:										
Brimley I	7.5	34.8	2.8	0.41	0.21	0.21	0.66	1.21	0.50	0.013
Brimley II	7.4	46.8	2.9	0.43	0.19	0.33	0.70	1.20	0.78	0.019

continued

Table 6 -- Continued

Soil Suborder and Series	pH	HCl 12.0 N ppm	HCl 0.1 N ppm	$Ca(NO_3)_2$ 0.2 N ppm	$Mg(NO_3)_2$ 0.2 N ppm	$MgSO_4$ 0.2 N ppm	$MgSO_4$ 0.4 N ppm	EDTA ppm	NH_4OAc 1.0 N ppm	H_2O ppm
Aquoll:										
Colwood I	7.5	36.0	4.4	0.45	0.16	0.33	0.78	1.73	0.87	0.016
Lenawee I	6.9	58.8	6.9	0.50	0.16	0.31	0.78	1.77	0.97	0.016
Orthod:										
Kalkaska	5.9	19.2	4.8	2.07	1.40	1.43	2.17	3.64	1.37	0.033
Karlin III	5.7	18.8	1.9	1.28	0.75	1.17	2.04	2.27	0.78	0.036
Udalf										
Hillsdale	6.6	34.2	2.5	0.82	0.37	0.41	0.84	1.32	0.63	0.033
Hodunk	6.3	30.8	1.7	0.85	0.26	0.55	0.84	1.43	0.63	0.030
Locke	5.8	16.8	2.3	1.37	0.74	0.90	1.74	2.00	1.10	0.045
Miami	7.2	27.3	2.1	0.50	0.13	0.38	0.70	1.14	0.83	0.016

Wisner II silty clay loam). As previously mentioned, total and extractable Zn were highly variable within and between suborders.

More than twice as much Zn was usually extracted from soils with 0.2 N $Ca(NO_3)_2$ as compared with 0.2 N $Mg(NO_3)_2$ indicating that Ca^{++} was more effective than Mg^{++} in replacing exchangeable Zn^{++} or $(ZnOH)^{+}$ at low salt concentrations. The Ca^{++} ion was possibly more effective than Mg^{++} in reducing the zeta potential because of the smaller hydrated size of Ca^{++}. Also, about twice as much Zn was extracted from soils by 0.4 N $MgSO_4$ as was extracted by 0.2 N $MgSO_4$, possibly because of the higher concentration of Mg ions and--to a much lesser extent--a longer extraction time and larger soil:solution ratio. More Zn was generally extracted by 0.2 N $MgSO_4$ than by 0.2 N $Mg(NO_3)_2$.

Higher amounts of Zn were extracted by Ca and Mg salts from the Metamora soil in the aqualf suborder, the soils in the orthod suborder, and the Locke soil in the udalf suborder than from other soils. The pH values of these soils ranged from 5.7 to 6.2 with an average of 5.9. Lesser amounts of Zn were extracted from soils in the aquept, aquod, and aquoll suborders where the pH values of these soils ranged from 6.9 to 7.9, with an average of 7.5. The quantity of Zn extracted from soils by Ca and Mg salts was fairly consistent between soils within the various suborders, except for the Locke soil in the udalf suborder which was higher in extractable Zn than other soils in this suborder.

Greater quantities of Zn were extracted by 0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$ [EDTA] from soils in the aqualf and orthod suborders and the Locke soil in the udalf suborder than from other soils; however, the 2 Charity soils in the aquept suborder contained larger quantities of EDTA extractable Zn than the other soils in that suborder. Perhaps some Zn was removed by the EDTA chelate from carbonate minerals of these highly calcareous soils. The amount of Zn removed from soils by this extractant was generally not consistent between soils within various suborders.

Greater amounts of Zn were extracted by 1.0 N NH_4OAc from the soils which contained large amounts of EDTA extractable Zn, except for the Charity soils. No consistency was observed for amount of 1.0 N NH_4OAc extractable Zn from soils within various suborders.

The Metamora soil in the aqualf suborder, soils in the orthod suborder, and soils, except Miami, in the udalf suborder contained the largest amount of H_2O extractable Zn. The pH values of these soils ranged from 5.7 to 6.6 with an average of 6.0. Smallest amounts of Zn were extracted from the Conover soil in the aqualf suborder, soils in the aquept suborder, soils in the aquod suborder, soils in the aquoll suborder, and the Miami soil in the udalf suborder. The pH values of these soils ranged from 6.9 to 7.9 with an average of 7.5. The quantity of Zn removed from soils by H_2O was only consistent within the aquoll and orthod suborders.

The amount of Zn extracted by Ca and Mg salts, EDTA, 1.0 N NH_4OAc, and H_2O generally increased as soil pH decreased; however, total and 0.1 N HCl extractable Zn were not correlated with soil pH values. Therefore, the Ca and Mg salts, EDTA, 1.0 N NH_4OAc, and H_2O removed largest amounts of Zn from soils in the orthod suborder, the Locke soil in the udalf suborder, and the Metamora soil in the aqualf suborder than from other soils. In addition, H_2O extracted comparatively large amounts of Zn from the Hodunk and Hillsdale soils in the udalf suborder, 1.0 N NH_4OAc extracted large amounts of Zn from Conover soil in the aqualf suborder, and EDTA extracted large amounts of Zn from the Conover soil and the 2 Charity soils in the aquept suborder. The amount of Zn extracted by Ca and Mg salts was fairly consistent for soils within the same suborder, but the amount of Zn removed by other extractants (listed in Table 6) was generally not consistent for soils within the same suborder.

Zinc Extracted From Soils After Final Cropping

Liming soils after the first and/or second crop of pea beans generally resulted in a significant decrease in Zn extracted by H_2O, 1.0 N NH_4OAc, 0.1 N HCl, and EDTA after the third cropping (Table 7). The amount of Zn extracted by these 4 extractants was not appreciably altered during cropping of unlimed soils.

Soils with pH values less than 6.4 (Metamora I soil in the aqualf suborder, soils in the orthod suborder, and all

Table 7. Amount of Zn extracted from Michigan soils by 4 extractants before and after growing 3 crops of pea beans. Rates of lime application are given for those soils that were limed.

