ZINC AND COPPER NUTRITION OF CORN ON MANITOBA SOILS

By

ADOLF S. K. NYAKI

A Thesis submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of Master of Science

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Winnipeg, Manitoba

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ABSTRACT

Zinc and Cu nutrition of corn (Zea mays L) was studied both under controlled and field environments on soils low in DTPA extractable Zn and/or Cu. The influence of fertilizer P on the extent and severity of Zn and Cu deficiencies in corn was also investigated.

Application of as little as 2 ppm Zn as $ZnSO_4.7H_2O$ increased dry matter yield of eight-week old corn shoots when grown under controlled environment on an Almasippi loamy very fine sand containing 0.51 ppm DTPA extractable Zn. However, when corn was grown in the field on an Almasippi loamy fine sand containing 0.52 ppm DTPA extractable Zn, Zn fertilization had no influence upon grain or total dry matter yields despite additions of up to 32 kg Zn/ha. Similarly, application of Zn on a Reinland fine sandy loam and Neuenburg very fine sandy loam containing 1.25 and 0.76 ppm Zn, respectively, did not increase total dry matter yield of corn shoots. Zinc concentration and uptake into corn shoots were increased both in the field and in the greenhouse. Drought severely restricted growth in the field experiments and was likely at least partially responsible for the lack of response in yield to Zn fertilization.

Increasing the level of P from 50 to 200 ppm accentuated Zn deficiency in the greenhouse when Zn was not applied resulting in a drastic decrease in dry matter yield and severe Zn deficiency symptoms. This effect was not evident in the field, likely due to lack of response to applied P as a result of dry weather.

Corn did not respond to applied Cu either in the field on an

Almasippi loamy fine sand containing 1.1 ppm DTPA extractable Cu or under controlled environment on an Almasippi loamy very fine sand containing 0.23 ppm Cu although Cu concentrations and/or uptake into corn shoots were increased significantly by Cu fertilization both in the field and greenhouse.

Corn was found to be Zn deficient in the greenhouse regardless of P level when the Zn concentration in mature leaf blades just prior to silking was less than 7.0 ppm. The critical level in corn shoots depended upon the level of P decreasing from 12.5 ppm Zn when 50 ppm P were applied to 7.5 ppm when the P level was increased to 200 ppm.

Levels of Fe and Mn in plant tissue were adequate in all cases for optimum growth but N, K and S levels were often not quite adequate, particularly in the greenhouse. The Zn critical levels determined in the greenhouse could not be applied to field conditions and may have been influenced by deficiencies of N, K and S. Critical levels could not be determined in the field because of the lack of response in yield to Zn fertilization.

The influence of soil volume on Zn response under controlled environment was also studied. Zinc fertilization increased dry matter yield of corn shoots at silking. Dry matter yield was also increased with increasing soil volume. Zinc concentration or uptake was not influenced by soil volume when Zn was not applied suggesting that the often observed greater frequency of response to Zn fertilization under controlled conditions is caused by some factors other than the restricted soil volume under controlled conditions. When Zn was applied, Zn uptake decreased with increasing soil volume likely because of decreasing root-available Zn contact and/or depressive effect caused by

increasing P uptake with increasing soil volume.

The uptake of all macronutrients into corn shoots increased with increasing soil volume because of increasing dry matter yield. However in the case of P and K plant concentrations also increased, suggesting that expanding soil volume increased plant uptake of P and K. The increase in yield with increasing soil volume may have resulted at least partially from correction of P and/or K deficiencies since plant concentrations of these nutrients were marginal.

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INTRODUCTION

Land area devoted to grain corn in Manitoba increased from 2,226 hectares in 1960 to 101,214 hectares in 1981. However, like many other crops, a limited amount of information is available concerning the micronutrient requirements of corn, particularly Zn and Cu. An extensive survey carried out in the mid-seventies indicated that on the basis of tissue analysis Zn was likely limiting corn yields in approximately 50% of Manitoba fields. The soils in the areas studied were perhaps not supplying enough Zn, but the plant critical levels of Zn in corn earleaves used to arrive at these conclusions were determined in the United States where growing conditions were quite different from those of Manitoba. Plant critical levels of Zn and Cu under Manitoba conditions need to be established. The increasing use of P fertilizers on the light textured corn soils and the known interaction between P and Zn necessitate studying the influence of applied P upon the extent and severity of Zn and Cu deficiencies.

The greater frequency of response to micronutrients by crops grown under controlled environment as opposed to field conditions is difficult to explain despite the large amount of information reported regarding the influence of such factors as temperature, soil pH, soil texture, $CaCO_3$ content and organic matter content on micronutrient availability to crops. It has been suggested that the restricted soil volume involved in greenhouse experiments may be responsible for the larger and more frequent responses to micronutrient fertilization in the greenhouse. Studies were therefore initiated:

(1) to determine if corn would respond to Zn and Cu fertilization both under field and greenhouse conditions;

(2) to determine the plant critical levels of Zn and Cu under both conditions;

(3) to determine the influence of applied P on the critical levels determined, and

(4) to determine the influence of soil volume upon Zn response in corn.

LITERATURE REVIEW

Incidence of Zinc and Copper Deficiencies

Zinc and Cu deficiencies in field crops are scattered throughout the world and occasionally become major soil fertility problems. The severity and the pattern of deficiency symptoms varied from one crop to another (Burleson, *et al.*, 1961; Bingham, *et al.*, 1960; Boawn and Leggett, 1964; Sharma, *et al.*, 1968; and Viets, *et al.*, 1954). Corn was reported as one of the most sensitive to low levels of soil Zn. Viets, *et al.* (1954) compared the susceptibility of beans, potatoes, onions and mustard to Zn deficiency and found that of the four crops, beans were most susceptible. Extreme variation in susceptibility to Zn deficiency among corn varieties was also reported. Halim (1968) found that some corn inbreds exhibited early resistance to Zn deficiency but became susceptible at later stages of growth while others were susceptible in early stages but became resistant later.

In contrast to Zn, corn did not appear to be particularly susceptible to Cu deficiency although some cases were reported in which corn was found to be Cu deficient. Berger (1962) reported that Zn deficiency in corn was prevalent in twenty states in the United States but Cu deficiency in corn was reported in only three states. Various crops were also rated with respect to their degree of response to micronutrient fertilization under conditions which were favourable to deficiency. The response of corn to Zn addition was rated as high but response to Cu was rated as medium (Anon, 1970).

Work reported thus far on the nutritional status of Manitoba corn (Racz, 1967; Smid and Spratt, 1974; and Spratt and Andrews, 1978) revealed that corn in Manitoba might be deficient in Zn. Sadler and Fehr (1975) reported that nearly half of the corn grown in Manitoba was Zn deficient but that Cu levels were usually sufficient. However, these conclusions together with those of Smid and Spratt (1974) and Spratt and Andrews (1978) were based upon plant critical levels established in the United States where growing conditions were different from those of Manitoba. Zinc and Cu applications to Manitoba corn in the field resulted in slight yield increases but these were not statistically significant (Racz, 1967).

Elsewhere, however, a number of significant yield increases to Zn and/or Cu fertilization in corn were reported (Berger, 1962; Coffman and Miller, 1973; Navrot and Ravikovitch, 1969; Oplinger and Ohlrogge, 1974; and Terman and Allen, 1964).

In contrast to corn, Zn and/or Cu responses were reported in other crops in Manitoba, particularly in the growth chamber. There were no responses to either Zn or Cu in cereal crops on mineral soils in the field although Akinyede (1978) obtained total dry matter yield increases in the environmental chamber in barley which had been fertilized with Cu and Zn. Similarly there were no responses to Zn or Cu in flax in the field although Haluschak (1972) reported significant dry matter yield increases to added Zn and Cu in the growth chamber. Out of seven experiments with blackbeans in the field, responses in grain yield to added Zn occurred only in one experiment (Loewen-Rudgers, 1978). However, Hedayat (1978) obtained significant dry matter yield increases in blackbeans and fababeans to added Zn and Cu in the environmental chamber. McKenzie (1980) also reported increases in blackbean dry matter yield as a result of Zn fertilization in the environmental chamber.

These findings indicate that responses to micronutrient fertilization on mineral soils were more prevalent in the growth chamber or greenhouse than in the field where significant yield increases occurred very infrequently. However, on organic soils, responses to Cu occurred both in the field and in the growth chamber although responses in the growth chamber were larger. McAndrew (1979) obtained significant increases in wheat grain yields on organic soils in the field after fertilizing with Cu. Copper additions to barley and oats in the field resulted in small increases in grain yields but these were not significant. However, in the growth chamber there were responses to Cu in wheat, barley, oats, flax and rapeseed although wheat and flax were considerably more responsive to Cu than the other three crops. Tokarchuk, et al. (1979) and Reid and Racz (1980) reported similar grain yield increases in wheat receiving Cu on organic soils. On one site, Reid and Racz (1980) also reported responses to Cu fertilization of barley. Rapeseed grain yields were not significantly increased by Cu fertilization. It is possible that if corn were grown on organic soils it would be deficient in Cu. But, the cool microclimate on organic soils in Manitoba precludes their use for corn production.

Soils likely to be Zinc and Copper Deficient

Reports in the literature from other areas Peech (1941); Berger (1962); Bingham, et al. (1964); Thorne (1957); and Vintosh, et al. (1973) suggested that Zn deficiency should be most likely in Manitoba on high-lime soils particularly when coarse-textured and when the weather is cool and wet during the early growing season. Work done by

McGregor (1972) and Akinyede (1978) on such soils resulted in responses to Zn application in the growth chamber in wheat and barley, but as mentioned earlier there were no responses to Zn on such soils in the field. Reports from other areas suggested that Cu deficiency should be most likely in Manitoba on organic (peat) soils but sandy soils may also be Cu deficient because of absolutely low levels of Cu. The lower pH of many sandy soils should make the Cu that is there quite available. Sandy soils containing lime may be higher in total Cu but their higher pH decreases plant availability of Cu. As mentioned earlier, Cu deficiencies were observed in Manitoba crops on organic soils by Tokarchuk, et al. (1979) and Reid and Racz (1980), and Cu fertilization resulted in increased yields. Copper fertilization did not increase wheat, oat, barley or flax yields on sandy mineral soils containing low available Cu. But crop yields in those experiments were often limited by other factors such as hail, frost, drought and armyworm damage.

The severity and extent of deficiency depended on the type of crop as well as weather conditions that prevailed during the growing season. Tokarchuk, et al. (1979) for example, reported significant yield increases to Cu fertilization in wheat on organic soils but no response in barley while Reid and Racz (1980) working on similar soils reported increases in barley yields on one site as a result of Cu fertilization. Despite lack of responses to Cu in wheat in 1980, wheat grain yields at all locations were greater than those obtained in previous years. Those increases were attributed to warmer temperatures in 1980. It should be apparent from the information presented thus far concerning the incidence of Zn and Cu deficiencies in Manitoba that more work is needed in order to determine the true extent and severity of both Zn and Cu deficiencies in Manitoba corn.

Zinc and Copper Deficiency Symptoms in Corn and Other Crops

Tisdale and Nelson (1975) indicated that Zn deficiency symptoms began in most crops on the younger leaves as interveinal chlorosis. In many crops Zn deficiency resulted in shortened internodes which led to rosetted appearance in crops such as flax. Zinc deficiency in corn and sorghum was often called "white bud" because the newly emerging leaves appeared pale green or white. Viets, et al. (1954) reported that in corn interveinal chlorosis was accompanied by severely shortened internodes and severe stunting of the entire plants. Similar symptoms were observed earlier in corn by Barnette (1935). More recently, Bates and Johnstone (1975) reported that Zn deficiency in corn in Ontario was very common but was rarely severe. It occurred in patches in the field at the 4th to 6th leaf stage. They described the less severe Zn deficiency symptoms as broad whitish stripes on one or both sides of the midrib in the second and third leaf from the top.

As mentioned earlier, Halim, et al. (1968) found that not only the degree but also the pattern of Zn deficiency symptoms varied with strains of corn. He observed that susceptible varieties had poor root development and that they either exhibited white chlorosis or purple coloration at the base of the shoot. Others exhibited "white bud" symptoms. He added that under severe conditions one cross developed necrosis of leaves followed by death of the plants.

Severity of Zn deficiency also varied among crops as mentioned before. Viets, et al. (1954) found that field beans were very sensitive to Zn deficiency compared to crops such as potatoes, wheat, barley, oats and alfalfa which did not exhibit Zn deficiency symptoms when grown on the same soil as the beans. They added that in some cases application of Zn did not result in significant yield increases although Zn deficiency symptoms were very apparent, while in other cases yield increases were obtained on applying Zn fertilizer without any visible Zn deficiency symptoms. Berger (1962) reported increases of up to 30% in corn yields on applying Zn without apparent Zn deficiency symptoms. Similar findings were reported by Shukla and Morris (1967).

Giordano (1966) reported that Zn deficiency symptoms appeared in corn in the field three to four weeks after seeding. The time of appearance of Zn deficiency symptoms may vary particularly in the greenhouse depending on the factors which affect Zn availability such as soil and air temperature, light conditions, soil pH and available soil P.

Tisdale and Nelson (1975) and Berger (1962) also described symptoms of Cu deficiency in crops as yellowing and stunting of the younger leaves which later became pale as severity increased, followed by dieback of the older leaves. Teakle, et al. (1941) reported that leaves of Cu deficient corn became chlorotic, followed by withering and graying of the tips. They added that the tips later bent and lost turgor and those of newly emerging leaves died. This description indicates that Cu deficiency symptoms in corn is mainly confined to the leaves while in the case of Zn the internodes are also affected as described before. Experience with vegetable crops showed that when adequate Cu was lacking, flowering failed to take place (Tisdale and Nelson, 1975). Like Zn, tolerance to low Cu varied among crops. McAndrew (1979) proposed the order of tolerance to low Cu as rapeseed> barley> oats> wheat>

flax.

Plant Critical Levels

The definition of plant "critical level" varied greatly among researchers. Ulrich, et al. (1967) defined plant critical level as the nutrient concentration in the plant which produced 90% of the maximum yield. Jones (1967) and Farhoomand, et al. (1968) defined it as the nutrient concentration in the plant below which growth or crop yield was restricted. Oplinger and Ohlrogge (1974) defined critical levels from the economic point of view as the nutrient concentration beyond which further application of nutrient did not return a profit. Occasionally, responses to micronutrient fertilization were reported in which nutrient concentration in the tissue were above critical levels. Oplinger and Ohlrogge (1974) reported such findings in corn.

Many workers demonstrated that critical levels varied among crops and depended upon the plant part sampled, as well as the stage of growth. Taking this into consideration, Jones (1967) emphasized that careful sampling was important for meaningful interpretation of plant critical levels. The earleaves nutrient concentration at silking was normally used as a standard for comparison in corn. Using the earleaves Jones (1967) reported that Zn deficiency occurred when the Zn concentration at silking was less than 10 ppm while Cu deficiency occurred when the earleaves Cu concentration was less than 2 ppm. However, Stukenholtz, et al. (1966) reported that the earleaf critical level of Zn varied from 12 ppm in some hybrids of corn to 20 ppm in others. Melsted, et al. (1969) felt that the critical level of Zn in the earleaves was 15 ppm while that of Cu was 5 ppm. They added that these levels were also valid for wheat sampled as a whole plant at the boot stage and for soybeans when the youngest mature leaves and petioles at early podding were sampled. Some workers also used whole corn plants to establish critical concentrations of Zn and/or Cu in the plants. Coffman and Miller (1973) found that the critical level of Zn in thirty-day old corn plants was 12 ppm. Lockman (1969) used whole plants 30-45 days after emergence and reported that corn at this stage was sufficient in Zn when the concentration in the plants was 20-50 ppm and sufficient in Cu when the levels were 7-20 ppm. Critical levels of Zn and/or Cu in other crops in Manitoba were reported. Akinyede (1978) found that the critical Zn and Cu concentrations in six-week old barley grown in the environmental chamber were 12.5 ppm and 5.2 ppm, respectively. McGregor (1972) reported critical levels of Zn and Cu in eight-week old flax as 13 ppm and 3 ppm, respectively. McKenzie (1980) determined plant critical level of Zn in blackbeans in the growth chamber. He found that at the early flowering stage blackbeans were Zn deficient when tissue concentration was less than 10 ppm, the lower limit of the marginal range.

Jones (1973) criticized the use of critical levels on the grounds that they designated only the lower end of the sufficiency range. Instead, he suggested the use of concentration ranges termed deficiency, marginal and sufficiency as used earlier by Jones (1967) when he reported that ranges of 20-70 ppm Zn in the earleaves at silking were sufficient. Neubert, et al. (1969) reported a Zn sufficiency range in corn earleaves of 50-150 ppm. McAndrew (1979) reported the marginal range of Cu as 2.3-3.7 ppm for barley, 1.7-2.5 ppm for oats, 3.0-4.9 ppm for wheat, 2.4-3.5 ppm for flax and 1.7-2.7 ppm for rapeseed at 45, 49, 52, 43, and 43 days after seeding, respectively.

From the information reported it is evident that there were considerable variations in the concentration ranges as well as critical levels among crops and even within the same crop. The large differences were attributed by various workers to changes in environmental factors such as soil moisture and temperature (Jones, 1973; Bates, 1971; Melsted, et al., 1969; and Oplinger and Ohlrogge, 1974). It is important therefore that when interpreting results of plant analyses the conditions which prevailed during the growing season should also be considered.

Nutrient interactions also influenced plant concentrations as well as critical levels (Peck, et al., 1969; Stukenholtz, et al., 1966; and Walker, et al., 1969). Phosphorus-Zn interaction was one of the most commonly reported. Boawn, et al. (1964) suggested that a critical P/Zn ratio should be used rather than a critical Zn concentration. This suggestion was not supported by Stukenholtz (1966) who indicated that corn could withstand luxurious amounts of P provided some modest amounts of Zn were present. Giordano and Mortvedt (1969) were also not in favour of the use of critical P/Zn ratio.

Determination of plant critical levels was also sometimes complicated by what was commonly known as the "Steenbjerg effect" after Steenbjerg (1951). He found that in certain cases when the nutrient concentration was plotted against yield the curves obtained were "C shaped" such that a somewhat higher concentration of nutrient in the plant signified either an extremely deficient or an adequate supply of nutrient. Bates (1971) discussed the nature of such curves and suggested that they could be avoided by choosing the right plant part for tissue analysis.

There were differences in opinion in the literature as to the applicability to field conditions of plant critical levels determined in the greenhouse (Bould, 1964; Clement, 1964; Joham, 1951; Mackenzie, 1967; and Ulrich and Hills, 1967). Because of the role of environmental factors in determining the critical levels of nutrients in the plant, Bates (1971) suggested that critical levels determined in the greenhouse could not be valid in the field.

Soil Critical Levels

The critical level of a plant nutrient in the soil was defined as the level of nutrient in the soil that separated a deficient soil from a non-deficient soil (Trierweiler and Lindsay, 1969; Brown, *et al.*, 1971; Matt, 1972; Navrot and Ravikovitch, 1968; and Ravikovitch, *et al.*, 1968). The critical level for Cu and Zn in the soil depended on the extractant as well as the test crop used. Lindsay and Norvell (1978) reported that their DTPA soil test was a good indicator of the Zn status of neutral to alkaline soils and suggested that 0.8 ppm Zn was the critical level for corn. Using the same extractant the critical level for Cu using corn as a test crop was 0.2 ppm. Using 1% EDTA solution for extraction of Zn, Brown, *et al.* (1971) found Zn deficient corn on soils containing less than 1.25 ppm available Zn. Trierweiler and Lindsay (1969) used a solution containing 1.0 $\underline{M}$ $(NH_4)_2CO_3$ and 0.01 $\underline{M}$ EDTA at a pH of 8.6 and found that corn was Zn deficient when the level of Zn was less than 1.4 ppm. Brown, *et al.* (1971) found that the critical level of Zn in the soil for corn using DTPA extraction was 0.5 ppm. Using a solution containing 1.0 $\underline{N}$ NH_4OAc and 0.01 $\underline{M}$ Na_2DP at a pH of 7.0 Ravikovitch, *et al.* (1968) found that the critical level of Zn in the soil for corn was 1.0 ppm.

It should be apparent from the foregoing discussion that micronutrient soil and plant critical levels are influenced by a number of environmental factors so that critical levels of other areas are likely not applicable to Manitoba. Therefore soil and plant critical levels for Zn and Cu in Manitoba corn need to be established.

Factors Affecting Zinc and Copper Availability

It was mentioned earlier that responses to micronutrient fertilization in Manitoba were far more frequent in the greenhouse or environmental chamber than in the field. This could have resulted from differences between the field and greenhouse in environmental factors such as soil and air temperature, light intensity and soil volume. For this reason it seems appropriate to discuss the effects of these factors together with others upon the availability of soil and fertilizer Zn and Cu.

Soil pH

Lindsay (1972) reported that the solubility and consequent availability of Zn in the soil was highly pH dependent. He indicated that at high pH the Zn was normally present as an insoluble $Zn(OH)_2$ complex and that at high pH Zn was more adversely affected than Cu. Dolar and Keeney (1971) reported that Cu uptake by oats was best predicted by inclusion particularly of soil pH and that Cu availability generally decreased with increasing pH. Earlier studies by Wear (1956) revealed that 92% of the variation in Zn uptake by sorghum was caused by pH changes.

Some workers attributed the effect of some P fertilizers on Zn availability to their effect on soil pH (Terman, et al., 1966). They found a positive correlation between depression in soil pH and corn forage yield. Since many workers reported that different P carriers had varying effects on soil pH, it would appear that P sources were important in determining Zn availability in soils.

Other workers also reported pH dependent Zn and Cu retention mechanisms in the soil. Bingham, _et al._ (1964) reported that the retention by H-montmorillonite increased with increases in pH. Kalbasi, _et al._ (1977) worked on the mechanism of Zn retention by Fe and Al oxides and demonstrated that the absorption by these compounds also increased as the pH increased.

Soil Temperature and Moisture

Bauer, _et al._ (1965) reported increased availability of indigenous Zn with increasing soil temperature. He also found that Cu concentrations in carrot leaves increased as the temperature increased. Burleson, _et al._ (1961) and Martin, _et al._ (1965) observed that the severity of P-induced Zn deficiency decreased with increasing temperature. Burleson, _et al._ (1961) indicated that the low Zn uptakes by crops under cold wet conditions were due to poor root development. Ganiron, _et al._ (1969) reasoned that the effect of temperature was mainly on the availability of soil Zn rather than uptake or translocation in the plant. In other studies yield and Zn uptake by corn decreased as the soil temperature was lowered from 24°C to 13°C (Ellis, _et al._, 1964). Similar trends were observed by Thorne (1957) and Hodgson (1963). Ganiron, _et al._ (1969) demonstrated in solution culture experiments that temperature had more effect on the growth of corn seedlings than Zn rate or carrier.

Growth chamber studies in Manitoba with blackbeans revealed that Zn deficiency was very severe at low temperatures, particularly at high levels of P when Zn was not added (McKenzie, 1980). Like other workers he noted that increase in temperature markedly increased soil and fertilizer Zn availability. These observations suggest that Zn and Cu deficiencies should be more likely to occur in spring when soil temperatures are still low, particularly on organic soils which warm up more slowly. Later in the season as the soil warms up the deficiency symptoms should be less severe.

Soil Texture

The availability of soil Zn and Cu was related to soil texture. Thorne (1957) reported that Zn deficiency was often found on sandy soils but deficiency was also found on fine textured soils, on mucks and peats. However, Gilbert (1952) and Nikitin (1954) reported higher soil Zn availability on sandy soils compared to clays. These observations led some workers to suggest the possibility of Zn and Cu fixation by clay soils as was later reported. Bingham, et al. (1964) for example found that H-montmorillonite clays retained appreciable amounts of Zn and Cu. Other studies by Navrot and Ravikovitch (1969) revealed that total Zn increased with increasing clay content. Udo, et al. (1970) also reported that considerable amounts of native Zn in some calcareous Arizona soils were retained by the clay fraction. Kalbasi and Racz (1978) found that in a number of Manitoba soils the HNO_3+$HClO_4$ extractable soil Zn was highly correlated to Fe and Al as well as clay content. They suggested from the soils studied that regardless of Soil Great Group and Subgroup, Fe and Al oxides were the major matrices for

Zn in Manitoba soils. Thus, the positive correlation between clay content and total soil Cu and Zn levels reported by other workers perhaps could be explained by the fact that Fe and Al oxides are often clay sized and/or that they occur as coatings on silicate clay minerals. Only a relatively small portion of the Cu or Zn associated with Fe and Al oxides would be available to plants. This might explain the observations by some workers that clay soils (which could contain more Fe and Al oxides) were more deficient in Cu or Zn than sandy soils. But, most workers reported that sandy soils, particularly those containing lime, were more likely deficient in Zn and Cu than clay soils. The much larger total Cu and Zn concentrations in heavier soils resulting from greater retention of Cu and Zn which in turn is caused by the low solubility of Cu and Zn associated with Fe and Al oxides often may more than compensate for the low plant availability of micronutrients associated with sesquioxides.

Soil Organic Matter

A considerable amount of work was reported that showed that organic matter affected micronutrient availability, particularly Cu. The greater incidence of Cu deficiency on organic soils was probably at least partially caused by complexing of Cu by organic matter. Hodgson, et al. (1966) estimated that about 98% of the Cu in the soil was tied up in the organic matter fraction. Zinc was also complexed by organic matter, but Zn-organic matter complexes were generally more soluble and therefore more plant available than Cu-organic matter complexes. Miller and Ohlrogge (1958a and 1958b) found that water extracts of manure and other organic residues solubilized Zn in soil but at the same time reduced its uptake by plants. Studies by Maclean and Langille (1976) showed that extractable Zn was mostly affected by soil pH while organic matter and clay contents affected both Zn and Cu retention. Hamilton (1979) reported that the degree of decomposition of organic matter was also important in assessing the availability of Cu since the strength of bonding was found to increase with the increasing degree of decomposition. These observations indicate that the form of organic matter may be an important aspect of Cu retention by organic soils.

Available Phosphorus

Available soil P was found to affect the availability of micronutrients, particularly Zn. However, there were differences in opinion as to the actual mechanism and the site of P-Zn interaction although most workers suggested that it was a physiological mechanism (Boawn and Brown, 1968; Boawn and Leggett, 1964; Burleson, et al., 1961; Khan and Zende, 1977; Prabhakaran and Babu, 1975; and Stukenholtz, et al., 1966). In many cases P had an antagonistic effect on Zn availability to corn, (Burleson, et al., 1961; Stukenholtz, et al., 1966; and Sharma, et al., 1968) as well as to other crops (Haluschak, 1971; Judy, et al., 1964; and Melton, et al., 1970). In other reports, however, high rates of P enhanced Zn availability (Pauli, et al., 1968; Brown, et al., 1970; Marinho and Igue, 1972; Elsokkary, et al., 1981; and Ganiron, et al., 1969).

Adriano and Murphy (1970) reported that the severity of P-Zn interaction varied with the source as well as the methods of P application. Such variation might have resulted from variable effects of P carrier and placement method on soil pH. Terman and Allen (1964) argued that different P carriers affected the soil pH differently and since pH influenced Zn availability in the soil, they concluded that P sources should also influence Zn availability. Later, Giordano and Mortvedt (1966) also found that locally acid-forming P carriers such as concentrated superphosphate could increase the solubility of slightly soluble Zn carriers. The differential effects of different N carriers on the availability of soil Zn as observed by Terman, et al. (1966) was also attributed to their differential effects on soil pH. The extent and severity of P-Zn interaction was also influenced by the amounts of free $CaCO_3$ as well as climatic factors (Murphy, et al., 1981).

High P rates were found to depress Cu uptake by corn (Bingham and Garber, 1960 and Singh and Keefer, 1970). On the other hand, Haluschak (1971) found a very small effect of P on Cu uptake by wheat and flax. Earlier studies by Bingham (1963) revealed that high P rates decreased Cu contents in citrus but not in beans, corn or tomatoes.

Calcium Carbonate Content

Zinc deficiency was reported in corn as well as other crops on high-lime soils (Shukla and Morris, 1967; Berger, et al., 1961; Berger, 1962; Pauli, et al., 1968; and Navrot and Ravikovitch, 1969). Lindsay (1972) attributed the high incidences of Zn deficiences on high-lime soils to the inherently high pH and its detrimental effects on Zn availability. Besides the formation of $Zn(OH)_2$ complex, Udo, et al. (1970) suggested that absorption as well as precipitation mechanisms could also have been involved in the retention of Zn by carbonates. It was mentioned previously that the solubilities of Zn and Cu associated with Fe and Al oxides decreased with increasing pH.

Thorne (1957) warned that the presence of $CaCO_3$ in the soil may not necessarily indicate a Zn deficiency hazard as reported by many workers. His suggestion was supported by the work done by Navrot and Ravikovitch (1969) in which there was no significant correlation between yield or plant Zn concentration and the proportion of $CaCO_3$ in the soil. However, when they considered the form of $CaCO_3$ involved, they found a good correlation between "carbonate clay" fraction and Zn uptake.

An effect of $CaCO_3$ on P-Zn interaction was also reported in the literature. Although high-lime soils and heavy applications of P were found to be some of the factors which accentuate Zn deficiency in crops. some workers found that the availability of Zn was actually increased when P fertilization was practiced on calcareous soils, perhaps as a result of local soil acidification (Brown, et al., 1970; Pauli, et al., 1968; Chaudry, 1977; Elsokkary, et al., 1981; and Orabi, et al., 1981). Murphy (1981) argued that large amounts of free $CaCO_3$ tended to mask the P-Zn interaction, but the P fertilizer could have also decreased the soil pH and made Zn more available.

Zinc and Copper Source and Method of Application

Brown and Krantz (1966) reported that both organic and inorganic Zn sources were equally effective when mixed throughout the soil but when banded, ZnEDTA was more effective in supplying Zn to corn. Macronutrient carriers of Zn were very poor sources of Zn for corn (Murphy, et al., 1971). Further comparisons of organic and inorganic carriers of Zn revealed that inorganic sources were superior in supplying divalent metals such as Zn^{++} and Cu^{++} to plants while chelated sources were ideal for the trivalent metals such as Fe^{+++} (DeKock, 1957 and Guinn and Joham, 1962). Judy (1967) determined the availability of Zn from ZnEDTA and $ZnSO_4 \cdot 7H_2O$ for pea beans both under field and greenhouse conditions. In both cases Zn uptake was higher in plots receiving ZnEDTA. On the other hand, field studies with corn did not show an advantage of ZnEDTA over $ZnSO_4 \cdot 7H_2O$ (Ganiron, et al., (1969).

Recent studies in Manitoba as reviewed by Loewen-Rudgers, et al. (1978) indicated that chelated sources of Zn and Cu were superior to inorganic sources of Zn and Cu to barley and field beans. Boawn (1973) attributed the superiority of chelated sources to their easy mobility. He argued that the lack of mobility of the inorganic carriers increased their susceptibility to fixation. On the other hand, Tisdale and Nelson (1975); Wallace, et al. (1957); and Weinstein, et al. (1954) felt that chelate sources were more available because they were absorbed by the plant as a molecule, a theory that was not consistent with the findings of Lindsay (1974) and Halvorson, et al. (1977). Lindsay (1974) postulated that with chelated sources the metal was released and absorbed by the plant. As a result, further dissociation was necessitated to restore equilibrium. He maintained that this was a buffering mechanism where dissociation maintained ion concentration in the soil solution.

Wallace (1981) reported that dicot plants excreted H^+ when they were Fe deficient but this was not observed in Fe deficient monocots. The H^+ decreased the stability of the chelate by splitting it into the chelating agent and the Fe. Under these conditions he argued that the dicots were able to pick up the Fe more readily. He concluded that with monocots which did not excrete H^+, Fe chelates were relatively poor sources of Fe. Romheld and Marschner (1981) also reported that Fe inefficient plant species such as corn could not take up Fe from Fe chelates as well as Fe efficient plants such as sunflowers. He also attributed the greater ability of Fe efficient plants in taking up Fe to their ability to split the chelate and take up only Fe. No reference could be found in the literature, however, to indicate that corn was inefficient in taking up Zn from Zn chelates.

The theories put forward on the behaviour of inorganic and organic Zn and Cu carriers in the soil suggest the need for appropriate placement methods to enhance their availability to crops. Studies in Manitoba, for example, revealed that mixing Zn and Cu sulphates throughout the surface soil was more effective in increasing plant uptake compared to banding with the seed which was more effective than sidebanding (Loewen-Rudgers, 1978). The lack of mobility of Zn and Cu from these carriers was usually given as the reason why they became more available when mixed throughout, since in doing so the contact with the roots was increased. However, many P fertilizers also form insoluble compounds upon contact with the soil. The most efficient method of applying such P fertilizers is in concentrated bands. Hedayat (1978) attributed the greater Zn uptake by blackbeans when $ZnSO_4 \cdot 7H_2O$ was mixed throughout the soil as opposed to banding to a greater proportion of total Zn applied remaining soluble when mixed throughout the soil. He presented data which suggested that the proportion of Zn remaining soluble after application of $ZnSO_4 \cdot 7H_2O$ decreased with increasing concentrations (i.e. banding). The effect with P fertilizers is exactly the opposite. Mortvedt and Giordano (1969) indicated that the availability was increased even more if the $ZnSO_4.7H_2O$ was ground into fine powder. Boawn (1973); Brinkerhoff, et al. (1966); and Shaw, et al. (1954) also reported that the availability of Zn from $ZnSO_4.7H_2O$ was enhanced when it was mixed throughout. On the other hand, Brown and Krantz (1966) reported that chelated sources were not as sensitive to placement methods as the inorganic sources. Mixing the chelates throughout the soil was as effective as banding the carriers.

Crop Variety

It was mentioned previously that considerable variability was reported in crops with respect to their ability to utilize soil Zn. Brown, et al. (1962) worked with fourteen plant species on a calcareous soil and found that seven developed Zn deficiency symptoms, two developed Fe deficiency symptoms, while five developed no micronutrient deficiencies. Similarly, the degree of response to Zn and Cu fertilization varied among corn varieties. Shukla and Raj (1976) compared eight corn genotypes and found that Zn concentrations in the tissue varied from 7.4 ppm to 20.5 ppm. In studies with different varieties of wheat, Shukla and Raj (1974) reported tissue Zn levels ranging from 4.2 ppm to 28.3 ppm. The differences observed were attributed to differences in the ability of the various genotypes or varieties to exploit soil Zn and translocate it to the shoot. Differences in early uptake of Zn by corn inbred lines were also observed by Massey and Loeffel (1967). These observations suggest that crop variety should be taken into consideration when interpreting the results of micronutrient fertilizer evaluation studies.

Soil Volume

There were no reports in the literature concerning the influence of container size or soil volume on response to micronutrient fertilization. A few reports were, however, available with respect to macronutrient responses as influenced by soil volume. Cornforth (1968) reported increasing yields of several different crops as the soil volume was increased. However, he found that as the soil volume was increased the intensity of the root system decreased. Responses to fertilizer P were larger in the larger volumes of soil, while responses to applied N were greater in the smaller volumes of soil, but the uptakes of both N and P increased with increasing soil volume. In studies with corn, Baker and Woodruff (1961) found that for optimum nutrition greater concentrations of P were required in smaller containers compared to larger ones. Larsen and Sutton (1963) reported higher dry matter yields of ryegrass as soil volume was increased. Phosphorus uptake also followed the same trend as the yield. Using tracer techniques, Armiger, *et al.* (1957) showed that alfalfa contained more P from fertilizer P in the smaller pots when pots of various sizes were compared. Gross-Brauckmann (1972) found that when P was not applied, P uptake increased with increasing soil volume, but when it was applied, the efficiency of uptake decreased with increasing amounts of soil. Cornforth (1968) also showed that when fertilizer N or P were added their uptake per litre of soil decreased as soil volume increased and that in soil without fertilizer N, increasing soil volume increased the N:P ratio in the crop.