Suborder and Series	Total Lime Applied	PPM Zn extracted before cropping				PPM Zn extracted after final cropping			
		Distilled Water	1.0 N NH_4OAc	0.1 N HCl	0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$	Distilled Water	1.0 N NH_4OAc	0.1 N HCl	0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$
	pp2m								
Aqualf:									
Conover	28,000	0.019	1.17	5.3	3.51	0.016	0.33	4.6	2.07
Metamora I	36,000	0.031	0.93	2.2	2.15	0.013	1.15	2.1	0.83
Aquept:									
Breckenridge	24,000	0.018	0.75	4.3	1.40	0.015	0.35	4.2	1.17
Charity I	----	0.019	0.60	2.8	2.28	0.015	0.72	2.0	2.17
Charity II	----	0.014	0.65	0.8	2.90	0.014	0.75	0.8	2.50
Hettinger	----	0.021	1.00	6.0	1.50	0.016	1.18	6.4	1.60
Sims I	28,000	0.016	0.78	4.5	1.28	0.015	0.42	4.3	1.09
Sims II	----	0.019	0.83	4.2	1.80	0.018	0.68	4.5	1.74
Wisner I	----	0.014	0.83	3.7	1.47	0.016	0.55	3.8	1.20
Wisner II	----	0.011	0.68	0.8	1.32	0.014	0.72	0.4	1.20
Aquod:									
Brimley I	20,000	0.013	0.50	2.8	1.21	0.013	0.40	2.9	1.00
Brimley II	28,000	0.019	0.78	2.9	1.20	0.015	0.68	2.8	0.97

continued

Table 7 -- Continued

Suborder and Series	Total Lime Applied	PPM Zn extracted before cropping				PPM Zn extracted after final cropping			
		Distilled Water	1.0 N NH_4OAc	0.1 N HCl	0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$	Distilled Water	1.0 N NH_4OAc	0.1 N HCl	0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$
	pp2m								
Aquoll:									
Colwood I	24,000	0.016	0.87	4.4	1.73	0.012	0.40	4.0	1.38
Lenawee I	28,000	0.016	0.97	6.9	1.77	0.012	0.50	6.0	1.54
Orthod:									
Karlin III	36,000	0.036	0.78	1.9	3.64	0.024	0.87	1.9	3.12
Kalkaska	36,000	0.033	1.37	4.8	2.27	0.021	1.15	4.7	2.00
Udalf:									
Hillsdale	28,000	0.033	0.63	2.5	1.32	0.012	0.58	2.5	1.60
Hodunk	6,000	0.030	0.63	1.7	1.43	0.015	0.42	1.0	1.08
Locke	34,000	0.045	1.10	2.3	2.00	0.020	0.85	2.0	1.12
Miami	24,000	0.016	0.83	2.1	1.14	0.012	0.41	2.1	0.86

soils except Miami in the udalf suborder) contained only about one-half as much H_2O extractable Zn after liming as they did prior to liming; other soils contained about three-fourths as much water extractable Zn after liming. Only one-half as much 1.0 N NH_4OAc extractable Zn was removed from soils in the aquept, aquod, and aquoll suborders after liming as before liming, but other soils contained variable amounts of 1.0 N NH_4OAc extractable Zn after liming. Soils in the aqualf suborder contained only 50 percent as much EDTA extractable Zn after they were limed while other limed soils contained approximately 75 percent as much EDTA extractable Zn as they did prior to liming.

Relationship Between Extractable Soil Zinc and Yield and Zinc Uptake by Pea Beans

Of the 20 soils used in the greenhouse experiment (discussed in previous section), yields were increased or not affected by Zn fertilization on 12 soils, but were decreased by Zn fertilization on the remaining 8 soils. In order to relate Zn soil tests to pea bean yields, only the results from the 12 soils where yields responded positively were used. Since actual yields varied significantly on the different soils, relative rather than actual yields were used in all correlations with soil tests. Relative yields again were calculated using the equation previously given.

Highest linear correlations between relative yield and extractable Zn were obtained when soil Zn was extracted with 1.0 N NH_4OAc, H_2O, and 0.1 M EDTA + 1.0 M $(NH_4)_2CO_3$ [EDTA] while significant correlations were obtained when Zn was extracted with 0.2 N $Ca(NO_3)_2$ and 0.2 N $MgSO_4$ (Table 8). While the correlation coefficient was statistically significant, the correlation between relative yield and 0.2 N $Mg(NO_3)_2$ extractable Zn was not real, as it indicated that yield decreased as extractable Zn increased. No linear correlation between yield and extractable Zn was noted when soils were extracted with 0.1 N HCl, 12 N HCl, or 0.4 N $MgSO_4$.

In order to determine if a non-linear relationship existed between relative yield and extractable soil Zn, multiple correlations between extractable Zn and relative yield were calculated using the following equation (Zn = extractable soil Zn):

$$\text{Relative Yield} = a + b(Zn) + C(Zn^2)$$

With the use of this quadratic equation, higher correlations between relative yield and extractable Zn were obtained when soil Zn was extracted with 0.2 N $Mg(NO_3)_2$, 12 N HCl, and 0.4 N $MgSO_4$ than were obtained by fitting linear regressions, but correlations between Zn removed by other extractants and relative yield were not greatly improved (Table 8). No multiple correlation coefficients were given for 0.1 N HCl, since the curve fitted using the computer program was not compatible with established yield response data.

Since yield response to Zn application in the greenhouse, together with the factors discussed in the preceding

Table 8. Linear and multiple correlation coefficients between relative yield of the first crop of pea beans and extracted soil Zn (Zn) and extractable soil Zn plus soil pH (Zn + pH).

Extracting Agents	Correlation Coefficients		
	Linear	Multiple	
	Zn	Zn	Zn + pH
	r	R	R
Distilled water	0.52**	0.53**	---
0.2 N $Mg(NO_3)_2$	-0.32*	0.52**	---
0.2 N $Ca(NO_3)_2$	0.38**	0.45**	---
0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$	0.43**	0.50**	0.71**
0.1 N HCl	0.28	---	0.61**
12 N HCl	0.09	0.34*	---
0.2 N $MgSO_4$	0.29*	0.33*	---
1.0 N NH_4OAc	0.55**	0.55**	---
0.4 N $MgSO_4$	0.02	0.35*	---

*Significant at 0.05 level.

**Significant at 0.01 level.

discussion section concerning extractable Zn on the different soils, indicated that Zn availability was related to soil pH, another series of multiple regression equations were fitted using the following equation (pH = soil pH):

$$\text{Relative Yield} = a + b(\text{Zn}) + c(\text{Zn}^2) + d(\text{pH}) + e(\text{pH}^2) + f(\text{Zn} \cdot \text{pH})$$

Higher correlations were obtained with EDTA and 0.1 N HCl when soil pH was included in the correlations (Table 8). Multiple correlation coefficients are not reported for H_2O and 1.0 N NH_4OAc extractable Zn, since the curves fitted using the computer program were again not compatible with yield response data.