Root distribution and density were also related to soil volume. Stevenson (1967) studied the root system of sunflowers, wheat and clover as related to soil volume and found that although the root system was larger with increased soil volume, the density was less. He postulated that when root systems were crowded, each root interfered with the water supply of nearby roots, so that the water uptake and growth of the whole plant was restricted. Root density may also influence nutrient uptake in a similar manner. If adequate water were always applied, the container size might influence crop growth primarily because of influence on nutrient uptake.

Reports in the literature concerning the influence of soil volume upon response to macronutrients fertilization appear to suggest that the uptake of soil macronutrients increased with increasing soil volume and that the uptake of fertilizer macronutrients decreased with increasing soil volume. In other words, responses to macronutrient fertilization decreased with increasing soil volume. One would expect that a plant would have access to more soil in the field than in the greenhouse such that responses to macronutrient fertilization should be larger and more numerous in the greenhouse. The same may also be true for micronutrients although there was little evidence in the literature to support such a conclusion.

It is also likely that nutrient mobility, root distribution and fertilizer placement would also influence soil volumes effect upon response to micronutrient fertilization.

MATERIALS AND METHODS

A. Soil Analysis

(1) Soil pH

Soil pH was determined electrometrically by the method described by Peech (1965). Fifty ml distilled water were added to 50g air-dried soil and shaken for 30 minutes. The pH of the suspension was then determined using a Beckman Zeromatic pH meter.

(2) Conductivity

Conductivity of the same suspension used for the pH determination was read directly in mmhos/cm using a Radiometer conductivity meter type CDM2d.

(3) Soil Texture

The textural class of the soils used were determined by the hand or "feel" method.

(4) Organic Matter

Percent organic matter was determined using the oxidation method described by Walkley and Black (1934). One-half gram of soil was oxidized by excess $K_2Cr_2O_7$ in the presence of excess H_2SO_4. The excess $Cr_2O_7^{=}$ was back-titrated with $FeSO_4$ using the Fisher automatic titrimeter.

(5) Inorganic Carbon

One gram of air-dried soil was heated with 40 ml of 10% HCl for ten minutes. The CO_2 evolved was drawn by suction through a drying and absorption train consisting of concentrated H_2SO_4, a tube of dehydrite and calcium chloride. The amount of CO_2 evolved was determined by weighing the tube before and after trapping the gas. The results were expressed in percent $CaCO_3$ equivalent.

(6) Nitrate Nitrogen

Nitrate nitrogen was extracted by shaking 2.5g of air-dried soil with 50 ml of 0.5 N $NaHCO_3$ for 30 minutes. Half of the extract was used for nitrate determination and the other half for phosphorus determination. The nitrate was determined electrometrically using napthylethylenediamine dihydrochloride and measuring the absorbance at 420 mμ.

(7) $NaHCO_3$ Extractable Phosphorus

Part of the extract from the nitrate determination was analysed for phosphorus using the acid molybdate method of Murphy and Riley (1962). Ascorbic acid was used to reduce the phosphomolybdate complex and the absorbance of the blue colour developed measured at 815 mμ.

(8) Extractable Potassium

Potassium was extracted by shaking 2.5g of air-dried soil with 25 ml of 1.0 N NH_4OAc for 30 minutes. The sample was then filtered through Whatman No. 1 filter paper. Potassium was then determined with a flame photometer using lithium as an internal standard.

(9) Sulphate-Sulphur

Twenty-five grams of air-dried soil were shaken with 50 ml of 0.001 M $CaCl_2$ for 30 minutes. The extract was passed through a cation exchange resin and reacted with methylthymol blue to form a blue-coloured chelate. The amount of uncomplexed methylthymol blue (gray colour) was measured at 460 mμ and was equivalent to the amount of SO_4-S present.

(10) DTPA Extractable Zn, Cu, Mn and Fe

Plant available Zn, Cu, Mn and Fe were determined using the method described by Lindsay and Norvell (1969) as modified by the Kansas State University Soil Testing Laboratory. To 25g of air-dried soil 50 ml of DTPA (Diethylenetriaminepentaacetic acid) solution adjusted to pH 7.3 were added. The mixture was shaken for two hours and then filtered through Whatman No. 42 filter paper. Zinc, Cu, Mn and Fe were then determined on the extract using Perkin-Elmer Model 560 Atomic Absorption Spectrophotometer.

(11) Field Capacity

Air-dried soil was placed in acrylic cylinders measuring 4.5 cm in diameter and 20.5 cm in height. Water was then slowly added until the wetting front had moved one third of the way down the cylinder. After equilibrating for 48 hours the wetted portion of the sample was dried at 105°C for 24 hours and the moisture content calculated on oven-dry basis. This moisture content was taken as the field capacity.

B. Plant Analysis

(1) Total Zn, Cu, Mn and Fe

Two-grams of oven-dried plant sample were pre-digested in ten ml of concentrated HNO_3 for about one hour. Five ml of 70% $HClO_4$ were then added and the samples further digested until the contents of the Micro-Kjeldhal flasks turned clear. The samples were cooled, ten ml of deionized water added and then filtered through Whatman No. 42 filter paper into 25 ml volumetric flasks and made up to volume. Zinc, Cu, Fe and Mn concentrations in the digest were determined using the Atomic Absorption Spectrophotometer.

(2) Total Ca, Mg and K

One-half ml of the plant digest used for the micronutrient determination was diluted to 15 ml, 1.5 ml $LiNO_3$ added and Ca, Mg and K determined on the Atomic Absorption Spectrophotometer.

(3) Total Phosphorus

An aliquot from the plant digest was diluted to bring the P concentration to the correct range for adequate colour development using the acid molybdate method described by Murphy and Riley (1962). Ascorbic acid was used to reduce the phosphomolybdate complex and the absorbance measured at 815 mμ using the Bausch and Lomb Spectronic 710 calorimeter.

(4) Total Sulphur

An aliquot from the plant digest was diluted depending on the S concentration of the samples and the S determined using the same method used for the soil samples.

(5) Total Nitrogen

One-gram of ground oven-dried plant material was digested for one hour in 25 ml of concentrated H_2SO_4. To increase the temperature and rate of oxidation one Kelpak containing HgO catalyst, K_2SO_4 and Na_2SO_4 salts was added to each digestion flask. The digest was then cooled and 250 ml of distilled water added, after which 50 ml of 50% NaOH were added slowly. The ammonia liberated on distilling the mixture was collected in a 2% boric acid solution containing mixed indicator. The ammonium was later determined by titrating with 0.1 N H_2SO_4.

Procedure for Cleaning Pots and Glassware

Pots and glassware were washed using the procedure given below:

(1) They were thoroughly soaked and washed in detergent and water to remove foreign particles;

(2) rinsed with tap water followed by 3-4 rinses with distilled water;

(3) soaked in 0.1 M Na_2EDTA and rinsed thoroughly in deionized water and finally

(4) soaked in 1.0 M HCl for 5-10 minutes and rinsed 6-8 times with small quantities of distilled deionized water.

I. Zinc and Copper Experiments

Soil

Soil for the two-pot experiments was collected from near Macgregor, Manitoba (SW 29-11-10 W) in the fall of 1979. The Almasippi soils in this area were suspected to be low in available Zn and/or Cu for optimum corn production. The soil was taken from the 0-15 cm depth and stored under low temperature conditions to minimize further microbial activities. Later, the soil was air-dried, crushed and mixed thoroughly.

Experimental Design and Procedure

Two experiments were conducted on growth benches to determine the effect of fertilizer Zn and Cu upon growth and nutrient uptake of corn. Six Zn rates, 0, 2, 4, 8, 16 and 32 ppm Zn as $ZnSO_4 \cdot 7H_2O$ or six Cu rates, 0, 1, 2, 4, 8 and 16 ppm Cu as $CuSO_4 \cdot 5H_2O$ and two levels of P, 50 and 200 ppm P as $Ca(H_2PO_4)_2$ were arranged factorially and replicated three times in a completely randomized design. Pots were moved at regular intervals on the growth benches to minimize variation in environmental conditions.

Each pot contained 5.5 kg of soil. All fertilizers were dissolved in deionized water and the appropriate amount of solution pipetted uniformly onto the entire soil mass, spread thinly on brown paper. The entire soil mass was then thoroughly mixed.

Nitrogen was added as NH_4NO_3 at a rate of 100 ppm N initially and then 25 ppm N after four weeks and, lastly, 25 ppm N in the fifth week after emergence. Potassium and S were added as K_2SO_4 at a rate of 231 ppm K. Copper was added to the Zn experiment as $CuSO_4 \cdot 5H_2O$

at a rate of 10 ppm Cu and Zn added to the Cu experiment at a rate of 15 ppm Zn as $ZnSO_4 \cdot 7H_2O$. Magnesium was added in both experiments at a rate of 10 ppm Mg as $MgSO_4$ after suspecting Mg deficiency about six weeks after seeding.

Six corn seeds, variety Pride 1108 were seeded about 2.5 cm deep. The moisture content was then brought to about 80% of field capacity and kept at this level until all seeds had emerged. After emergence the moisture content was brought to field capacity daily using deionized water. The plants were thinned to two plants in each pot by the end of the first week after emergence.

Growing conditions such as temperature, humidity and light intensity were not as well controlled as they would have been in a growth chamber. The temperature immediately below the bulbs was generally around 30°C but the room temperature was generally below this. The light period was 16 hours and was maintained at an intensity of about 250 $\mu E/m^2S$ at the plant tops.

The plants were allowed to grow for about eight weeks at which time tasseling was just beginning. Two mature leaf blades from the 6th and 7th leaves were harvested from each plant and dried at 65°C for 48 hours. The remaining plant material was chopped into small pieces and placed into separate paper bags and dried at 65°C to constant weight. The dry matter yields of the two leaves and the remaining material were then determined and the leaf and the remaining material ground in a small coffee grinder separately for later nutrient analysis.

II. Field Experiments

Field experiments were conducted near Macgregor and Morden, Manitoba in which the response in growth and nutrient concentration to Zn fertilization were studied. The main experiment was located on an Almasippi loamy fine sand near Macgregor (SE 19-11-9 W) near the area where the soil for the Zn and Cu growth bench experiments was collected.

Three smaller experiments were located near Morden at NE 29-3-4 W on a Reinland fine sandy loam, NE 30-3-5 W on a Neuenburg very fine sandy loam and NE 28-3-5 W on a Hochfeld fine sandy loam. The three sites were referred to as Enns, Nikkels and Toews sites, respectively. The last site was abandoned due to extreme variability in the plot caused by uneven germination.

Experimental Design and Procedure

The main experiment was arranged in a split plot design. Six rates of Zn, 0, 2, 4, 8, 16 and 32 kg Zn/ha as $ZnSO_4 \cdot 7H_2O$ and a 0 Cu treatment were superimposed upon three levels of P, 0, 25 and 100 kg P/ha as MCP. The three P treatments were replicated four times in a randomized complete block design and the seven micronutrient treatments completely randomized within each P level. Each plot measured 3.66m x 6.1m. There were four 91-cm rows of Pioneer 3996 corn in each plot with plants spaced about 17-cm apart within each row, resulting in a plant population of 55,000 plants per ha.

The Zn and Cu fertilizers were dissolved in deionized water and spread evenly on the surface of the respective plots and later worked into the soil, using a disc plough. Each plot except the Cu check received 10 kg Cu/ha as $CuSO_4 \cdot 5H_2O$. Phosphorus treatments were sidebanded at seeding 5-cm below and 5-cm to the side on both sides of the row. Nitrogen and K were also sidebanded at seeding in the same manner as P, as NH_4NO_3 at a rate of 50 kg N/ha and KCl at a rate of 100 kg K_2O/ha. Earlier, 100 kg N/ha had been added by the farmer as aqueous ammonia. Sulphur at a rate of 34 kg S/ha was applied about six weeks after seeding as $(NH_4)_2SO_4$ using a hand operated applicator called Planet Junior. Through this an additional 30 kg N/ha were also added.

About three weeks after seeding the herbicide Banvel 3 was applied at a rate of 560 g/ha active ingredient to control Canadian thistle. Other weeds such as quack grass were controlled by hoeing.

Six entire corn plants were harvested at random from each plot about eight weeks after seeding. The plants were chopped into small pieces, washed thoroughly in deionized water and then oven-dried to constant weight at 65°C. The dry matter yield of each plot was then estimated on the basis of the total number of plants for each plot. The dry samples were ground in a Wiley Mill and subsamples taken for analysis.

Fifteen earleaves from each plot were sampled about ten weeks after seeding at which time most plants were silking. The leaves were dried whole at 65°C to constant weight and then ground in a Wiley Mill for tissue analysis.

Finally, grain harvests were taken from 3-metre lengths of the two middle rows. The husks were removed from the cobs and the cobs dried at room temperature for about two weeks. The cobs were then shelled and the grain further dried to about 6.7% moisture content. The grain yields were then determined and adjusted to the standard moisture content of 14.0%

Smaller experiments near Morden were conducted in simple paired plots. The two treatments were 0 kg Zn/ha and 16 kg Zn/ha as dissolved $ZnSO_4 \cdot 7H_2O$ sprayed onto the soil surface and disced in to 10 cm before seeding. The treatments were replicated four times in a randomized complete block design. Copper was applied to all plots at a rate of 10 kg Cu/ha as $CuSO_4 \cdot 5H_2O$ in the same manner as the $ZnSO_4 \cdot 7H_2O$. Other nutrients were all sidebanded using the following rates and carriers:

Nitrogen:	100 kg N/ha as NH_4NO_3
Phosphorus:	50 kg P_2O_5/ha as $Ca(H_2PO_4)_2$
Potassium:	100 kg K_2O/ha as KCl
Sulphur:	30 kg S/ha as $CaSO_4 \cdot 2H_2O$.

Total plant samples were taken about eight weeks after seeding for nutrient analysis. Earleaves were also collected using the same procedure as for the Macgregor site.

Due to frost damage grain samples were not obtained at the two Morden sites. Instead, dry matter yields were estimated by determining the total fresh weight of each plot followed by the fresh weight and oven-dry weight of a subsample. The plants at this stage were close to the dent stage. All samples were ground and nutrient concentrations determined.

III. Soil Volume Experiment

Many workers postulated that restricted soil volume in growth chamber experiments was likely the cause of the more frequent responses to micronutrient fertilization in pot experiments. This experiment was designed to investigate the influence of soil volume on Zn response in corn using soil taken from the field site near Macgregor, Manitoba. The soil was prepared in the same way as the soil used in the Zn and Cu experiments.

Experimental Design and Procedure

Four soil weights, 5, 10V, 10H and 20 kg/pot and two rates of Zn, 0 and 8 ppm Zn as the Zn chelate $Na_2ZnEDTA$ were arranged factorially and replicated three times in a completely randomized design. Pots were moved at regular intervals on the growth benches and in the greenhouse to minimize variation in environmental conditions.

The pots were constructed to provide for increase in soil volume by increasing depth and width both separately and together. The inside dimensions of the containers and the soil masses are shown in (Figure 1).

The pots were made from chipboard and lined with plastic bags to avoid any leakage. A constant height of the soil surface was maintained throughout by using false bottoms in those pots in which the soil was 17.8-cm in depth.

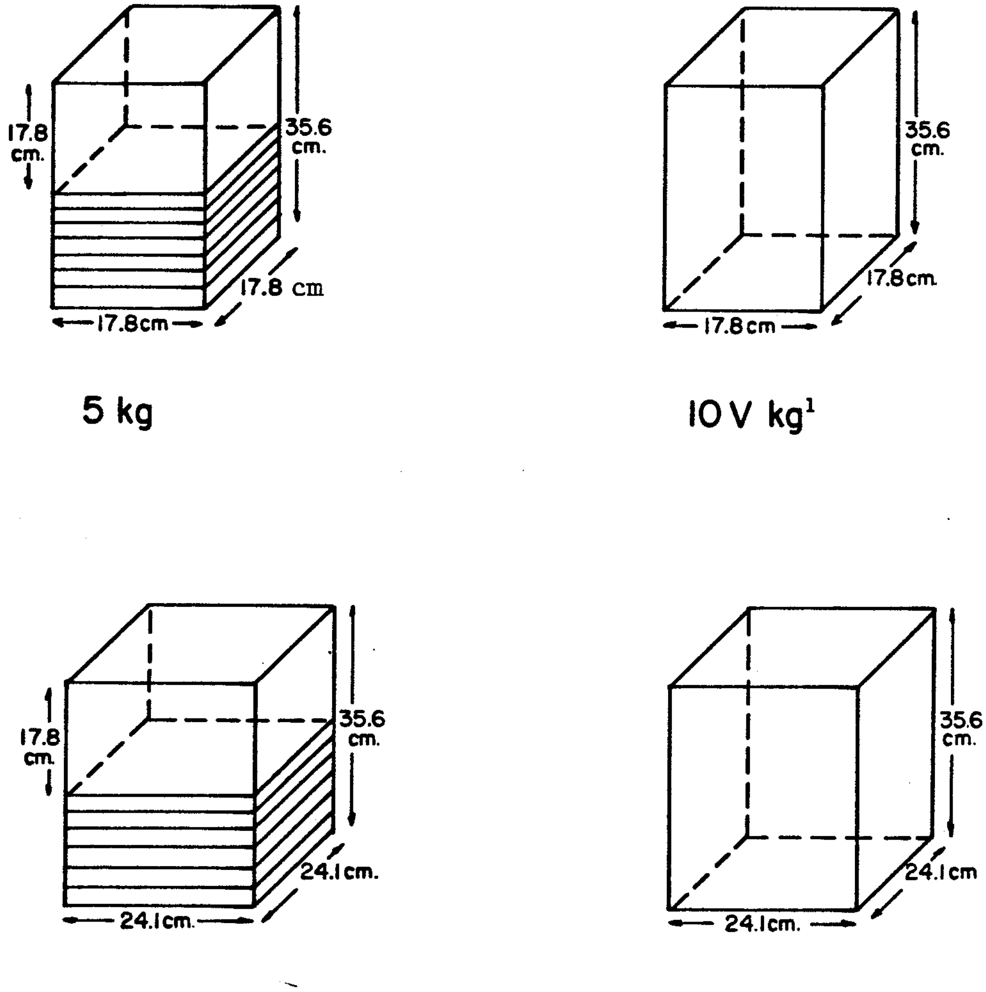
All nutrients in all four treatments were dissolved and mixed with a volume of soil having the dimension of the 5 kg soil treatment and positioned in the top centre of each pot. Zinc was applied at the rates of 0 and 8 ppm as $Na_2ZnEDTA$ on the basis of 5 kg of soil.

Nitrogen was added to all pots as NH_4NO_3 and $NH_4H_2PO_4$ at a rate of 200 ppm N based upon 5 kg of soil, P as $NH_4H_2PO_4$ at 200 ppm P, K and S as K_2SO_4 at 181 ppm K, Mg as $MgSO_4$ at 10 ppm Mg and Cu as NaCuHEDTA at 4 ppm Cu.

Four corn seeds, variety Pioneer 3996, were planted at a depth of about 2.5-cm. The plants were grown under slightly warmer conditions compared to the Zn and Cu experiments. After five weeks the plants were transferred to a greenhouse where they were grown to the silking stage. Fifty ppm N were added weekly beginning in the fifth week up to the last week. Altogether, additional 200 ppm N were added in this way.

Earleaf samples were harvested at silking, which varied from 52 days to 62 days after planting. These were dried at 65°C to constant weight. The remaining plant material was harvested 62 days after planting by chopping the plants into small pieces into paper bags. The samples were also dried at 65°C to constant weight, dry matter yield determined and then ground in a Wiley Mill for nutrient analysis.

FIGURE 1: Dimensions of pots and soil masses used to vary soil volume



5 kg

10 V kg[1]

10 H kg[2]

20 kg

Footnotes:

[1] Vertical Expansion of Soil Volume

[2] Horizontal Expansion of Soil Volume

RESULTS AND DISCUSSION

I. GROWTH BENCH ZINC EXPERIMENT

Corn was grown for about eight weeks on benches under artificial light, on a slightly alkaline Almasippi loamy very fine sand containing low available Zn in order

(1) to determine if corn would respond to Zn fertilization under a controlled environment;

(2) to determine the critical concentration of Zn in the corn tissue under such conditions and

(3) to determine the influence of added P on the critical level as well as the concentration and uptake of other nutrients.

Soil Characteristics

The soil was low in carbonate content but the pH was quite high (Table 1). This in conjunction with low absolute Zn levels due to coarse texture likely resulted in low availability of soil Zn. The soil was also low in DTPA available Cu. But, available Fe and Mn were adequate according to the critical levels suggested by Lindsay and Norvell (1978). The soil was also quite low in NO_3-N, P, K and S. These nutrients were added as basal applications except for P whose amount varied with treatment.

TABLE 1

Soil Characteristics for the Growth Bench Zinc and Copper Experiments

Soil Name	Almasippi
Textural Class	Loamy very fine sand
pH	7.9
Conductivity (mmhos/cm)	0.4
$CaCO_3$ (%)	2.1
Organic Matter (%)	3.18
NO_3-N (ppm)	8.8
PO_4-P (ppm)	5.8
Exch. K (ppm)	125
SO_4-S (ppm)	3.8
DTPA Cu (ppm)	0.23
DTPA Zn (ppm)	0.51
DTPA Fe (ppm)	11.0
DTPA Mn (ppm)	29.0
F.C. Moisture content (%)	29.3

Plant Appearance

Generally corn plants had a healthy appearance throughout the eight-week period suggesting that the nutrients supplied by the soil, supplemented by the amounts added through fertilization were reasonably adequate. However, plant analysis indicated that some nutrients, particularly N and S, were not adequate. Slight nitrogen deficiency symptoms were evident and additional N may have not corrected the deficiency to a satisfactory level.

Where P accentuated Zn deficiency as will be shown later, the plants were severely stunted with severely shortened internodes. Two broad white bands were also observed between the midrib and the leaf margins on both sides of the midrib of the second and third leaf from the top (Figure 6). These symptoms were typical of the "white bud" symptoms described in the literature.

Phosphorus deficiency symptoms were exhibited particularly in the treatments receiving 50 ppm P.

Dry Matter Yield

Dry matter yield of corn shoots at tasseling was influenced by levels of P and Zn (Table 2). There was also a significant interaction between P and Zn levels. Increasing the level of P from 50 to 200 ppm increased dry matter yield. This was expected since the soil was low in available P. However, since 50 ppm P was already a fair amount of P the response to additional P shows that corn has a relatively high requirement for P under controlled conditions. It should be noted that P deficiency symptoms were evident particularly for those plants receiving the lower level of P.

Increasing the level of Zn from 0 to 2 ppm increased dry matter yield. Yields were not increased further by 4, 8 and 16 ppm Zn. The highest Zn level decreased dry matter yields which it will be shown later could have resulted from Zn accentuated P deficiency.

Increasing the P level when Zn was not added decreased dry matter yield dramatically whereas for every treatment receiving supplemental Zn dry matter yield was increased by increasing the level of P. Such P-Zn interaction was also observed by other workers such as Burleson, et al. (1961) and Stukenholtz, et al. (1966). These results also indicate that Zn was required for P utilization by corn. The findings are in agreement with those reported by Stukenholtz (1966) who indicated that corn could withstand luxurious amounts of P provided some modest amounts of Zn were present.

Plant Zn Concentration and Uptake

Zinc fertilization was effective in increasing tissue Zn concentration and uptake (Tables 3, 4 and 5). Generally the tissue Zn content was increased only when the rate of Zn was above 4 ppm but Zn uptake into shoots was increased by each successive increment.

Increasing P from 50 to 200 ppm decreased total plant shoot Zn concentration as well as uptake. This was particularly true for Zn uptake at the 0 Zn level. This strengthens the assertion that P accentuated Zn deficiency.

There was significant P-Zn interaction in total plant shoot Zn concentration. When no Zn was applied increasing the P level increased the plant Zn concentration whereas additional P decreased plant Zn concentration at all other levels of Zn except 32 ppm. The relatively high Zn

TABLE 2

Influence of Fertilizer P and Zn upon Dry Matter Yield of Eight-week Old Corn Shoots (g/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	29.3[3]e	6.8[3]f	18.1[2]c
2	39.3 d	47.1 abcd	43.2 a
4	41.5 cd	54.0 a	47.8 a
8	40.3 cd	51.4 ab	45.8 a
16	37.9 de	49.1 abc	43.5 a
32	30.1 e	44.2 bcd	37.2 b
P Main Effect	36.4[1]B	42.1 A	

[1] Values followed by different capital letters are significantly different at the 5% level using Duncan's Multiple Range Test.

[2] Values followed by different letters in this column are significantly different at the 5% level using Duncan's Multiple Range Test.

[3] Significant P-Zn interaction.
Values followed by different letters in both columns are significantly different at the 5% level using Duncan's Multiple Range Test.

TABLE 3

Influence of Fertilizer P and Zn on Zn Concentration in Corn Leaves (ppm)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	6.1[1]	4.4[1]	5.3 d
2	8.0	5.8	6.9 d
4	10.5	6.8	8.7 cd
8	16.6	13.3	14.9 c
16	23.6	21.1	12.4 b
32	31.9	31.9	31.9 a
P Main Effect	16.1 A	13.9 A	

[1] Interaction not significant when no letters follow these values.

TABLE 4

Influence of Fertilizer P and Zn on Zn Concentration in Corn Shoots (ppm)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	9.8 f	13.1 ef	11.5 d
2	14.3 ef	7.7 f	11.0 d
4	20.2 de	9.7 f	14.9 d
8	28.6 c	11.7 f	20.2 c
16	38.9 b	25.2 cd	32.0 b
32	65.6 a	43.8 b	54.7 a
P Main Effect	29.6 A	18.5 B	

TABLE 5

Influence of Fertilizer P and Zn on
Zn Uptake into Corn Shoots (μg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	268	69	168 f
2	504	381	442 e
4	767	501	634 d
8	1069	585	827 c
16	1362	1205	1284 b
32	1801	1814	1808 a
P Main Effect	961 A	759 B	

concentration for 0 Zn, 200 ppm P likely resulted from a concentration effect due to the low dry matter yield brought about by P accentuating Zn deficiency. The decrease in Zn concentrations at all other Zn levels may have resulted from dilution and/or additional P decreasing Zn uptake and/or translocation to the shoots.

Plant Cu Concentration and Uptake

The Cu concentrations in the leaf blades suggest that it was unlikely that the plants were Cu deficient. In addition, a considerable amount of Cu (10 ppm) was added to every pot and the plants were not exhibiting Cu deficiency symptoms. Although sampled slightly before silking the leaf blades sampled were from the earleaf position and the leaf directly above this. Melsted (1969) reported the critical concentration of Cu in corn earleaves at tasseling as 5 ppm. All leaf blade Cu concentrations in the present experiment were well above that level. The high Cu concentration in the Zn control was due to concentration effect as a result of low dry matter yield obtained due to P accentuated Zn deficiency.

Increasing the level of applied Zn decreased Cu concentrations in corn tissue particularly when going from 0 to 2 ppm Zn (Tables 6 and 7). This effect was likely due to dilution caused by the increasing dry matter yield with increasing Zn rather than by actual Zn-Cu interaction since the Cu uptake was increased with increasing Zn (Table 8). The general increase in Cu uptake with increasing Zn was likely due to response in dry matter yield to Zn fertilization (Table 2).

Phosphorus fertilization did not influence Cu concentrations in corn plants. However, total Cu uptake into shoots decreased significantly with increasing P. This was likely due to the drastically decreased dry matter yield of the 0 Zn, 200 ppm P treatment. Although P accentuated Cu deficiency cannot be ruled out, it seems rather unlikely since Cu fertilization in the Cu experiment did not increase corn shoot yields when Cu concentrations were as low as those in this experiment. In addition, adequate Cu was added to all the treatments.

There was significant P-Zn interaction in Cu concentration and uptake. The interaction in Cu concentration resulted from increase in Cu concentration as P was increased when no Zn was applied, while Cu concentrations either were not influenced or were decreased by increasing P at higher Zn levels. The increase in Cu concentration with

TABLE 6

Influence of Fertilizer P and Zn on Cu Concentration in Corn Leaves (ppm)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	11.3 b	14.1 a	12.7 a
2	8.2 cde	10.1 bc	9.1 b
4	7.8 de	6.2 e	7.0 c
8	7.6 de	7.1 de	7.4 c
16	7.9 de	7.8 de	7.8 bc
32	9.1 cd	7.2 de	8.2 bc
P Main Effect	8.6 A	8.7 A	

TABLE 7

Influence of Fertilizer P and Zn on Cu Concentration in Corn Shoots (ppm)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	7.3 b	12.9 a	10.1 a
2	4.2 d	3.7 de	4.0 bc
4	3.8 de	2.5 e	3.2 c
8	3.6 de	3.6 de	3.6 bc
16	4.5 cd	3.6 de	4.1 bc
32	5.8 c	3.4 de	4.6 b
P Main Effect	4.9 A	5.0 A	

TABLE 8

Influence of Fertilizer P and Zn on
Cu Uptake into Corn Shoots (μg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	233 a	90 d	162 c
2	190 abc	218 ab	204 a
4	178 bc	164 c	172 bc
8	173 c	208 abc	191 abc
16	190 abc	208 abc	199 ab
32	192 abc	170 c	181 abc
P Main Effect	193 A	176 B	

increasing P at 0 Zn was due to the concentration effect caused by P accentuated Zn deficiency whereas the decreasing Cu concentration with increasing P was likely caused by dilution.

The significant P-Zn interaction in Cu uptake was caused by the decrease in Cu uptake with increasing P at 0 Zn as opposed to no effect of P upon Cu uptake at all other Zn levels.

Plant Fe Concentration and Uptake

Phosphorus fertilization did not influence tissue Fe concentration or uptake by corn (Tables 9, 10 and 11). Zinc fertilization on the other hand influenced both Fe concentration and uptake.

Corn plants receiving Zn contained less Fe than plants receiving no Zn. The high Fe concentration in the Zn control particularly at the high level of P was likely due to concentration effect resulting from low dry matter yield since Zn uptake into the shoots was lower than in other treatments. Akinyede (1978) obtained an opposite trend in barley shoots on applying Zn. It is possible that the influence of Zn on Fe nutrition by crops differ from one crop to another.

There was significant P-Zn interaction in Fe concentration and uptake. The interaction in Fe concentration resulted from an increase in Fe concentration in the treatment that did not receive Zn when the level of P was increased to 200 ppm. All other Fe concentrations were similar at all levels of Zn. The interaction in Fe uptake was caused by the decrease in Fe uptake with increasing P at 0 Zn. In contrast to the Zn control, Fe uptake was increased at the high rate of P when the Zn level was 16 ppm and 32 ppm.

On the basis of the critical level of 15 ppm for Fe in corn earleaves suggested by Melsted, et al. (1969) the corn plants were not Fe deficient. The levels of DTPA available Fe in the soil were also adequate. In addition, Fe deficiency symptoms were not evident.

TABLE 9

Influence of Fertilizer P and Zn on Fe Concentration in Corn Leaves (ppm)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	83.6 bc	120.7 a	102.2 a
2	88.3 b	74.0 bc	81.2 b
4	82.4 bc	70.4 c	76.4 b
8	89.4 b	72.9 bc	81.2 b
16	86.5 bc	80.3 bc	83.4 b
32	82.8 bc	78.8 bc	80.8 b
P Main Effect	85.5 A	82.6 A	

TABLE 10

Influence of Fertilizer P and Zn on Fe Concentration in Corn Shoots (ppm)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	44.5 b	81.4 a	62.9 a
2	38.4 bcd	26.3 d	32.3 b
4	37.7 bcd	29.8 d	33.8 b
8	36.1 bcd	38.5 bcd	37.3 b
16	37.0 bcd	39.7 bcd	38.4 b
32	38.2 bcd	42.4 bc	40.3 b
P Main Effect	38.7 A	43.0 A	

TABLE 11

Influence of Fertilizer P and Zn on Fe Uptake into Corn Shoots (μg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	1492 cd	626 e	1059 b
2	1821 abcd	1601 cd	1711 a
4	1821 abcd	1911 abc	1866 a
8	1809 abcd	2339 a	2024 a
16	1707 bcd	2238 a	1972 a
32	1376 d	2124 ab	1750 a
P Main Effect	1672 A	1790 A	

Plant Mn Concentration and Uptake

Phosphorus fertilization did not influence Mn concentration in corn leaf blades. However, shoot Mn concentration decreased with increasing P (Table 13). The decrease in concentration could have resulted from an antagonistic effect of P on Mn nutrition by corn since the uptake also decreased (Table 14). But, it seems more likely that the decrease in Mn concentration resulted from dilution since the lower Mn uptake at 200 ppm P more likely resulted from the low dry matter yield obtained in the 0 Zn, 200 ppm P treatment where P accentuated Zn deficiency.

Application of Zn decreased Mn concentration in corn tissue but the uptake was increased. The decrease in Mn concentration was most likely due to dilution as a result of response in dry matter yield to Zn fertilization. The high Mn concentration in the Zn control resulted from a concentration effect due to low dry matter yield obtained as a result of P accentuated Zn deficiency.

There was significant P-Zn interaction in Mn concentration and uptake. The interaction in Mn concentration resulted from the increase in Mn concentration in the Zn control as the P level was increased to 200 ppm while at other Zn levels Mn concentrations either decreased or remained the same. The significant P-Zn interaction in Mn uptake was caused by the decrease in Mn uptake with increasing P at 0 Zn due to the low dry matter yield while Mn uptake at other Zn levels was either unaffected by P or increased with increasing P.

Manganese levels in the leaf blades were adequate according to the critical level of 15 ppm reported in the literature by Melsted, _et al._ (1969). Plant available Mn levels in the soil also suggest that

TABLE 12

Influence of Fertilizer P and Zn on Mn Concentration in Corn Leaves (ppm)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	54.0 b	99.4 a	76.7 a
2	46.3 bc	41.9 cd	44.1 bc
4	42.4 cd	34.5 d	38.4 cd
8	40.2 cd	36.1 d	38.1 d
16	45.3 d	36.4 d	40.8 cd
32	53.8 b	40.5 cd	47.2 b
P Main Effect	47.0 A	48.1 A	

TABLE 13

Influence of Fertilizer P and Zn on Mn Concentration in Corn Shoots (ppm)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	48.6 a	54.7 a	51.7 a
2	35.2 bcd	27.1 cde	31.2 bc
4	33.6 bcd	23.8 e	28.7 c
8	35.7 bc	23.7 e	29.7 c
16	34.7 bcd	26.6 de	30.7 bc
32	38.5 b	33.6 bcd	36.1 b
P Main Effect	37.7 A	31.6 B	

TABLE 14

Influence of Fertilizer P and Zn on
Mn Uptake into Corn Shoots (μg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	1441 ab	460 c	951 b
2	1448 a	1372 ab	1410 a
4	1425 ab	1360 ab	1393 a
8	1470 a	1293 ab	1382 a
16	1360 ab	1372 ab	1366 a
32	1235 b	1504 a	1369 a
P Main Effect	1396 A	1227 B	

the plants were likely not deficient in Mn.