With the curve fitted using the computer program, yields were increased on soils on which Zn extracted by EDTA and 0.1 N HCl increased when soil pH values of 7.0 and 7.5 were included in the correlations (Figures 2 and 3). Highest yields could be expected from soils at pH 7.0 on which 1.5 and 3.5 ppm Zn were extracted with EDTA and 0.1 N HCl respectively. Highest yields could be expected from soils at pH 7.0 on which 2.5 and 7.0 ppm Zn were extracted with EDTA and 0.1 N HCl respectively. Only small increases in yield of pea beans would be expected after addition of Zn to similar Michigan soils with pH values equal to or less than 7.0, but increases in yield after Zn application would be expected to vary greatly with amounts of EDTA or 0.1 N HCl extractable Zn from soils with pH values of approximately 7.5.

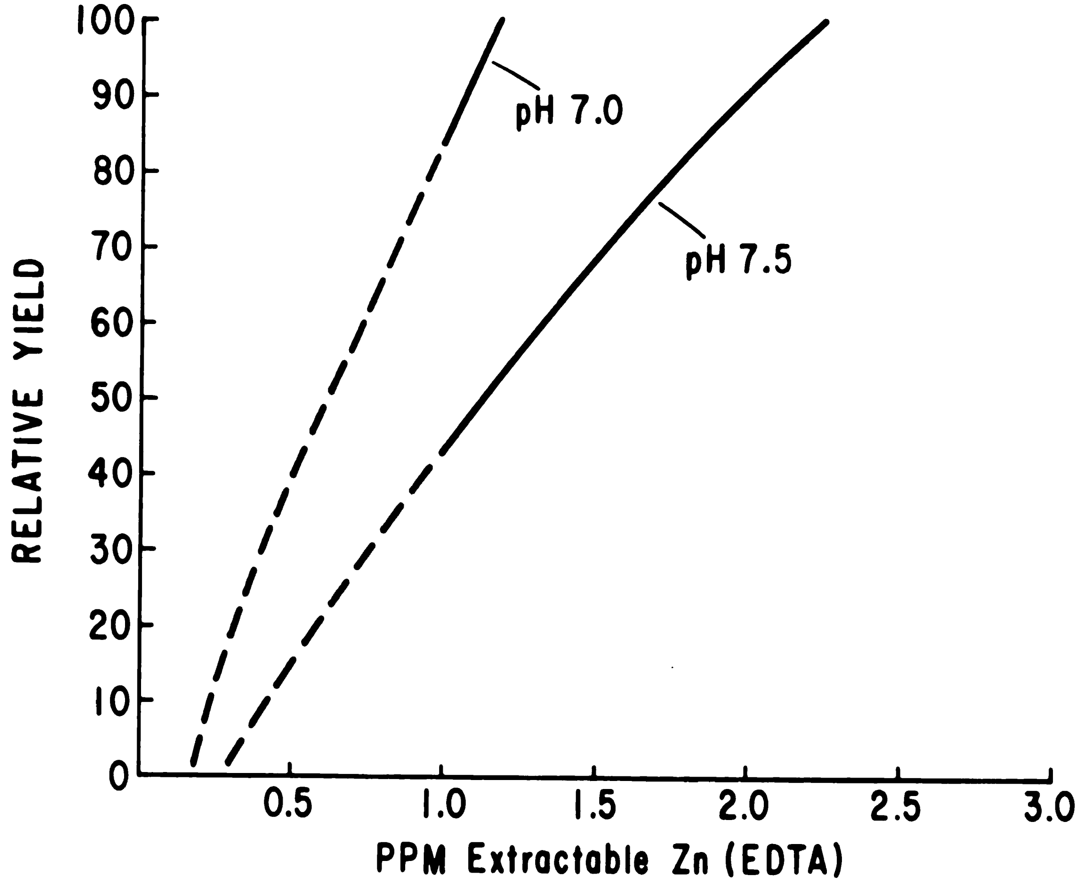

Figure 2. Relation between relative yield and 0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$ extractable Zn at pH 7.0 and pH 7.5.

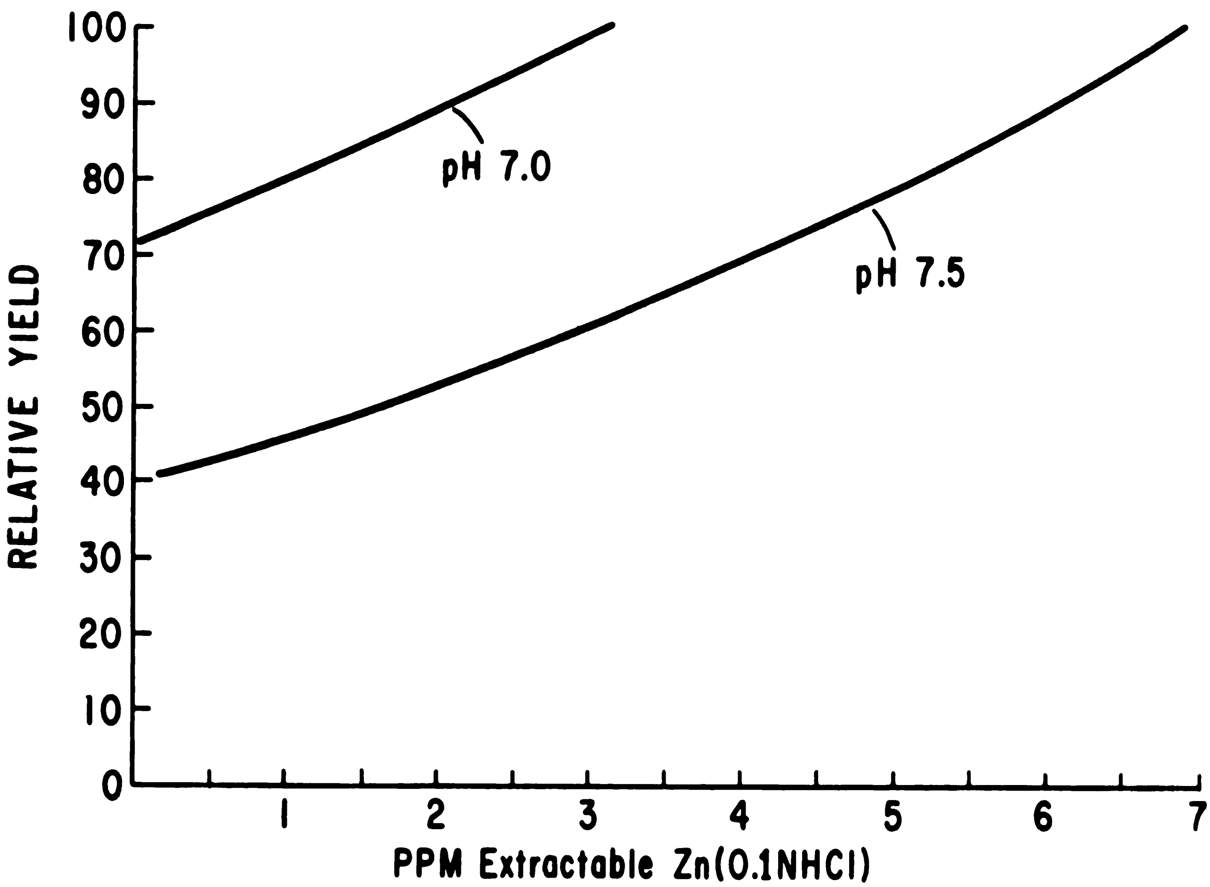

Figure 3. Relation between relative yield and 0.1 N HCl extractable Zn at pH 7.0 and pH 7.5.

Highly significant linear correlations between plant uptake of Zn and soil extractable Zn were obtained when the extractants used were H_2O, EDTA, or 1.0 N $(NH_4)_2OAc$ (Table 9). No correlation between Zn uptake and extractable Zn was noted when these 20 soils were extracted with 0.1 N HCl. Amount of Zn removed from soils by beans was highly linearly correlated with soil pH, but curves fitted using the computer program for multiple correlations were not compatible with established Zn uptake data.

Field Results

Extractable Zn (0.1 N HCl) was determined for 15 soils where field experiments with pea beans were located from 1964 to 1967, inclusively (Table 10). Relative yields were highly correlated with 0.1 N HCl extractable Zn (Figure 4, $r = 0.60$). Multiple correlations which included soil pH were not determined, since pH only varied from 7.2 to 8.0.

Using the equation calculated for the field experiments, maximum yields were obtained when the soil contained 8.2 ppm extractable Zn.

Table 9. Linear correlations between extractable Zn, pH, and Zn uptake by pea beans on 20 Michigan soils used in greenhouse and laboratory evaluations.

Independent Variables	Linear Correlation Coefficients r
H_2O	0.84**
0.01 <u>M</u> EDTA + 1.0 <u>M</u> $(NH_4)_2CO_3$	0.43**
0.1 <u>N</u> HCl	-0.04
1.0 <u>N</u> NH_4OAc	0.52**
pH	-0.79**

**Significant at 0.01 level.

Table 10. Yield of pea beans, soil pH, and concentrations of Zn extracted from 15 Michigan soils utilized for field studies.

Soil Suborder and Type	Year of Experiment	County	Average Without Zn bu/ac	Maximum With Zn bu/ac	pH	Zn Extracted by 0.1 N HCl ppm
Aquept:						
Pickford clay loam	1965	Arenac	20.0	26.3	7.4	4.7
Pickford clay loam	1966	Arenac	16.2	26.1	7.4	4.1
Pickford clay loam	1967	Arenac	16.2	26.6	7.4	3.7
Sims clay loam I	1965	Saginaw	23.6	27.4	7.2	5.2
Sims clay loam II	1966	Bay	22.2	30.0	7.3	4.2
Tappan loam	1964	Tuscola	15.4	20.1	7.7	5.2
Wisner silty clay loam	1966	Saginaw	0.0	24.1	7.8	0.8
Wisner clay loam	1964	Saginaw	12.3	16.7	7.7	2.8
Wisner clay loam	1964	Saginaw	7.6	37.4	7.4	5.2
Wisner silty clay loam	1965	Saginaw	0.0	----	8.0	0.7
Wisner silty clay loam	1967	Saginaw	16.7	27.9	7.8	0.8
Aquod:						
Brimley silt loam I	1965	Midland	4.2	22.0	8.0	2.8
Brimley silt loam II	1966	Midland	18.9	33.5	7.7	2.9
Brimley silt	1967	Midland	25.1	31.8	7.7	3.0
Aquoll:						
Colwood loam	1964	Midland	29.1	35.3	7.7	4.4

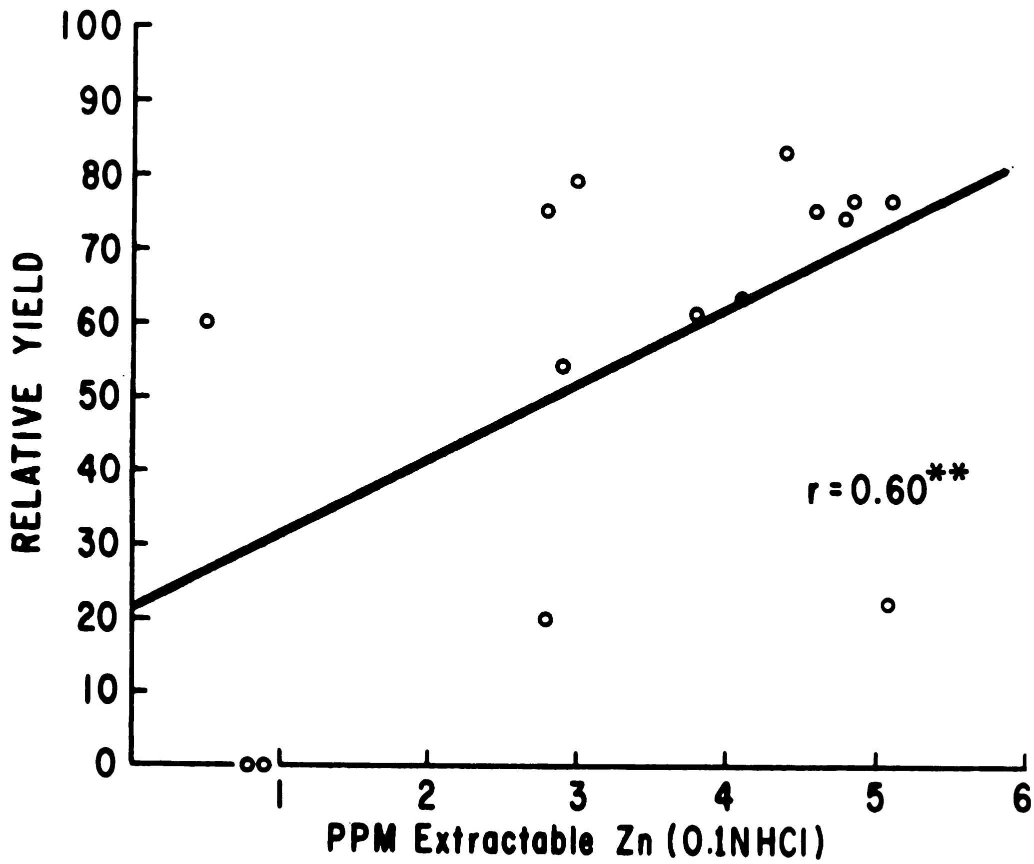

Figure 4. Relation between relative yield in the field and Zn extracted from soils by 0.1 N HCl.