Plant P Concentration and Uptake

Phosphorus fertilization was effective in increasing plant P concentration and uptake (Tables 15, 16 and 17). Such a response was expected on the basis of the low level of available P in the soil. On the basis of earleaf critical level of 0.25% reported by Melsted, *et al.* (1969) the plants that received 200 ppm P had adequate P in the leaf blades but the level was slightly low for the 50 ppm P treatment. Lack of adequate P in this treatment is supported by the P deficiency symptoms exhibited as mentioned earlier.

TABLE 15

Influence of Fertilizer P and Zn on P Concentration in Corn Leaves (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.28 c	0.73 a	0.51 a
2	0.22 de	0.38 b	0.30 b
4	0.21 e	0.26 cd	0.24 c
8	0.20 e	0.26 cd	0.23 c
16	0.20 e	0.25 cde	0.22 c
32	0.21 e	0.25 cde	0.23 c
P Main Effect	0.22 B	0.36 A	

TABLE 16

Influence of Fertilizer P and Zn on P Concentration in Corn Shoots (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.24 bc	0.38 a	0.31 a
2	0.18 d	0.26 b	0.22 b
4	0.18 d	0.21 cd	0.19 c
8	0.18 d	0.24 bc	0.21 bc
16	0.17 d	0.24 bc	0.21 bc
32	0.18 d	0.27 b	0.23 b
P Main Effect	0.19 B	0.27 A	

TABLE 17

Influence of Fertilizer P and Zn on
P Uptake into Corn Shoots (mg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	72.6	32.8	52.7 d
2	73.7	129.7	101.7 a
4	75.6	116.1	95.9 ab
8	73.2	123.1	98.1 ab
16	64.3	120.3	92.3 bc
32	56.2	117.6	86.9 c
P Main Effect	69.3 B	106.6 A	

Increasing Zn from 0 to 4 ppm decreased both leaf and shoot P, but there was no further decrease in P concentration at higher Zn levels. Those decreases were likely due to dilution as a result of response in dry matter yield to Zn fertilization. The high P concentration and the corresponding low uptake obtained in corn receiving no Zn were due to low dry matter yield caused by P accentuated Zn deficiency at the 200 ppm P level.

The lower P uptake at the highest level of Zn resulted from the decreased dry weight caused by Zn "toxicity". Perhaps at least a portion of this Zn "toxicity" resulted from Zn accentuated P deficiency.

Plant S Concentration and Uptake

The S concentration in the leaf blades suggest that the plants were likely S deficient according to the critical level of 0.1% of S in corn suggested by Barber and Olson (1968) despite addition of about 95 ppm S as K_2SO_4. If the S values are correct the possibility that some of the apparent response in dry matter yield to Zn may have been due to the S in the $ZnSO_4 \cdot 7H_2O$ source can not be ruled out.

Increasing P from 50 to 200 ppm increased shoot and leaf concentrations as well as S uptake (Tables 18, 19 and 20). The increase in S concentration in leaves likely resulted from a concentration effect in the 0 Zn, 200 ppm P treatment as supported by the corresponding low S uptake. However, it seems that P somehow increased S uptake and/or translocation of S to the leaves, as shoot S concentrations increased with increasing P without a concentration effect at 0 Zn and the increase in S uptake was very dramatic.

Zinc application increased S concentration in the leaves as a result of a concentration effect for the 0 Zn, 200 ppm P treatment. But, shoot S concentration and S uptake into shoots increased with increasing Zn. The high S content at the highest rate of Zn was at least partly due to concentration effect due to the suspected Zn "toxicity" but could also have been caused by application of 16 ppm S through the 32 ppm Zn treatment.

There was significant P-Zn interaction in S concentration and uptake. The interaction obtained in the leaves was due to the increase in S concentration with increasing P due to low dry matter in the 0 Zn 200 ppm P while P did not influence S concentration at other Zn levels. The interaction in the entire plant shoot was due to the higher S

TABLE 18

Influence of Fertilizer P and Zn on S Concentration in Corn Leaves (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.04 b	0.25 a	0.15 a
2	0.07 b	0.07 b	0.07 bc
4	0.06 b	0.05 b	0.05 bc
8	0.04 b	0.05 b	0.05 c
16	0.07 b	0.08 b	0.08 b
32	0.07 b	0.08 b	0.08 b
P Main Effect	0.06 B	0.10 A	

TABLE 19

Influence of Fertilizer P and Zn on S Concentration in Corn Shoots (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.11 cd	0.11 cd	0.11 bc
2	0.11 cd	0.10 d	0.10 bc
4	0.10 d	0.09 d	0.10 c
8	0.09 d	0.13 bc	0.11 bc
16	0.09 d	0.14 b	0.12 b
32	0.10 d	0.18 a	0.14 a
P Main Effect	0.10 B	0.12 A	

TABLE 20

Influence of Fertilizer P and Zn on
S Uptake into Corn Shoots (mg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	28.6 e	10.0 f	19.3 d
2	38.7 cde	43.6 cd	41.2 c
4	38.2 cde	46.9 c	42.5 bc
8	34.9 cde	58.8 b	46.9 ab
16	33.0 de	67.2 ab	50.1 a
32	28.3 e	69.0 a	48.7 ab
P Main Effect	33.6 B	49.2 A	

concentration for rates of Zn above 8 ppm at the higher rate of P. P-Zn interaction in S uptake was also caused by the low dry matter in the treatment receiving no Zn when the rate of P was 200 ppm.

Plant Ca Concentration and Uptake

Calcium concentration in the leaf blades suggest that Ca was adequate according to levels reported in the literature (Appendix 1).

Calcium concentration in the corn tissue was not influenced by P fertilization (Tables 21 and 22).

The effect of Zn application on Ca concentration followed a similar trend as most of the other nutrients. The shoot Ca concentration was high in the treatment receiving no Zn due to the concentration effect in the 0 Zn, 200 ppm P treatment. The low Ca uptake in the same treatment also resulted from low dry matter yield in the 0 Zn 200 ppm P treatment (Table 23).

There was a significant P-Zn interaction in leaf Ca concentration as well as in Ca uptake resulting once again from the concentration effect and the low dry matter yield in the 0 Zn, 200 ppm P treatment.

Plant Mg Concentration and Uptake

Magnesium levels in the corn leaves were adequate. The critical level of Mg suggested by Melsted, et al. (1969) in corn earleaves was 0.25%.

Additional P did not influence leaf Mg concentration or Mg uptake significantly but decreased shoot Mg concentration, probably as a result of dilution (Tables 24, 25 and 26).

There was no significant P-Zn interaction in leaf or shoot Mg concentration. The significant P-Zn interaction in Mg uptake was caused by P accentuated Zn deficiency in the 0 Zn, 200 ppm P treatment.

The small decreases in leaf and shoot Mg concentrations with increasing Zn likely resulted from dilution caused by the response in growth to Zn fertilization which also resulted in the increase in Mg uptake with increasing Zn.

TABLE 21

Influence of Fertilizer P and Zn on Ca Concentration in Corn Leaves (%)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	0.37 c	0.55 a	0.46 a
2	0.44 bc	0.44 bc	0.44 ab
4	0.42 bc	0.43 bc	0.42 ab
8	0.46 b	0.46 b	0.46 a
16	0.42 bc	0.41 bc	0.42 ab
32	0.41 bc	0.36 c	0.39 b
P Main Effect	0.42 A	0.44 A	

TABLE 22

Influence of Fertilizer P and Zn on Ca Concentration in Corn Shoots (%)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	0.67	0.70	0.68 a
2	0.57	0.62	0.61 ab
4	0.56	0.52	0.53 b
8	0.56	0.42	0.49 b
16	0.55	0.44	0.49 b
32	0.60	0.45	0.53 b
P Main Effect	0.59 A	0.52 A	

TABLE 23

Influence of Fertilizer P and Zn on
Ca Uptake into Corn Shoots (mg/pot)

Zn Rate ppm	P Rate ppm 50	P Rate ppm 200	Zn Main Effect
0	179 cd	45 e	112 e
2	221 b	273 a	247 a
4	219 b	262 a	241 ab
8	217 bc	218 bc	218 bc
16	196 bcd	210 bcd	203 cd
32	172 bcd	192 bcd	182 d
P Main Effect	210 A	200 A	

TABLE 24

Influence of Fertilizer P and Zn on Mg Concentration in Corn Leaves (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.38	0.41	0.39 ab
2	0.42	0.44	0.43 a
4	0.37	0.37	0.37 ab
8	0.35	0.41	0.38 ab
16	0.35	0.36	0.35 b
32	0.36	0.36	0.35 b
P Main Effect	0.37 A	0.39 A	

TABLE 25

Influence of Fertilizer P and Zn on Mg Concentration in Corn Shoots (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.81	0.55	0.68 a
2	0.68	0.69	0.69 a
4	0.66	0.61	0.63 a
8	0.48	0.33	0.40 b
16	0.53	0.36	0.45 b
32	0.55	0.35	0.45 b
P Main Effect	0.62 A	0.48 B	

TABLE 26

Influence of Fertilizer P and Zn on Mg Uptake into Corn Shoots (mg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	216 bc	35 d	126 c
2	249 ab	305 a	277 a
4	251 ab	308 a	279 a
8	185 c	172 c	178 b
16	187 c	178 c	183 b
32	156 c	155 c	155 bc
P Main Effect	207 A	192 A	

Plant K Concentration and Uptake

The corn plants might have been K deficient according to the critical level of 1.90% suggested by Melsted, et al. (1969) for corn earleaves at tasseling. This was surprising since 231 ppm K were added.

Phosphorus fertilization increased K concentrations in both leaves and shoots (Tables 27 and 28). Since K uptake into the shoots also increased as P rate was increased from 50 ppm to 200 ppm it can be concluded that high P increased K uptake and/or translocation into the shoots.

There was a significant P-Zn interaction in K uptake into the shoots due to a decrease in uptake with increasing P when Zn was not applied, while K uptake increased with increasing P at all other Zn levels. Once again, the low uptake for the 0 Zn, 200 ppm P treatment was due to the low dry matter yield resulting from P accentuated Zn deficiency.

Zinc fertilization did not affect K concentrations. However, K uptake was significantly lower in the treatment receiving no Zn.

Plant N Concentration

The N concentrations were determined on bulked samples therefore no statistical analysis could be performed. Nitrogen in the corn leaves was below the critical level of 3% suggested by Melsted, et al. (1969). This was not expected since the slight N deficiency symptoms disappeared after each of the two 25-ppm additional N increments. It is quite conceivable that N deficiency modified the responses to P and Zn and critical Zn levels derived from this work should be used with some caution.

Generally, additional P decreased N concentrations in the tissue as a result of dilution except where Zn was not added where the usual concentration effect brought about by P accentuated Zn deficiency was involved. Other than the concentration effect at 0 Zn, 200 ppm P, rates of Zn had little influence upon plant N concentration (Tables 30 and 31).

TABLE 27

Influence of Fertilizer P and Zn on K Concentration in Corn Leaves (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	1.08	1.56	1.32 a
2	0.87	1.29	1.08 a
4	0.86	1.21	1.04 a
8	0.92	1.22	1.07 a
16	1.15	1.38	1.26 a
32	1.43	1.33	1.38 a
P Main Effect	1.05 B	1.33 A	

TABLE 28

Influence of Fertilizer P and Zn on K Concentration in Corn Shoots (%)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	0.59	1.23	0.91 a
2	0.69	1.12	0.90 a
4	0.88	0.89	0.89 a
8	0.61	0.76	0.69 a
16	0.50	0.98	0.74 a
32	0.66	1.12	0.89 a
P Main Effect	0.65 B	1.05 A	

TABLE 29

Influence of Fertilizer P and Zn on K Uptake into Corn Shoots (mg/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	198 cd	91 d	145 b
2	280 cb	256 a	403 a
4	358 bc	507 a	433 a
8	268 c	414 ab	341 a
16	227 c	509 a	368 a
32	240 c	510 a	375 a
P Main Effect	252 B	426 A	

TABLE 30

Influence of Fertilizer P and Zn on N Concentration in Corn Leaves

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	2.56	3.18	3.02
2	2.14	2.00	2.07
4	2.13	1.92	2.02
8	2.21	1.97	2.09
16	2.20	1.99	2.09
32	2.56	2.00	2.28
P Main Effect	2.30	2.17	

TABLE 31

Influence of Fertilizer P and Zn on N Concentration in Corn Shoots

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	2.65	3.40	3.02
2	2.04	1.92	1.98
4	1.99	1.47	1.73
8	2.03	2.02	2.03
16	2.39	1.61	2.00
32	2.49	2.04	2.27
P Main Effect	2.26	2.08	

Plant Zn Critical Levels

The critical level of Zn in corn leaf blades (6th and 7th leaf at tasseling) as well as total plant shoots were determined using the approach used by McAndrew (1979) for critical levels of Cu in barley, wheat, oats rapeseed and flax. The critical ranges determined for the leaves were generally not influenced by the P rate (Figures 2 and 3). The deficient, low, sufficient and toxic levels are also shown below.

	Deficient	Low	Sufficient	"Toxic"
50 ppm P	< 7.5	7.5-15	15-25	25 +
200 ppm P	< 7.0	7.0-15	15 +	—

The lack of influence of P rate on the various ranges is not surprising since the concentration of Zn in the leaves was not influenced by P fertilization (Table 3). Since the dry matter yield curve did not slope turn down at higher levels of Zn when 200 ppm P were applied, it is likely that the so-called toxic range at 50 ppm P was caused by Zn accentuated P deficiency rather than Zn toxicity.

Total Plant Shoot Critical Levels

In contrast to the critical levels determined in the leaves shoot critical levels were influenced by the level of P (Figures 4 and 5). The different critical ranges are also shown below.

	Deficient	Low	Sufficient	"Toxic"
50 ppm P	< 12.5	12.5-20	20-45	45 +
200 ppm P	< 7.5	7.5-15	15 +	—

In this case corn was Zn deficient when the shoot Zn concentration was below 12.5 ppm for the low P rate, but when the level of P was increased to 200 ppm corn was deficient in Zn when the shoot Zn concentration was below 7.5 ppm. This is not surprising since shoot Zn concentrations were less at 200 ppm P than at 50 ppm P due both to dilution and high P decreasing Zn uptake and/or translocation to the shoots. These results point out that there are many factors which influence plant Zn critical levels. Not only is it important when determining a critical level to optimize all factors other than Zn supply, but also one should accurately describe all environmental conditions when reporting a critical level.

Differences in the Zn concentration ranges between the leaves and entire shoots indicate that the plant part sampled for analysis also influences the critical level. Since the Zn concentration ranges in the leaves were not influenced by P, it would appear that it is a better plant part to use for diagnostic purposes. The use of earleaves as a standard for comparison is therefore supported by this data. However, as mentioned earlier factors other than P may influence the concentration of Zn in the earleaves, so further work is required to identify such factors so as to make critical levels determined more meaningful for diagnostic purposes.

The "Steenbjerg effect" observed by Steenbjerg (1951) was also observed in these results when 200 ppm P was applied (Figure 5). Plants that were highly Zn deficient (lower part of the graph) had Zn concentrations which were just as high as the plants that had adequate Zn (15 ppm +), but this was due to a concentration effect resulting from low dry matter yield caused by P accentuated Zn deficiency. This further suggests that care is needed in using concentrations of Zn in corn shoots for diagnostic purposes.

The results in Figures 2 and 3 suggest that corn plants containing less than 7.5 ppm Zn in the leaf blades were Zn deficient regardless of the P level. But, Zn deficiency symptoms were not as evident in corn receiving 50 ppm P as in corn receiving 200 ppm P. These results are in agreement with those reported by Berger (1962) who indicated that Zn deficiency could occur without evident deficiency symptoms.

As mentioned before, the leaf blades used for determination of the critical levels were taken slightly earlier than the silking stage which is recommended in the literature. In addition, the lack of adequate N may have influenced the critical levels reported in this experiment. Therefore, the critical levels of Zn determined in this experiment have to be used with caution.