SUMMARY AND CONCLUSIONS

Sixty-five Michigan soils varied greatly in both total (12 N HCl) and acid extractable (0.1 N HCl) Zn, both within and between suborders and series. Soil pH increased with profile depth on most of the soils, and considerable variation was observed within and between suborders. Measurements of total and extractable Zn together with soil pH, did not identify those soils where additional Zn might be needed for beans.

Since measurements of total and 0.1 N HCl extractable Zn in Michigan soils did not adequately evaluate their Zn status, 20 of the 65 soils originally investigated were chosen for more intensive greenhouse and laboratory studies. Three Zn levels were established on each soil and 3 successive bean crops were subsequently grown on each soil. The effectiveness of various methods of extracting soil Zn was evaluated by correlating extracted soil Zn with yields and Zn uptake by the plants.

Yields of the first pea bean crop were increased by Zn application in soils testing above pH 7.1, and were not affected on soils testing 7.1 or lower. Marked yield decreases were noted when Zn was applied to soils testing below 6.3. The amount of Zn extracted by Ca and Mg salts, 0.01 M EDTA + 1.0 M $(NH_4)_2CO_3$ [EDTA], 1.0 N NH_4OAc, and H_2O

generally increased as soil pH decreased, but total and 0.1 N HCl extractable Zn were not correlated with soil pH values. Total concentration and uptake of Zn by pea beans was significantly greater in plants grown on coarse textured soils with pH values below 6.7 as compared to plants grown on the other soils. On the basis of these findings, pea beans would not be expected to respond to Zn application on soils with pH values below 7.0.

On soils where yields of the first crop were increased or not changed when Zn was applied, large increases in yields were obtained when Zn concentration in the tissue was increased from approximately 10 to 30 ppm. On all soils, highest yields were obtained when the Zn concentration in the plants was between 25 and 34 ppm.

Marked yield depressions resulted from a Zn concentration greater than 50 ppm. These yield depressions were attributed to Zn toxicity since yields were decreased on the same soil by the addition of Zn. This suggests that over 50 ppm Zn concentration may also be injurious to beans grown in the field.

The narrow range of 25 to 34 ppm Zn concentration for maximum yields of pea beans grown in the greenhouse was quite similar to Zn concentration found for maximum yield in the field. However, insufficient quantities of Zn were applied to soils to get significant yield depressions in the field. It is very probable that large field applications (10 pp2m or greater) of Zn on some Michigan soils, especially those with coarse textures and pH values less than 7.0, would result in injury due to toxicity.

Yields obtained in the greenhouse for the first crop were generally as high when 7.5 pp2m Zn were applied to soils as when 15.0 pp2m Zn were applied. Only one-half (4 pp2m) as much Zn as $ZnSO_4$ was needed to obtain highest yields in the field. Zinc concentration and uptake by plants increased with increasing rates of Zn fertilization in both the greenhouse and field.

Of the 20 soils used in the greenhouse experiment, yields of the first crop were increased or not affected by Zn fertilization on 12 soils, but were decreased by Zn fertilization on the remaining 8 soils. In order to relate Zn soil tests to yields, only the results from the first 12 soils were used. Since actual yields varied significantly on the different soils, relative rather than actual yields were used in all correlations between yields and soil tests. Relative yields were calculated using the following equation:

$$\text{Relative Yield} = \frac{\text{Actual Yield without Zn}}{\text{Maximum Yield with Zn}} \times 100$$

Highest linear correlations between relative yield and extractable Zn were obtained when soil Zn was extracted with 1.0 $\underline{N}$ NH_4OAc, H_2O, and EDTA.

Since yield response to Zn fertilizer in the greenhouse, together with other factors concerning extractable Zn on the different soils, indicated that Zn availability was related to soil pH, another series of multiple regression equations were fitted using the following equation (pH = soil pH):

$$\text{Relative Yield} = a + b(Zn) + c(Zn^2) + d(pH) + e(pH^2) + f(Zn \cdot pH)$$

Higher correlations were obtained with EDTA and 0.1 N HCl when soil pH was included in the correlations. With the curve fitted using the computer program, yields were increased on soils on which Zn extracted by EDTA and 0.1 N HCl increased if soil pH values of 7.0 and 7.5 were included in the correlations. Only small increases in yield would be expected after Zn fertilization of similar Michigan soils with pH values equal to 7.0, but increases in yield after Zn application would be expected to vary greatly with amounts of EDTA or 0.1 N HCl extractable Zn from soils with pH values of approximately 7.5. A similar relationship was observed on 15 soils when 0.1 N HCl extractable Zn was linearly correlated with relative yields in the field, but multiple correlations which included soil pH were not determined since pH only varied from 7.2 to 8.0. Using the equation calculated for the field experiments, maximum yields were obtained when the soil contained 8.2 ppm extractable Zn. Assuming a pH of 7.6 in the greenhouse experiment, maximum yields would have been obtained when the soil contained approximately 7 ppm extractable Zn. On the basis of both greenhouse and field studies, it was suggested that the 0.1 N HCl extraction procedure was the most desirable of all the Zn soil tests utilized in these experiments. It should be desirable, however, to initiate further field studies to better evaluate the EDTA extractant as a Zn soil test for Michigan soils.

For the second crop, lime was applied to all soils on which yield depressions were obtained after Zn application for the first crop. After liming the Locke and Hodunk soils in the udalf suborder and the Metamora soil in the aqualf suborder, yields were increased when Zn fertilizer was applied. On the Kalkaska and Karlin soils, liming appeared to depress yields, and Zn fertilizers were not effective in increasing yields. It is quite probable that liming some of these low pH soils of Michigan to pH values of 6.5 (the pH value recommended for most agronomic crops) would result in a Zn deficiency for Zn responsive crops such as pea beans.

For the third crop, lime was applied to all soils on which pH values were below 7.0 after the second crop. Yields were increased by Zn fertilization on 11 of the 13 limed soils. On the Kalkaska and Karlin soils, Zn fertilizers were again ineffective in increasing yields.

Liming for both the second and third crops progressively increased relative yield differences obtained from soils at the 0 and at the 15.0 pp2m Zn applications. The difference may be due to an increase of an insoluble compound such as calcium zincate with liming. Yields at each Zn level generally decreased when large quantities of lime were applied to soils. Increasing the rate of Zn application from 7.5 to 15.0 pp2m generally did not result in significant yield increases.

Zinc concentration and uptake by pea beans were generally increased by Zn fertilization on limed soils; however, liming soils for both the second and third crops resulted in a progressive decrease of Zn concentration and uptake in the plant. Similar quantities of Zn fertilizer were extracted from these soils by pea bean crops (a trace to 1.0 percent at both 7.5 and 15.0 pp2m Zn application). Liming soils after the first and/or second crop resulted in a significant decrease in Zn extracted by H_2O, 1.0 N NH_4OAc, 0.1 N HCl, and EDTA.

Yields of the second crop of beans were increased more than yields of the first crop after applying Zn to the unlimed soils. The greater response may have been due to higher P fertilization rates. Higher yields on soils with both 7.5 and 15.0 pp2m Zn applications may also have been due to higher P rates. A gradual increase in Zn uptake by beans was generally obtained at each Zn treatment on unlimed soils from the first to third crops, and the increase in uptake may have been due to a gradual decrease in pH values from the first to third crops. Uptake was inversely correlated with soil pH values. Similar quantities of Zn fertilizer were extracted from unlimed soils by pea bean crops (0.1 to 3 percent at both 7.5 and 15.0 pp2m Zn application).

Conclusions from this investigation considered to be most important were:

1. Pea beans generally did not respond to Zn application on soils with pH values below 7.0.

2. On all soils, highest yields were obtained when the Zn concentration in plants was between 25 and 34 ppm.
3. On the basis of both greenhouse and field studies, a 0.1 N HCl extraction procedure was found to be a good soil test for plant available Zn in Michigan.
4. Generally, yields were increased when Zn fertilizers were applied after liming soils which tested pH 6.3 or below.

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APPENDIX

Table 1A. Suborders and series, texture, depth, pH, extractable Zn, and county of 65 Michigan soils.

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil: Extractable Zn	ppm Zn in Soil: Total Zn	County
Aqualf:						
Conover	loam	0-11	7.1	5.3	63.2	Eaton
	clay loam	11-14	7.6	2.4	52.8	
	clay loam	14-22	7.3	3.9	53.6	
	loam	22-40	7.6	3.7	34.4	
	loam	40-48	8.1	0.6	38.0	
Macomb I	loam	0-12	7.2	6.9	46.4	Shiawassee
	loam	12-19	7.5	5.3	48.4	
	loam	19-30	7.6	6.9	55.2	
	loam	30-41	8.0	6.6	49.2	
Macomb II	sandy loam	0-10	7.5	2.4	47.6	Shiawassee
	sandy loam	10-16	7.2	1.3	54.8	
	sandy loam	16-21	7.1	1.4	41.2	
	loam	21-29	7.1	2.0	54.0	
	clay loam	29-34	6.7	3.2	74.8	
Metamora I	sandy loam	0-10	6.2	2.2	27.6	Ingham
	sandy loam	10-15	6.2	1.3	34.4	
	sandy loam	15-19	6.3	0.9	21.6	
	sandy loam	19-36	6.4	1.0	20.8	
	loamy sand	36-45	6.5	1.0	22.4	
	loam	45-55	6.2	2.2	44.0	
Metamore II	loam	0-7	7.2	7.5	40.8	Eaton
	sandy loam	7-12	7.3	1.8	29.6	
	sandy loam	12-24	7.5	0.4	27.2	
	loam	24-37	7.4	0.3	29.6	
	loam	37-46	7.5	0.7	32.8	

continued

Table 18.—(continued)