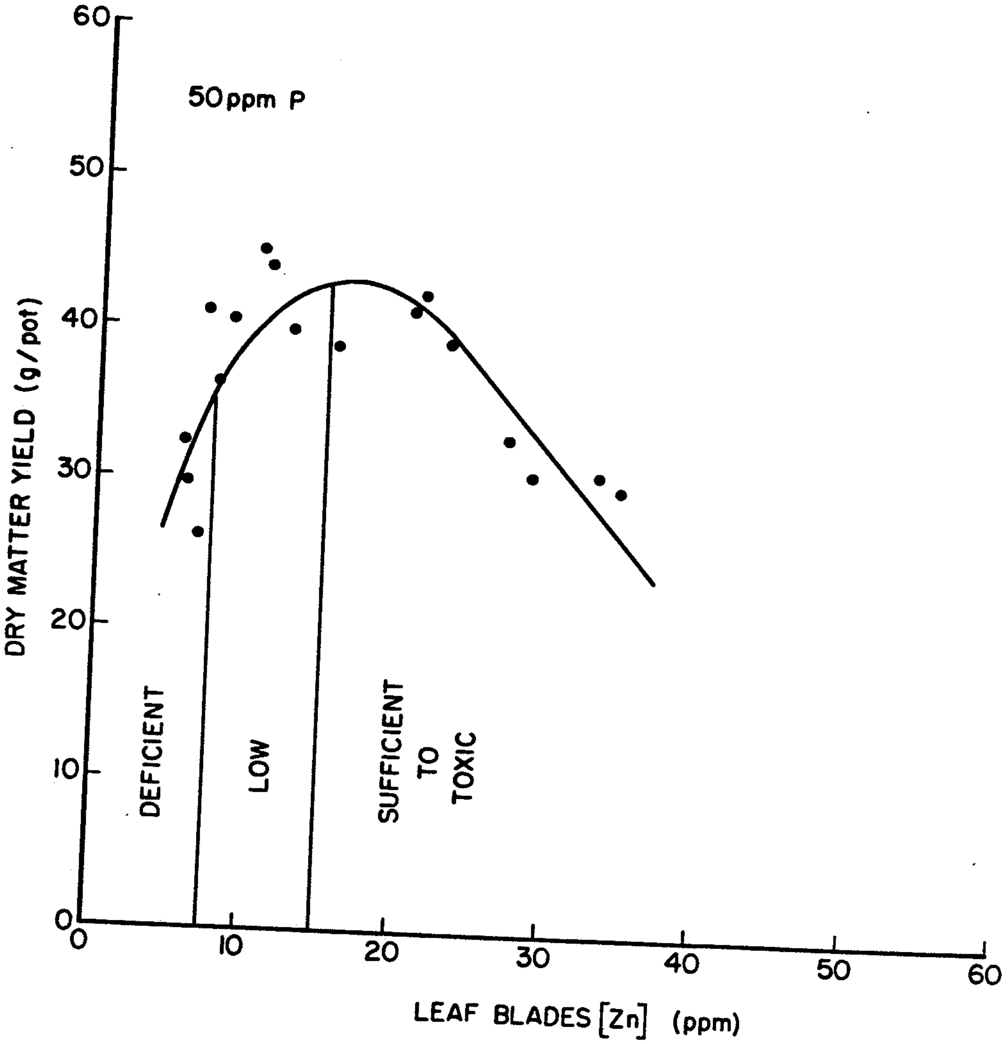


FIGURE 2: Critical Level of Zn in Mature Corn Leaf Blades

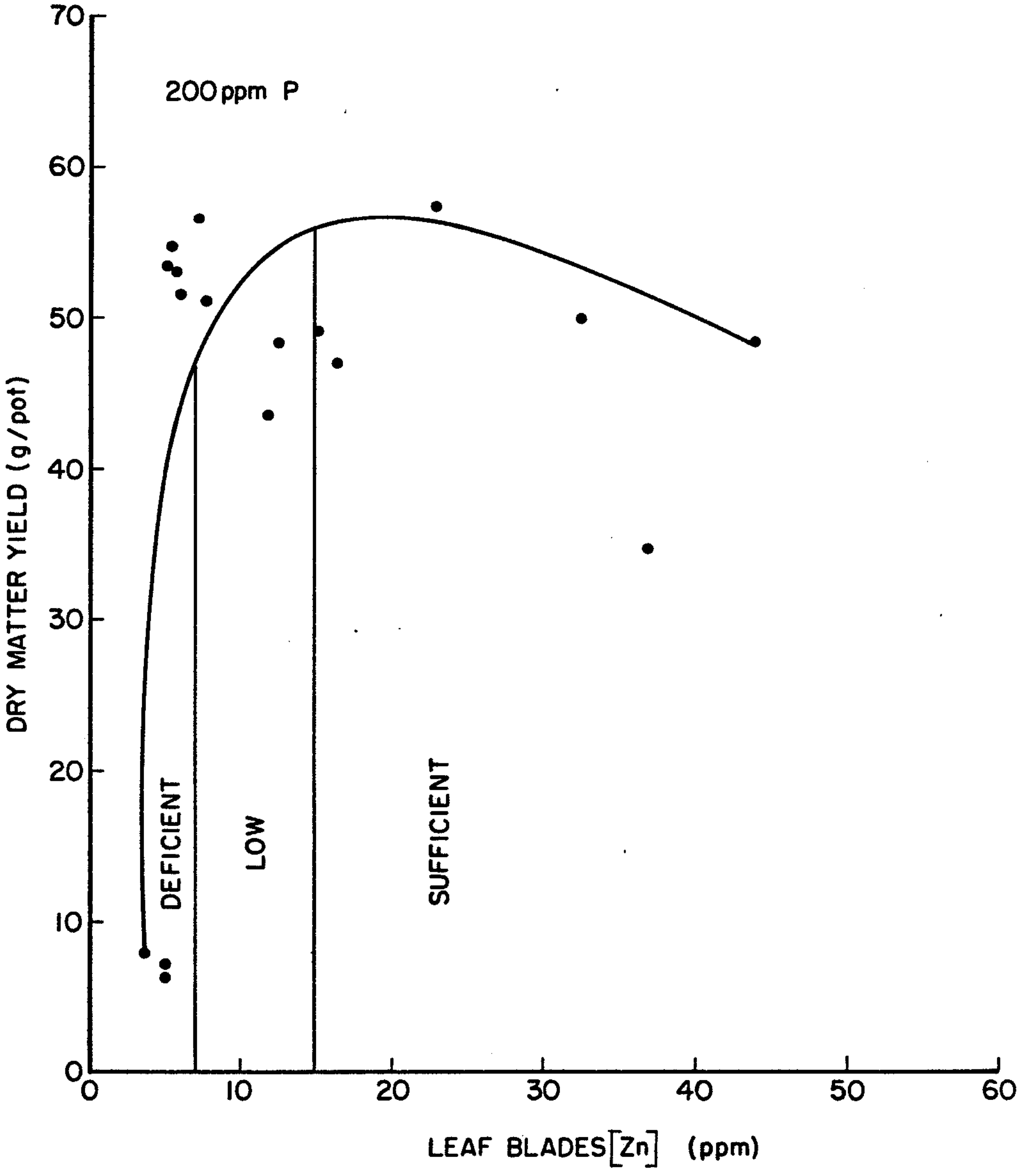


FIGURE 3: Critical Level of Zn in Mature Corn Leaf Blades

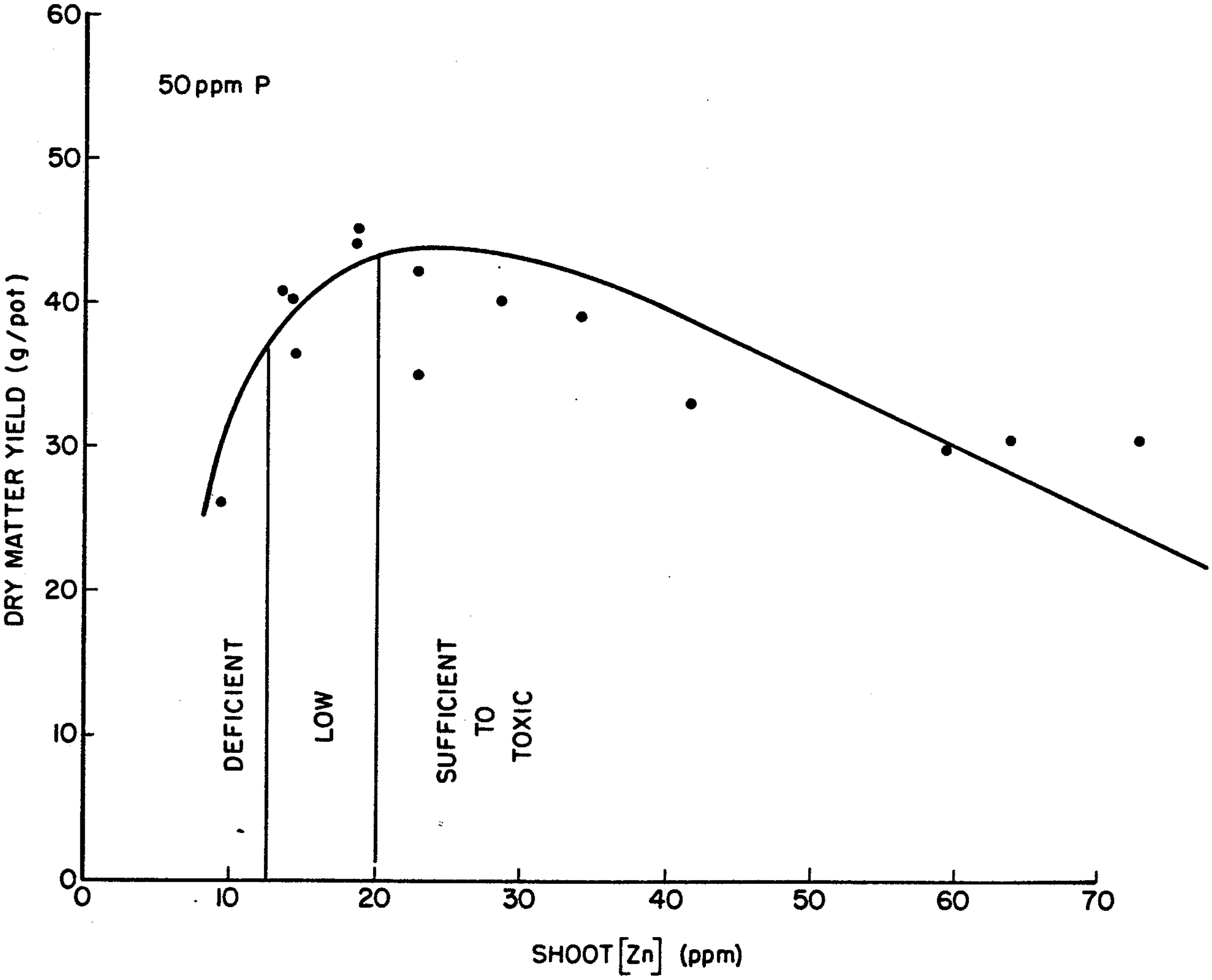


FIGURE 4: Critical Level of Zn in Corn Shoots

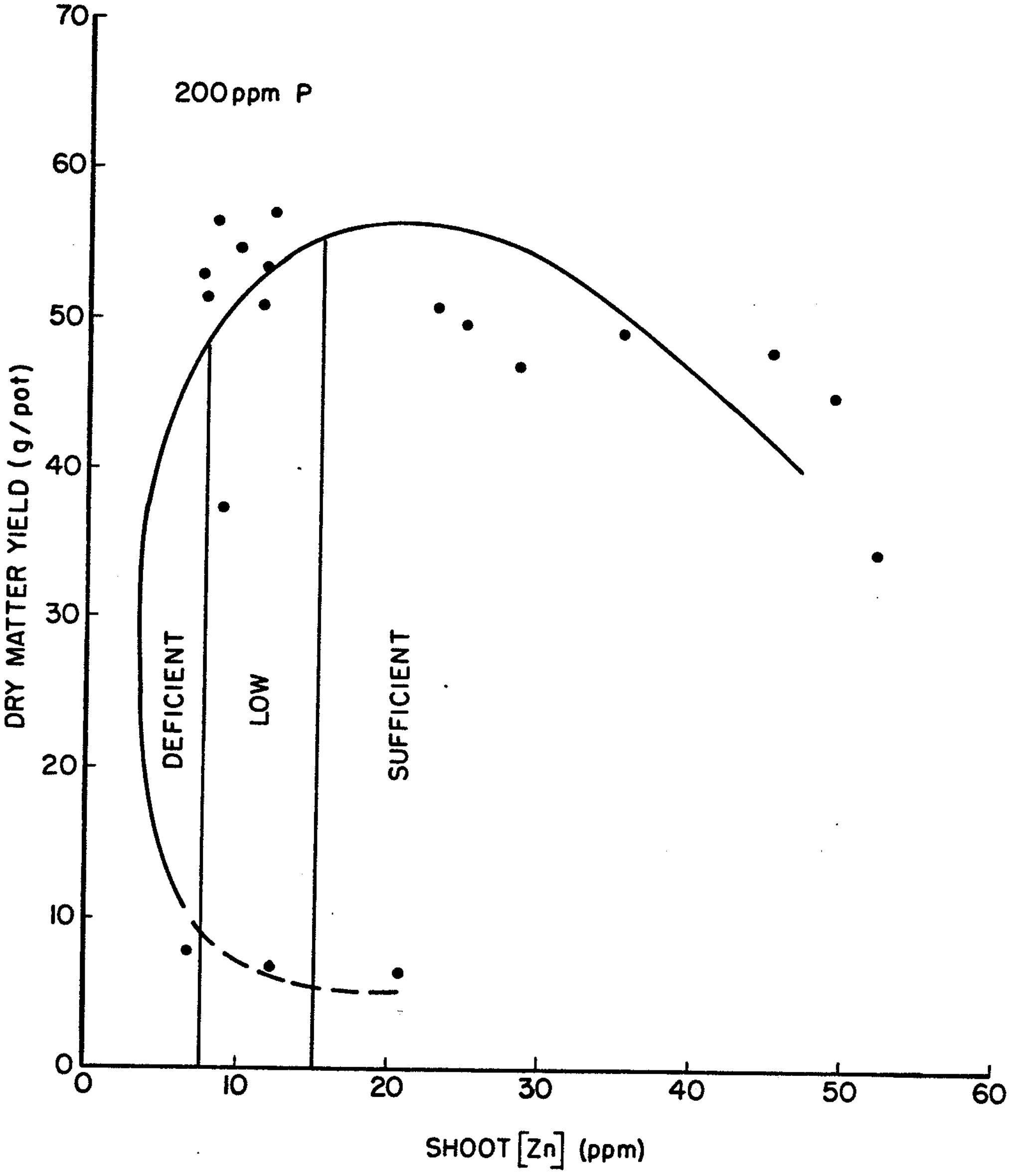


FIGURE 5: Critical Level of Zn in Corn Shoots

II. GROWTH BENCH COPPER EXPERIMENT

Corn was grown for about eight weeks on Almasippi loamy very fine sand, low in plant available Cu, under environmental conditions similar to those of the zinc experiment. The objectives of the study were

(1) to determine if corn would respond to Cu fertilization under controlled environment;

(2) to determine the critical level of Cu in corn shoots;

(3) to determine the influence of P on the critical level of Cu and

(4) to determine the influence of P-Cu interaction in dry matter yield, nutrient concentration and uptake by corn.

The soil physical and chemical characteristics were the same as those in the zinc experiment (Table 1).

Plant Appearance

Generally corn plants in this experiment had a healthy appearance although plant critical levels suggested in the literature indicated that some nutrients, particularly N, were not adequate for optimum growth. However, slight nitrogen deficiency symptoms were exhibited. Plants receiving 50 ppm P exhibited P deficiency symptoms but these were not as evident as those observed in the zinc experiment. Copper deficiency symptoms were not evident.

Dry Matter Yield

Dry matter yield of the total shoots of eight-week old corn plants increased as the level of P was increased from 50 to 200 ppm (Table 32). The response to P was similar to that obtained in the zinc experiment.

Dry matter yield was also influenced significantly by the level of fertilizer Cu, but the relationship between Cu level and dry matter yield was inconsistent and it can not be said that supplemental Cu increased dry matter yield. In contrast to the zinc experiment, there was no P-Cu interaction in dry matter yield.

Plant Cu Concentration and Uptake

Plant Cu concentrations were not influenced by P fertilization (Tables 33 and 34). However, Cu uptake was increased by additional P (Table 35), likely as a result of the higher dry matter yield at the higher P level. Since high P did not decrease Cu uptake at any level of Cu it is not surprising that P did not induce or accentuate Cu deficiency.

Copper fertilization increased both leaf and total plant shoot Cu as well as Cu uptake. Since Cu fertilization did increase Cu uptake the lack of response in dry matter yield to Cu fertilization suggests that the corn was not Cu deficient although the level of available Cu in the soil was low. In contrast, studies with other crops such as barley (Akinyede, 1978) and flax (Haluschak, 1972) indicated that responses to Cu fertilization were very frequent in the growth chamber on mineral soils low in available Cu. As such, one would expect the situation to be the same with corn. However, it was reported in the

TABLE 32

Influence of Fertilizer P and Cu upon Dry Matter Yield of Eight-Week Old Corn Shoots (g/pot)

Zn Rate ppm	P Rate ppm		Zn Main Effect
	50	200	
0	38.3	48.3	43.3 ab
1	31.1	41.5	38.3 ab
2	38.8	55.3	47.1 a
4	33.3	39.1	36.2 b
8	35.2	53.2	44.2 ab
16	30.9	53.8	42.3 ab
P Main Effect	35.3 B	48.5 A	

TABLE 33

Influence of Fertilizer P and Cu on
Cu Concentration in Corn Leaves (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	5.0	5.4	5.2 c
1	7.9	5.8	6.9 bc
2	8.0	7.5	7.8 ab
4	8.6	9.8	9.2 a
8	9.1	8.6	8.8 a
16	10.0	8.2	9.1 a
P Main Effect	8.1 A	7.5 A	

TABLE 34

Influence of Fertilizer P and Cu on
Cu Concentration in Corn Shoots (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	3.2	2.5	2.9 d
1	3.3	4.2	3.8 c
2	4.7	5.5	5.1 b
4	5.1	5.1	5.1 b
8	5.0	6.2	5.6 b
16	7.3	7.1	7.2 a
P Main Effect	4.8 A	5.1 A	

TABLE 35

Influence of Fertilizer P and Cu on Cu Uptake into Corn Shoots (μg/pot)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	136 d	139 d	137 d
1	143 d	185 cd	164 cd
2	205 cd	310 b	258 b
4	189 cd	225 c	207 c
8	200 cd	340 ab	270 ab
16	240 c	386 a	313 a
P Main Effect	186 B	264 A	

literature that corn was not particularly sensitive to Cu deficiency (Berger, 1962). In addition, it is not surprising that there was no response to Cu since Cu levels were not particularly low when compared to the critical level of 5.0 ppm suggested by Melsted, et al. (1969).

There was no significant P-Cu interaction in plant Cu concentrations. However, the greater increase in Cu uptake with increasing fertilizer Cu at the higher P level resulted in significant P-Cu interaction in total Cu uptake. As with Zn, perhaps corn plants receiving 200 ppm P were not as limited by P supply and therefore able to take up more Cu.