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	ppm Zn in Soil Total Zn	County
Aqualf:						
Nappanee I	loam	0-10	7.2	5.0	56.8	Monroe
	clay	10-30	7.3	3.7	34.4	
	clay	30-40	7.8	0.6	66.4	
Nappanee II	clay loam	0-7	7.3	8.0	54.5	Monroe
	clay	7-22	7.4	0.6	66.8	
	clay	22-42	7.8	0.7	62.2	
Aquept:						
Breckenridge	sandy loam	0-8	7.4	4.3	28.4	Midland
	sandy loam	8-20	7.6	4.3	23.6	
	loamy sand	20-36	8.3	0.8	9.2	
	clay loam	36-44	8.3	0.4	33.6	
Charity I	clay loam	0-9	7.7	2.8	42.4	Arenac
	clay	9-23	7.7	0.5	41.2	
	clay	23-43	7.8	0.6	51.6	
	clay	43-49	8.0	0.6	36.0	
Charity II	clay loam	0-8	7.9	0.8	40.0	Arenac
	clay	8-24	8.0	0.4	44.0	
	clay	24-36	8.1	0.6	31.6	
	clay	36-47	8.1	0.4	27.6	
Hettinger	silty clay loam	0-10	7.5	6.0	44.4	Midland
	silty clay loam	10-19	7.7	5.3	39.2	
	silty clay loam	19-33	7.7	2.9	36.8	
	silty clay loam	33-48	7.8	0.6	36.0	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Aquept:						
Pickford	clay loam	0-7	7.2	4.1	37.4	Arenac
	clay loam	7-18	7.3	2.8	40.0	
	clay	18-26	7.4	0.8	49.2	
	clay	26-40	7.7	0.4	41.2	
	clay	40-48	7.7	0.5	48.8	
Sims I	clay loam	0-11	6.8	4.5	40.0	Saginaw
	clay loam	11-25	7.3	2.9	36.8	
	clay loam	25-32	8.1	0.5	27.6	
	clay loam	32-49	8.1	0.4	42.0	
Sims II	clay loam	0-8	7.6	6.9	58.8	Bay
Sims III	clay loam	0-10	7.2	7.3	59.6	Saginaw
	clay loam	10-24	8.1	0.8	42.0	
	clay loam	24-37	7.9	6.0	48.0	
	clay loam	37-47	8.2	0.5	28.4	
Sims IV	clay loam	0-14	7.6	9.3	35.2	Bay
	clay loam	14-23	7.8	8.1	33.2	
	clay loam	23-40	8.1	0.8	30.8	
	clay loam	40-46	8.1	0.2	25.2	
Sims V	clay loam	0-8	7.6	8.6	33.2	Bay
	clay loam	8-27	7.8	3.3	28.0	
	clay loam	27-40	8.0	4.7	29.6	
	clay	40-45	8.2	0.3	24.4	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil: Extractable Zn	ppm Zn in Soil: Total Zn	County
Aquept:						
Sims VI	clay loam	0-12	7.8	1.1	45.2	Saginaw
	clay loam	12-24	8.1	2.0	42.0	
	clay loam	24-36	7.6	0.8	33.6	
	clay loam	36-48	8.1	0.5	32.8	
Sims VII	clay loam	0-11	7.5	8.0	54.0	Gratiot
	clay loam	11-32	8.0	0.5	40.8	
	clay loam	32-46	8.1	0.3	44.0	
Sims VIII	clay loam	0-11	5.9	7.5	53.2	Saginaw
	clay loam	11-15	6.6	7.8	60.8	
	clay loam	15-27	7.0	8.6	56.4	
	clay loam	27-38	6.5	9.1	71.2	
Sims IX	clay loam	0-0	7.8	18.2	64.8	Tuscola
	clay loam	9-28	7.9	5.4	53.2	
	clay loam	28-38	7.9	3.8	52.4	
	clay loam	38-48	8.0	0.6	41.2	
Tappan	loam	0-11	7.7	3.4	53.2	Tuscola
	loam	11-21	8.0	0.6	38.4	
	loam	21-31	8.2	0.4	34.4	
	loam	31-44	8.3	0.3	39.2	
Whittemore	clay loam	0-10	7.5	9.3	56.8	Arenac
	clay loam	10-23	7.3	4.5	54.0	
	clay loam	23-30	7.7	1.9	48.0	
	clay loam	30-45	8.3	0.4	26.4	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Aquept:						
Wisner I	loam	0-8	7.8	3.8	45.2	Bay
	clay loam	8-23	8.0	0.4	33.3	
	clay loam	23-33	8.1	0.4	31.2	
	clay loam	33-40	8.1	0.2	38.0	
Wisner II	silty clay loam	0-9	7.8	0.8	42.8	Bay
	clay loam	9-16	8.0	0.4	35.2	
	clay loam	16-34	8.1	0.4	42.8	
	clay loam	34-47	8.1	0.4	35.2	
Wisner III	loam	0-8	7.8	5.8	40.0	Bay
	clay loam	8-12	7.9	0.7	32.0	
	clay loam	12-18	7.9	0.7	32.0	
	clay loam	18-23	8.2	0.4	27.6	
	clay loam	23-36	8.3	0.4	27.2	
Wisner IV	loam	0-8	7.9	5.0	30.8	Bay
	loam	8-13	7.9	0.4	26.0	
	clay loam	13-20	8.1	0.5	22.4	
	clay loam	20-30	8.2	0.3	24.8	
	clay loam	30-40	8.2	0.3	24.8	
Wisner V	loam	0-10	7.9	3.7	28.0	Bay
	loam	10-12	7.6	0.7	22.0	
	clay loam	12-17	7.8	0.6	22.0	
	clay loam	17-23	7.8	0.8	24.8	
	clay loam	23-29	7.9	0.3	28.0	
	clay loam	29-40	7.7	0.3	22.8	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Aquept:						
Wisner VI	loam	0-8	7.9	4.5	33.6	Bay
	clay loam	8-14	7.7	0.7	22.4	
	clay loam	14-24	8.0	0.5	22.0	
	clay loam	24-30	8.1	0.3	28.4	
	clay loam	30-37	8.2	0.3	29.6	
Wisner VII	sandy clay loam	0-11	7.6	4.9	32.0	Bay
	clay loam	11-22	7.7	0.3	26.0	
	clay loam	22-32	8.2	0.6	28.0	
	clay loam	32-42	8.3	0.4	26.4	
Wisner VIII	loam	0-11	7.9	3.1	34.8	Bay
	loam	11-21	8.0	0.7	22.8	
	clay loam	21-35	8.0	0.3	40.0	
	clay loam	35-48	8.1	0.5	57.6	
Aquoll:						
Brookston I	loam	0-12	7.1	2.0	46.4	Eaton
	loam	12-16	7.3	1.7	34.4	
	loam	16-30	7.6	2.2	40.8	
	clay loam	30-40	7.6	2.4	46.4	
	clay loam	40-48	7.6	1.5	39.2	
Brookston II	loam	0-12	6.5	7.2	83.6	Eaton
	clay loam	12-18	6.5	5.9	85.2	
	clay loam	18-22	7.3	5.8	78.4	
	loam	22-43	8.2	0.5	33.2	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Aquoll:						
Brookston III	loam	0-9	6.8	3.1	44.0	Eaton
	loam	9-16	7.4	1.8	53.6	
	loam	16-24	7.5	3.0	49.2	
	clay loam	24-28	7.8	0.4	40.8	
	clay loam	28-37	8.3	0.3	38.0	
	clay loam	37-42	8.0	0.8	35.6	
Brookston IV	loam	0-8	7.2	2.9	40.8	Eaton
	loam	8-16	7.8	4.9	46.0	
	loam	16-22	7.9	0.6	36.8	
	clay loam	22-34	7.7	0.5	36.0	
	clay loam	34-42	8.3	0.6	35.2	
Brookston V	loam	0-10	7.0	4.2	40.4	Eaton
	loam	10-15	7.5	3.9	44.0	
	loam	15-24	7.5	3.9	41.2	
	clay loam	24-40	7.7	4.7	47.2	
	clay loam	40-45	7.9	0.7	42.4	
Colwood I	loam	0-9	7.7	4.4	36.0	Midland
	loam	9-29	7.8	4.2	53.2	
	loam	29-34	7.8	0.4	35.2	
	loam	34-46	8.0	0.3	51.2	
Colwood II	loam	0-9	7.8	5.4	39.2	Eaton
	loam	9-14	7.8	4.2	29.6	
	loam	14-22	8.0	5.0	22.8	
	loam	22-32	7.8	1.2	22.8	
	sandy loam	32-40	8.3	0.6	18.4	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	ppm Zn in Soil Total Zn	County
Aquoll:						
Hoytville I	clay loam	0-10	7.3	9-2	82.4	Monroe
	clay	10-18	7.0	19.6	80.0	
	clay	18-30	7.7	11.9	73.6	
	clay	30-42	7.8	0.6	88.0	
Hoytville II	clay loam	0-9	7.0	10.8	63.6	Lenawee
	clay	9-19	7.0	9.6	60.0	
	clay	19-35	7.9	5.3	64.0	
	clay	35-45	8.1	0.6	53.2	
Hoytville III	loam	0-10	6.4	8.2	58.8	Lenawee
	clay loam	10-30	7.5	3.1	60.4	
	clay	30-48	7.9	0.2	56.8	
Lenawee I	clay loam	0-11	6.9	6.9	58.8	Shiawassee
	clay loam	11-18	7.1	5.4	46.8	
	clay loam	18-32	7.2	6.3	42.8	
	clay loam	32-40	7.2	7.4	65.6	
Aquod:						
Brimley I	silt loam	0-13	7.7	2.9	46.8	Midland
	silt loam	13-25	7.7	0.9	34.0	
	silt loam	25-37	7.8	0.8	42.0	
	silt loam	37-48	8.1	0.2	37.2	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Aquod:						
Brimley II	silt loam	0-8	7.9	2.8	34.8	Midland
	silt loam	8-22	8.0	0.3	27.6	
	silt loam	22-31	8.2	0.7	25.2	
	silt loam	31-45	8.2	0.4	43.2	
Boralf:						
Kent	clay loam	0-8	5.5	2.9	34.4	Arenac
	clay loam	8-24	5.4	7.0	59.6	
	clay loam	24-30	7.8	0.4	40.4	
	clay loam	30-40	8.0	0.4	32.0	
	clay loam	40-48	8.2	0.3	42.4	
Ontonagon	clay	0-12	5.5	19.3	92.4	Ontonagon
Rudyard	clay loam	0-9	8.0	0.8	58.4	Midland
	clay	9-19	8.0	0.1	54.5	
	clay	19-26	7.7	8.0	55.2	
	clay	26-43	8.3	0.4	47.2	
Selkirk	clay loam	0-12	5.6	4.1	52.0	Arenac
	clay loam	12-18	5.5	4.5	46.4	
	clay	18-23	5.7	5.0	69.4	
	clay	23-42	7.6	0.4	59.6	
	clay	42-48	8.0	0.3	59.2	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Orthod:						
Emmet	sandy loam	0-7	7.4	4.5	42.4	Presque Isle
	sandy loam	7-9	7.2	3.7	43.6	
	sandy loam	9-16	7.2	2.5	31.6	
	sandy loam	16-30	7.8	0.7	16.4	
	sandy loam	30-48	8.3	0.5	20.8	
Kalkaska	loamy sand	0-8	5.5	4.8	19.2	Grand Traverse
	sand	8-17	5.6	2.1	15.6	
	sand	17-36	5.9	0.9	6.4	
	sand	36-47	5.8	1.0	8.4	
Karlin I	sandy loam	0-9	6.1	6.5	32.0	Grand Traverse
	loamy sand	9-14	6.6	1.2	19.6	
	sand	14-32	6.9	1.6	21.2	
	sand	32-36	6.7	1.4	5.6	
	sand	36-44	6.8	1.4	8.4	
Karlin II	sandy loam	0-9	5.8	3.4	30.8	Antrim
	sandy loam	9-20	5.4	1.4	27.2	
	sandy loam	20-29	5.3	0.8	20.0	
	loamy sand	29-37	5.5	0.9	24.0	
	sand	37-48	5.6	0.8	18.0	
Karlin III	sandy loam	0-8	5.7	1.9	18.8	Manistee
	loamy sand	8-14	5.7	1.9	15.6	
	sand	14-20	5.8	1.3	11.2	
	sand	20-30	6.0	1.1	10.0	
	sand	30-48	6.5	0.8	6.0	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Orthod:						
McBride	sandy loam	0-8	5.1	2.3	38.0	Lapeer
	sandy loam	8-12	5.8	0.9	31.6	
	sandy loam	12-15	6.3	1.0	33.6	
	sandy loam	15-24	6.1	2.1	35.2	
	sandy clay loam	24-32	6.7	4.5	54.8	
	loam	32-48	7.4	0.8	43.2	
Montcalm	loamy sand	0-10	4.8	2.1	26.8	Montcalm
Munising	sandy loam	0-10	5.3	3.2	17.6	Houghton
Udalf:						
Celina	loam	0-10	7.6	5.8	57.6	Genesee
	clay loam	10-17	7.7	4.9	54.8	
	clay loam	17-27	7.5	6.5	55.2	
	clay loam	27-29	7.9	2.2	53.2	
	clay	29-31	8.2	0.2	50.0	
	clay	31-42	8.3	0.5	47.2	
Hillsdale	sandy loam	0-9	6.6	2.4	35.2	Ingham
	sandy loam	9-16	6.8	1.0	32.0	
	loam	16-23	6.7	1.9	66.0	
	sandy loam	23-35	6.6	2.0	70.0	
	sandy loam	35-53	6.3	1.1	59.2	
Hodunk	sandy loam	0-12	6.3	1.7	30.8	Ingham
	loam	12-17	5.6	0.8	31.2	
	sandy loam	17-25	5.8	1.0	27.2	
	sandy clay loam	25-37	6.6	2.8	37.6	
	sandy clay loam	37-48	8.0	2.0	29.6	