TABLE 36

Influence of Fertilizer P and Cu on Zn Concentration in Corn Leaves (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	20.8	17.5	19.2 a
1	23.3	20.1	21.7 a
2	20.9	19.6	20.3 a
4	23.6	26.4	25.0 a
8	25.4	20.4	22.9 a
16	21.4	20.0	20.7 a
P Main Effect	22.6 A	20.6 A	

TABLE 37

Influence of Fertilizer P and Cu on Zn Concentration in Corn Shoots (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	43.3	26.3	34.8 ab
1	49.2	33.9	41.6 ab
2	52.3	31.9	42.1 a
4	37.8	29.4	33.6 b
8	45.8	31.0	38.4 ab
16	43.3	31.2	37.3 ab
P Main Effect	45.3 A	30.6 B	

TABLE 38

Influence of Fertilizer P and Cu on
Zn Uptake into Corn Shoots (μg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	1503	1207	1355 bc
1	1543	1311	1427 abc
2	1828	1610	1719 a
4	1214	1106	1160 c
8	1492	1555	1523 ab
16	1242	1589	1416 abc
P Main Effect	1470 A	1396 A	

Plant Zn Concentration and Uptake

The concentration of Zn in corn leaf blades were above the critical level of 15 ppm suggested in the literature for corn earleaves and were above the critical levels determined in the zinc experiment. Apparently, the uniform application of 15 ppm Zn was sufficient. Leaf Zn concentration was not affected by P fertilization (Table 36). However, shoot Zn concentration was decreased by additional P. The decrease in Zn concentration with increasing P likely resulted from dilution since total Zn uptake into the shoots was not influenced by the P level (Table 38). Added Cu did not influence leaf Zn concentrations but did affect shoot Zn concentration and Zn uptake. However, the results were inconsistent and difficult to interpret.

Plant Fe Concentration and Uptake

Levels of Fe in the leaf blades were adequate based on the critical level of 15 ppm suggested by Melsted, et al. (1969) for corn earleaves at silking. The only significant treatment effects involved shoot Fe concentration and uptake. The lowest concentration and uptake were obtained where the lowest yield was obtained (Tables 39, 40 and 41). But, as with Zn, the results were inconsistent and difficult to interpret.

Plant Mn Concentration and Uptake

Additional P decreased both leaf and shoot Mn concentrations (Tables 42 and 43). This may have resulted entirely from dilution as total Mn uptake was increased by additional P (Table 44).

Leaf Mn concentration increased with increasing level of Cu applied. Shoot Mn concentration and Mn uptake into shoots were not as consistently related to the level of Cu. However, shoot Mn concentrations and Mn uptake were generally higher at the higher Cu levels. Perhaps Cu somehow facilitated the uptake of Mn.

There was significant P-Cu interaction in leaf Mn concentration. The interaction resulted from the fact that Mn concentration increased more with increasing Cu at 50 ppm P than at 200 ppm P. Manganese concentrations in the leaf blades were well above the critical level of 15 ppm suggested by Melsted, et al. (1969). Manganese was therefore not limiting in this experiment.

TABLE 39

Influence of Fertilizer P and Cu on Fe Concentration in Corn Leaves (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	88.7	87.9	88.3 a
1	86.0	92.0	89.0 a
2	84.9	90.1	87.5 a
4	82.5	83.4	83.0 a
8	97.8	83.4	90.6 a
16	82.4	83.0	82.7 a
P Main Effect	87.0 A	86.6 A	

TABLE 40

Influence of Fertilizer P and Cu on Fe Concentration in Corn Shoots (ppm)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	53.4	59.0	56.2 ab
1	59.3	70.6	64.9 a
2	59.7	57.4	58.6 ab
4	52.1	48.4	50.3 b
8	60.3	56.1	58.2 ab
16	62.9	54.6	58.8 ab
P Main Effect	58.0 A	57.7 A	

TABLE 41

Influence of Fertilizer P and Cu on
Fe Uptake into Corn Shoots (µg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	2274	3079	2667 a
1	2237	3054	2646 a
2	2481	3396	2939 a
4	1895	2102	1999 b
8	2329	3150	2740 a
16	2026	3065	2545 a
P Main Effect	2207 B	2971 A	

TABLE 42

Influence of Fertilizer P and Cu on Mn Concentration in Corn Leaves (ppm)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	46.5 de	37.5 f	42.0 d
1	54.6 bc	40.7 cf	47.7 bc
2	49.2 cd	41.3 ef	45.3 cd
4	53.9 bc	42.2 ef	48.0 bc
8	58.6 b	42.5 ef	50.6 b
16	66.3 a	46.2 de	56.3 a
P Main Effect	54.9 A	41.7 B	

TABLE 43

Influence of Fertilizer P and Cu on Mn Concentration in Corn Shoots (ppm)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	41.2	31.3	36.3 b
1	41.6	38.3	40.0 ab
2	44.5	34.0	39.3 ab
4	42.1	33.3	37.7 ab
8	41.2	35.1	38.1 ab
16	46.1	38.4	42.3 a
P Main Effect	42.8 A	35.1 B	

TABLE 44

Influence of Fertilizer P and Cu on
Mn Uptake into Corn Shoots (μg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	1607	1549	1578 ab
1	1536	1601	1569 ab
2	1760	1854	1807 a
4	1462	1334	1398 b
8	1543	1924	1734 a
16	1520	2077	1799 a
P Main Effect	1571 B	1723 A	

Plant P Concentration and Uptake

Melsted, *et al.* (1969) suggested that the critical level of P in corn earleaves at silking was 0.25%. On this basis the plants receiving 50 ppm P were P deficient while those receiving the higher level of P were not deficient in P (Table 45). It was not surprising therefore that additional P significantly increased dry matter yield (Table 32) particularly when it is considered that the soil was low in available P.

Additional P increased both plant P concentrations and P uptake (Tables 45, 46 and 47). These results are similar to those obtained in the Zn experiment. Added Cu influenced significantly shoot P concentration as well as uptake. However, the relationship was inconsistent and difficult to interpret. There was no evidence that high Cu accentuated P deficiency, contrary to the effect of Zn upon P nutrition in the Zn experiment.

Plant S Concentration and Uptake

Sulphur concentrations in the leaf blades were generally adequate according to the critical level of 0.1% suggested by Barber and Olson (1968) for corn earleaves at silking. However, these levels were much higher compared to the levels obtained in the zinc experiment.

Similar to results in the zinc experiment leaf S as well as total S uptake into shoots were increased by additional P suggesting that P might have enhanced S uptake and/or translocation into the shoots (Tables 48 and 50). The decrease in S concentration in the shoots with increasing P likely resulted from dilution. The apparent increase in S uptake with increasing P was not due to S contamination

TABLE 45

Influence of Fertilizer P and Cu on P Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.19	0.23	0.21 a
1	0.16	0.28	0.22 a
2	0.17	0.26	0.22 a
4	0.16	0.24	0.20 a
8	0.14	0.23	0.19 a
16	0.15	0.26	0.20 a
P Main Effect	0.16 B	0.25 A	

TABLE 46

Influence of Fertilizer P and Cu on P Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.18	0.23	0.20 ab
1	0.18	0.26	0.22 ab
2	0.17	0.26	0.22 ab
4	0.19	0.24	0.21 ab
8	0.16	0.23	0.19 b
16	0.20	0.25	0.23 a
P Main Effect	0.18 B	0.25 A	

TABLE 47

Influence of Fertilizer P and Cu on P Uptake into Corn Shoots (mg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	75.2	108.8	92.0 ab
1	60.2	110.3	85.2 ab
2	66.2	141.4	103.8 a
4	61.4	92.3	76.8 b
8	54.8	120.9	87.8 ab
16	58.9	134.9	96.9 ab
P Main Effect	62.8 B	118.1 A	

TABLE 48

Influence of Fertilizer P and Cu on S Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.13	0.15	0.14 a
1	0.09	0.17	0.13 a
2	0.12	0.16	0.14 a
4	0.10	0.15	0.13 a
8	0.11	0.15	0.13 a
16	0.14	0.13	0.14 a
P Main Effect	0.11 B	0.15 A	

TABLE 49

Influence of Fertilizer P and Cu on S Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.20	0.20	0.20 a
1	0.21	0.20	0.20 a
2	0.19	0.18	0.18 a
4	0.24	0.16	0.20 a
8	0.19	0.16	0.18 a
16	0.24	0.19	0.21 a
P Main Effect	0.21 A	0.18 B	

TABLE 50

Influence of Fertilizer P and Cu on
S Uptake into Corn Shoots (mg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	70.2	96.5	83.3 a
1	64.4	78.9	71.7 a
2	67.1	97.0	82.0 a
4	72.2	63.5	67.9 a
8	61.3	85.7	73.5 a
16	67.3	96.6	81.9 a
P Main Effect	67.1 B	86.4 A	

in the P source as the P carrier used was reagent grade $Ca(H_2PO_4)_2$.

<u>Plant Ca Concentration and Uptake</u>

The Ca concentration in the leaf blades indicate that the corn was not deficient in Ca (Appendix 1).

Increasing P level from 50 ppm to 200 ppm P decreased leaf Ca concentration (Table 51). This was likely caused by dilution as total Ca uptake into total plant shoots increased with increasing P (Table 53). Although the increase in total Ca uptake into shoots with increasing P likely was caused primarily by response in dry matter yield to P, the Ca in the P carrier may have contributed to the higher Ca uptake at the

TABLE 51

Influence of Fertilizer P and Cu on Ca Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.48	0.51	0.49 b
1	0.55	0.48	0.52 ab
2	0.52	0.51	0.52 ab
4	0.62	0.47	0.52 ab
8	0.61	0.53	0.57 ab
16	0.62	0.58	0.60 a
P Main Effect	0.57 A	0.51 B	

TABLE 52

Influence of Fertilizer P and Cu on Ca Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.35	0.36	0.36 a
1	0.36	0.42	0.39 a
2	0.41	0.40	0.41 a
4	0.35	0.37	0.36 a
8	0.35	0.41	0.38 a
16	0.36	0.49	0.43 a
P Main Effect	0.37 A	0.41 A	

TABLE 53

Influence of Fertilizer P and Cu on
Ca Uptake into Corn Shoots (mg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	142	185	164 a
1	138	177	157 a
2	167	225	196 a
4	132	152	142 a
8	136	228	182 a
16	124	282	203 a
P Main Effect	139 B	208 A	

higher P level.

Copper level influenced significantly leaf Ca concentration (Table 51). It probably cannot be said that Cu enhanced Ca uptake as shoot Ca concentration and total Ca uptake into corn shoots were not influenced by Cu level.

Plant Mg Concentration and Uptake

Magnesium concentration in the leaf blades suggest that the plants were not Mg deficient according to the critical level of 0.25% suggested by Melsted, et al. (1969) for corn earleaves. Increasing P level decreased leaf Mg concentration which could have resulted from

TABLE 54

Influence of Fertilizer P and Cu on Mg Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.40	0.41	0.40 a
1	0.48	0.39	0.44 a
2	0.41	0.38	0.40 a
4	0.44	0.41	0.42 a
8	0.43	0.39	0.41 a
16	0.40	0.41	0.41 a
P Main Effect	0.43 A	0.40 B	

TABLE 55

Influence of Fertilizer P and Cu on Mg Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	0.30	0.40	0.35 b
1	0.33	0.43	0.38 b
2	0.36	0.43	0.39 ab
4	0.29	0.41	0.35 b
8	0.30	0.42	0.36 b
16	0.41	0.48	0.45 a
P Main Effect	0.33 B	0.43 A	

TABLE 56

Influence of Fertilizer P and Cu on
Mg Uptake into Corn Shoots (mg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	121	191	156 a
1	124	175	149 a
2	142	231	187 a
4	105	160	133 a
8	113	219	166 a
16	126	257	192 a
P Main Effect	122 B	206 A	

dilution as Mg uptake into shoots actually increased (Tables 54 and 56). Much of the increase in total Mg uptake into shoots with increasing P probably resulted from the response in dry matter yield to P fertilization. However, it is possible that P enhanced Mg uptake as shoot Mg concentration increased with increasing P.

Shoot Mg concentration was influenced significantly by Cu with the highest Cu level resulting in the highest Mg concentration (Table 55). However, it is by no means certain that Cu enhanced Mg uptake as leaf Mg concentration and Mg uptake into shoots were not influenced significantly by Cu fertilization (Table 56).

Plant K Concentration and Uptake

The levels of K in the leaf blades suggest that K was marginal for optimum nutrition although 231 ppm K were added. The suggested critical level for corn earleaves is 1.9% (Melsted, et al., 1969).

Additional P had no influence on leaf K but it increased both shoot K concentration and K uptake into shoots, suggesting that P may have enhanced K uptake (Tables 57, 58 and 59).

Added Cu had no influence on tissue K but significantly affected K uptake with the highest uptake resulting from the treatment that gave the highest dry matter yield.

Plant N Concentration

Like the zinc experiment the levels of N in the leaf blades suggest that the plants were N deficient on the basis of the critical level of 3% N suggested by Melsted, et al. (1969) for corn earleaves at tasseling. Although the soil was low in available NO_3-N N deficiency was not expected since slight N deficiency symptoms disappeared after each of the two 25-ppm additional N increments. Nitrogen deficiency may have been partially responsible in the lack of response to Cu fertilization.

Plant Cu Critical Levels

It was not possible to determine plant Cu critical levels since there was no response to Cu fertilization and no Cu deficiency symptoms.

TABLE 57

Influence of Fertilizer P and Cu on K Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	1.87	1.77	1.82 a
1	1.97	1.67	1.82 a
2	2.00	1.97	1.98 a
4	1.83	1.73	1.78 a
8	1.63	1.97	1.80 a
16	1.47	1.93	1.70 a
P Main Effect	1.79 A	1.84 A	

TABLE 58

Influence of Fertilizer P and Cu on K Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	0.42	0.83	0.62 a
1	0.52	0.83	0.68 a
2	0.47	0.79	0.63 a
4	0.63	0.63	0.63 a
8	0.30	0.68	0.49 a
16	0.50	0.54	0.52 a
P Main Effect	0.47 B	0.71 A	

TABLE 59

Influence of Fertilizer P and Cu on K Uptake into Corn Shoots (mg/pot)

Cu Rate ppm	P Rate ppm		Cu Main Effect
	50	200	
0	257	461	359 ab
1	272	399	335 ab
2	276	517	397 a
4	273	308	290 b
8	181	466	324 ab
16	206	373	289 b
P Main Effect	244 B	421 A	

TABLE 60

Influence of Fertilizer P and Cu on N Concentration in Corn Leaves (%)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	2.32	1.97	2.15
1	2.63	2.30	2.47
2	2.24	2.35	2.29
4	2.48	2.35	2.42
8	2.45	1.93	2.19
16	2.74	2.23	2.48
P Main Effect	2.47	2.19	

TABLE 61

Influence of Fertilizer P and Cu on N Concentration in Corn Shoots (%)

Cu Rate ppm	P Rate ppm 50	P Rate ppm 200	Cu Main Effect
0	2.20	1.87	2.04
1	2.40	2.22	2.31
2	2.24	2.09	2.17
4	2.44	2.26	2.36
8	2.37	1.94	2.16
16	2.73	2.09	2.41
P Main Effect	2.39	2.08	

III. FIELD EXPERIMENTS

Results of the zinc experiment indicated that Zn fertilization was effective in increasing corn dry matter yield as well as Zn concentrations and uptake into the shoots in the greenhouse. On the basis of these results a field experiment was conducted on a similar soil to determine if corn would respond to Zn application under field conditions. The experiment was also designed to obtain information about the critical plant Zn concentration under field conditions in Manitoba.

There was also evidence in the growth bench zinc experiment that high P accentuated Zn deficiency and also influenced plant Zn critical levels. Consequently, the influence of P fertilization upon plant Zn critical levels and upon severity of Zn deficiency in corn was also investigated in the field experiment.

Two smaller experiments were carried out to monitor the Zn as well as other nutrient concentrations in corn grown on different soils, one of which was also low in available Zn for corn.

Soil Characteristics

Soil pH ranged from slightly alkaline for the Reinland fine sandy loam to moderately alkaline for the other two sites (Table 62). The carbonate, soluble salt and organic matter contents were low at all three sites.

Plant available NO_3-N, P and K were adequate for the Reinland fine sandy loam but S content was low at this site. Plant available NO_3-N was also adequate for the Almasippi loamy fine sand but P and K were both low. The Neuenburg very fine sandy loam was very high in NO_3-N but both P and K were medium. The high level of NO_3-N obtained

TABLE 62

Soil Characteristics for Field Experiments

Soil Name	Almasippi	Reinland	Neuenburg
Texture	L F S	F S L	V F S L
pH (0-15 cm)	7.9	7.5	8.0
Conductivity (mmhos/cm) (0-15 cm)	0.35	0.20	0.24
$CaCO_3$ (%) (0-15 cm)	2.85	1.31	2.84
O.M. (%) (0-15 cm)	2.25	2.58	2.15
NO_3-N kg/ha (0-60 cm)	64.6	48.0	74.2
PO_4-P kg/ha (0-15 cm)	16.6	41.1	22.2
Exch. K kg/ha (0-15 cm)	153	308	207
SO_4-S kg/ha (0-60 cm)	72.3	22.8	80.1
DTPA Cu ppm (0-15 cm)	1.10	1.24	0.46
DTPA Zn ppm (0-15 cm)	0.52	1.25	0.76
DTPA Fe ppm (0.15 cm)	18.54	9.66	10.98
DTPA Mn ppm (0-15 cm)	4.76	10.47	20.36

for the Almasippi loamy fine sand was partially due to fall applied N.

On the basis of soil critical levels suggested by Lindsay and Norvell (1978) levels of DTPA extractable Cu, Fe and Mn were adequate for all three sites. However, the Almasippi loamy fine sand and Neuenburg very fine sandy loam were both low in plant available Zn.