continued

Table 1A -- continued

Suborder and Series	Texture	Depth (inches)	pH	ppm Zn in Soil Extractable Zn	Total Zn	County
Udalf:						
Kalamazoo	loam	0-9	6.1	3.0	30.0	Kalamazoo
	loam	9-18	6.0	1.3	27.6	
	loam	18-30	5.4	1.6	29.6	
	sandy loam	30-38	5.6	1.3	24.4	
	sand	38-48	6.0	1.4	22.8	
Lapeer	loam	0-14	6.6	6.0	29.2	Washtenaw
	sandy loam	14-35	7.1	5.3	27.2	
	sandy loam	35-56	7.0	0.6	27.2	
Locke	loam	0-11	5.8	2.3	16.8	Ionia
	sandy loam	11-22	5.8	1.6	18.0	
	sandy loam	22-28	5.6	2.5	24.8	
	sandy loam	28-36	5.9	1.7	26.8	
	sand	36-48	6.1	0.8	5.2	
Miami	loam	0-8	7.2	2.1	27.2	Eaton
	clay loam	8-12	6.6	1.0	38.4	
	clay loam	12-23	5.8	2.0	33.6	
	loam	23-42	7.8	2.1	16.0	
Udoll:						
Volinia	loam	0-10	5.6	3.5	44.8	Kalamazoo
	loam	10-14	5.0	1.4	48.0	
	loam	14-25	4.6	1.3	45.4	
	loamy sand	25-31	4.8	0.8	21.6	
	loamy sand	31-38	5.0	0.9	15.2	
	sand	38-48	5.1	0.9	9.6	