Growing Conditions and General Crop Appearance

Generally the crop at all three sites experienced dry conditions earlier in the growing season. As a result, germination was affected resulting in uneven growth. However, later in the season there was a considerable amount of moisture and this somewhat improved the general stand. Both P and Zn deficiency symptoms were evident at the main site near Macgregor, Manitoba, particularly earlier in the season. It should also be noted that temperatures were sometimes fairly low earlier in the season. It is possible that these conditions together with the dry weather might have accentuated Zn and P deficiencies and made it difficult to correct the deficiencies.

YIELDS

(1) Macgregor Site

The average dry matter yield of corn shoots at the initiation of the tasseling stage was 1238 kg/ha and the average grain yield was 3984 kg/ha. In a normal year grain yields would be higher than those obtained in this experiment.

Phosphorus fertilization was not effective in increasing either dry matter yield or grain yield (Tables 63 and 64). This was not expected since levels of plant available P in the soil were low. The P concentration in the earleaves at all fertilizer P levels were low according to the critical level of 0.25% suggested by Melsted, et al. (1969) (Table 80). Phosphorus deficiency symptoms were also observed in the field on all plots, particularly earlier in the season. It is possible as mentioned before that the cool weather experienced earlier in the season and the drought that followed not only may have accentuated the P deficiency but also made it difficult to correct the deficiency. The fertilizer did not dissolve until three to four weeks after seeding.

Zinc application was also not effective in increasing dry matter yields at the initiation of tasseling or grain yield. A response to Zn was expected since the level of DTPA available Zn in the soil was low according to the critical level of 0.8 ppm suggested by Lindsay and Norvell (1978). Added Zn only resulted in small statistically non-significant increases in both dry matter yield and grain yield, generally reaching a maximum at 8 kg Zn/ha. Such slight increases were reported earlier by Racz (1967). The lack of response to applied Zn might also have been caused by dry weather. There was no significant P-Zn interaction in either yields.

Copper fertilization had no influence upon dry matter or grain yield. Although lack of response may have been caused partially by moisture stress, a large response was not expected since the level of DTPA available Cu in the soil was adequate.

Previous work with other crops in Manitoba indicated that responses to micronutrients were far more prevalent in the growth chamber or greenhouse than in the field (Loewen-Rudgers, 1978). Although the influence of drought can not be fully evaluated in this work, this field experiment certainly did not refute the general rule that responses to micronutrient fertilization are more likely to occur

TABLE 63

Influence of Fertilizer P, Zn and Cu on Corn Shoot Dry Matter Yield at Tasseling (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	1074	1285	1018	1125 a
2	1152	1378	1198	1243 a
4	1129	1102	1264	1165 a
8	1328	1364	1472	1388 a
16	933	1195	1450	1193 a
32	1009	1662	1314	1328 a
0 Cu 16 Zn	914	1404	1365	1228 a
P Main Effect	1077 A	1342 A	1297 A	

TABLE 64

Influence of Fertilizer P, Zn and Cu on Corn Grain Yield (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	3819	3850	3392	3687 a
2	3906	4600	3658	4055 a
4	4040	3787	4271	4032 a
8	4341	4499	4453	4431 a
16	3149	3831	4303	3761 a
32	3656	4498	4003	4052 a
0 Cu 16 Zn	3570	3950	4117	3879 a
P Main Effect	3779 A	4145 A	4028 A	

in the greenhouse than in the field.

(2) Enns and Nikkels Sites

Due to frost damage grain yields were not obtained at these sites. As at Macgregor, Zn fertilization was not effective in increasing silage yield at either site (Table 65). A response to applied Zn was expected at Nikkels site on the basis of plant soil critical level suggested by Lindsay and Norvell (1978).

TABLE 65

Influence of Fertilizer Zn upon
Corn Silage Yields (m.t./ha)

Zn Rate Kg/ha	Enns Site	Nikkels Site
0	7.92	8.64
16	7.60	8.33
t (0.05)	NS	NS

NUTRIENT CONCENTRATION AND UPTAKE

(1) Macgregor Site:

Plant Zn Concentration and Uptake

Application of 100 kg P/ha decreased Zn concentration in the plant shoots (Table 66). However, since the uptake was not affected the decrease might have been due to dilution. In other words there was no strong evidence that P induced or accentuated Zn deficiency. Like the growth bench Zn experiment P fertilization did not influence earleaf Zn concentration (Table 67).

Application of 8 or more kg Zn/ha increased Zn concentrations in the shoots and earleaves as well as Zn uptake. However, 32 kg Zn/ha

TABLE 66

Zn Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	18.9	14.2	11.6	14.9 d
2	19.2	15.1	12.7	15.6 d
4	19.8	15.0	13.5	16.1 cd
8	20.6	17.9	18.1	18.8 bc
16	25.4	18.9	15.6	20.0 ab
32	27.2	22.6	16.6	22.1 a
0 Cu 16 Zn	24.3	20.4	19.2	21.3 ab
P Main Effect	22.2 A	17.7 AB	15.3 B	

TABLE 67

Earleaf Zn Concentration at Silking as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	10.2	10.9	7.8	9.6 b
2	10.9	12.5	8.7	10.7 b
4	11.2	11.1	8.7	10.3 b
8	11.6	12.1	12.1	11.9 ab
16	12.5	13.9	13.8	13.4 a
32	16.4	14.3	15.3	15.3 a
0 Cu 16 Zn	16.2	13.8	13.2	14.4 a
P Main Effect	12.7 A	12.7 A	14.4 A	

TABLE 68

Zinc Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (g/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	19.8	19.2	12.1	17.0 e
2	23.6	22.4	14.9	20.3 ce
4	22.3	17.1	17.3	18.9 de
8	26.8	26.8	27.5	27.0 b
16	23.0	23.8	21.9	22.9 bcd
32	28.2	38.4	20.9	29.2 a
0 Cu 16 Zn	23.2	29.3	26.2	26.2 ab
P Main Effect	23.8 A	25.3 A	20.1 A	

were required to increase earleaf Zn concentration above the critical level of 15 ppm suggested by Melsted, et al. (1969). Perhaps this was partially responsible for the lack of response to Zn fertilization. It is perhaps more likely that the dry conditions were more important in limiting response to Zn. It is also possible that the plant critical level under Manitoba conditions is lower than 15 ppm as all corn regardless of treatment exhibited Zn deficiency symptoms early in the growing season due to the cool, dry growing conditions which likely limited uptake of both fertilizer and soil Zn. But, these symptoms disappeared totally even in corn receiving no Zn. This is further evidence that critical level of Zn may be lower than 15 ppm in Manitoba.

TABLE 69

Cu Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	3.73	3.19	3.44	3.45 a
2	3.74	3.60	3.03	3.45 a
4	3.78	3.78	3.16	3.57 a
8	3.44	3.70	3.20	3.55 a
16	3.62	3.88	3.02	3.45 a
32	3.51	4.19	3.39	3.37 a
0 Cu 16 Zn	2.62	3.35	2.30	2.76 b
P Main Effect	3.51 A	3.67 A	3.08 A	

TABLE 70

Earleaf Cu Concentration at Silking as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	4.18	4.46	3.55	4.06 a
2	4.50	5.44	3.36	4.43 a
4	4.14	4.52	3.35	4.00 a
8	4.28	4.86	4.14	4.42 a
16	3.99	4.63	3.36	4.00 a
32	4.52	3.94	3.63	4.03 a
0 Cu 16 Zn	3.22	3.10	3.24	3.18 b
P Main Effect	4.12 A	4.42 A	3.52 A	

TABLE 71

Cu Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (g/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	4.0	4.4	3.4	3.9 a
2	4.5	5.3	3.6	4.5 a
4	4.5	4.3	4.0	4.3 a
8	4.9	5.5	4.7	5.0 a
16	3.3	4.7	4.2	4.0 a
32	3.5	7.1	4.5	5.0 a
0 Cu 16 Zn	2.4	4.8	3.0	3.4 a
P Main Effect	3.8 A	5.1 A	3.9 A	

Plant Cu Concentration and Uptake

Levels of Cu in the earleaves were nearly all slightly below the critical level of 5 ppm suggested by Melsted, et al. (1969). But, the critical level may also be lower here in Manitoba. It seems unlikely that all corn plants were Cu deficient particularly when it is considered that 10 kg Cu/ha were added to all treatments except the Cu check plot and that no Cu deficiency symptoms were exhibited.

Copper application increased Cu concentration in the shoots and earleaves, but, Cu uptake into shoots was not affected (Tables 69, 70 and 71). Phosphorus or Zn fertilization had no effect on Cu concentration or uptake.

TABLE 72

Fe Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	89.5	70.2	97.2	85.7 a
2	91.4	67.4	91.9	83.6 a
4	112.2	74.8	87.2	91.4 a
8	76.2	68.1	64.9	69.7 a
16	94.8	66.4	83.4	81.5 a
32	79.2	69.5	77.4	75.4 a
0 Cu 16 Zn	84.4	88.1	74.3	82.3 a
P Main Effect	89.7 A	72.1 A	82.3 A	

TABLE 73

Earleaf Fe Concentration at Silking as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	41.9	51.9	47.2	47.0 a
2	43.6	51.6	43.8	46.3 a
4	40.1	44.5	39.3	41.3 a
8	47.3	48.0	43.0	46.1 a
16	39.3	47.3	42.1	42.9 a
32	44.9	40.0	48.1	44.3 a
0 Cu 16 Zn	40.1	46.3	43.5	43.3 a
P Main Effect	42.5 A	47.1 A	43.8 A	

TABLE 74

Fe Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (g/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	94.0	85.4	104.3	94.6 a
2	100.5	91.4	105.9	99.3 a
4	120.6	76.9	110.7	102.7 a
8	97.0	84.1	98.9	93.3 a
16	85.0	79.5	120.8	95.1 a
32	77.8	114.0	99.6	97.1 a
0 Cu 16 Zn	72.7	108.9	100.8	94.1 a
P Main Effect	92.5 A	91.4 A	105.9 A	

Plant Fe and Mn Concentration and Uptake

Both Fe and Mn concentration in the corn earleaves suggest that these nutrients were adequate. Melsted, et al. (1969) suggested a critical level of 15 ppm for both nutrients. Phosphorus, Zn or Cu fertilization did not affect the concentration or uptake of either Fe or Mn (Tables 72, 73, 74, 75, 76 and 77).

TABLE 75

Mn Concentration in Corn Shoots at Tasseling
as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	37.1	27.9	44.8	36.6 a
2	33.0	31.0	42.5	35.5 a
4	37.5	32.8	40.5	36.9 a
8	33.8	27.9	36.9	32.9 a
16	39.3	31.1	37.7	36.0 a
32	33.2	32.5	35.4	33.7 a
0 Cu 16 Zn	38.1	36.4	34.5	36.3 a
P Main Effect	36.0 A	31.4 A	38.9 A	

TABLE 76

Earleaf Mn Concentration at Silking
as affected by P, Zn and Cu Fertilization (ppm)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	45.6	42.5	58.1	48.7 a
2	45.0	46.8	53.6	48.5 a
4	43.8	47.9	48.4	46.7 a
8	43.0	38.5	54.9	45.5 a
16	42.6	45.0	53.4	47.0 a
32	42.4	40.5	49.8	44.2 a
0 Cu 16 Zn	46.3	45.0	50.3	47.2 a
P Main Effect	44.1 A	43.7 A	52.6 A	

TABLE 77

Mn Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (g/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	39.8	33.9	47.6	40.4 a
2	36.5	44.1	49.9	43.5 a
4	42.7	35.7	50.6	43.0 a
8	44.4	36.1	55.7	45.4 a
16	36.7	35.7	55.0	42.5 a
32	32.5	51.9	44.3	42.9 a
0 Cu 16 Zn	34.7	49.6	48.7	44.3 a
P Main Effect	38.2 A	41.0 A	50.3 A	

TABLE 78

Earleaf N Concentration at Silking
as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	2.79	2.78	2.74	2.77 a
2	2.84	2.86	2.64	2.78 a
4	2.75	2.79	2.83	2.79 a
8	2.81	2.79	2.75	2.78 a
16	2.79	2.80	2.71	2.76 a
32	2.88	2.88	2.83	2.86 a
0 Cu 16 Zn	2.85	2.88	2.87	2.86 a
P Main Effect	2.81 A	2.83 A	2.77 A	

Concentration and Uptake of N, P, K, S, Ca, and Mg

The application of P, Zn or Cu did not affect the concentration of any of the macronutrients above in the total plant or earleaves (Tables 78, 79, 80, 82, 83, 85, 86, 88 and 89). Similarly, with the exception of S, the uptakes of these nutrients were not influenced by any of the treatments (Tables 81, 84, 87 and 90). The higher S uptake in the treatment receiving 100 kg P/ha was likely due to S present in the superphosphate.

Levels of P in the earleaves were all below the critical level of 0.25% suggested by Melsted, et al. (1969). The low temperature and

TABLE 79

P Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.24	0.23	0.28	0.25 a
2	0.21	0.25	0.26	0.24 a
4	0.23	0.22	0.27	0.24 a
8	0.23	0.21	0.22	0.22 a
16	0.24	0.23	0.25	0.24 a
32	0.22	0.23	0.25	0.23 a
0 Cu 16 Zn	0.23	0.23	0.24	0.23 a
P Main Effect	0.23 A	0.23 A	0.25 A	

TABLE 80

Earleaf P Concentration at Silking as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.16	0.19	0.17	0.17 a
2	0.16	0.18	0.18	0.17 a
4	0.15	0.17	0.17	0.16 a
8	0.16	0.17	0.17	0.17 a
16	0.15	0.18	0.17	0.17 a
32	0.14	0.15	0.17	0.16 a
0 Cu 16 Zn	0.17	0.17	0.16	0.16 a
P Main Effect	0.15 A	0.17 A	0.17 A	

TABLE 81

P Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	2.56	2.85	2.94	2.78 a
2	2.35	3.33	2.91	2.86 a
4	2.60	2.33	2.53	2.83 a
8	3.03	2.80	3.25	3.03 a
16	2.20	2.70	3.58	2.83 a
32	2.15	3.80	3.33	3.09 a
0 Cu 16 Zn	2.07	3.20	3.15	2.81 a
P Main Effect	2.42 A	3.00 A	3.24 A	

drought earlier in the season may have decreased availability of both soil and fertilizer P. In addition, P deficiency symptoms were evident at the early stages of growth.

Levels of S and K in earleaves of all corn were usually below the respective critical levels of 0.1% and 1.9% reported in the literature (Melsted, et al. 1969 and Barber and Olson, 1968). However, adequate amounts were added as basal treatments. The levels of N, Ca and Mg in the earleaves were adequate. The deficient levels of P, K, and S make it difficult to draw any meaningful conclusions concerning Zn nutrition.

TABLE 82

K Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	1.09	1.01	1.11	1.07 a
2	0.93	0.96	0.99	0.96 a
4	1.09	0.87	1.05	1.00 a
8	1.01	0.94	0.99	0.98 a
16	1.04	0.84	0.97	0.93 a
32	0.97	0.93	1.06	0.99 a
0 Cu 16 Zn	1.01	0.91	1.01	0.98 a
P Main Effect	1.02 A	0.92 A	1.02 A	

TABLE 83

Earleaf K Concentration at Silking as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.92	0.77	1.11	0.93
2	0.86	1.09	0.97	0.97 a
4	0.95	0.76	0.94	0.88 a
8	0.79	0.89	0.82	0.83 a
16	0.73	0.92	0.80	0.82 a
32	0.91	1.05	0.95	0.97 a
0 Cu 16 Zn	0.85	1.04	0.98	0.95 a
P Main Effect	0.86 A	0.93 A	0.94 A	

TABLE 84

K Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	11.4	12.6	11.4	11.8 a
2	11.0	12.7	12.0	11.9 a
4	12.1	9.0	13.0	11.3 a
8	13.2	12.1	14.1	13.1 a
16	9.5	10.5	13.8	11.3 a
32	10.0	15.5	13.9	13.1 a
0 Cu 16 Zn	9.1	11.9	14.0	11.7 a
P Main Effect	10.9 A	12.0 A	13.1 A	

TABLE 85

S Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.11	0.12	0.14	0.12
2	0.13	0.09	0.12	0.11 a
4	0.11	0.12	0.16	0.13 a
8	0.12	0.11	0.13	0.12 a
16	0.12	0.10	0.13	0.12 a
32	0.10	0.13	0.14	0.12 a
0 Cu 16 Zn	0.13	0.13	0.14	0.13 a
P Main Effect	0.12 A	0.11 A	0.14 A	

TABLE 86

Earleaf S Concentration at Silking as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.09	0.10	0.09	0.09 a
2	0.09	0.10	0.09	0.09 a
4	0.07	0.11	0.08	0.08 a
8	0.06	0.10	0.09	0.08 a
16	0.07	0.11	0.08	0.08 a
32	0.09	0.11	0.08	0.10 a
0 Cu 16 Zn	0.07	0.10	0.08	0.08 a
P Main Effect	0.08 A	0.10 A	0.08 A	

TABLE 87

S Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	1.12	1.39	1.47	1.33 a
2	1.23	1.26	1.34	1.28 a
4	1.11	1.25	1.90	1.42 a
8	1.45	1.45	1.65	1.51 a
16	1.02	1.14	1.63	1.26 a
32	1.00	2.05	1.81	1.62 a
0 Cu 16 Zn	1.11	1.63	2.01	1.58 a
P Main Effect	1.15 B	1.45 a b	1.69 A	

TABLE 88

Ca Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.43	0.36	0.38	0.39 a
2	0.38	0.33	0.41	0.37 a
4	0.42	0.36	0.41	0.40 a
8	0.40	0.35	0.35	0.36 a
16	0.38	0.35	0.44	0.39 a
32	0.37	0.36	0.44	0.39 a
0 Cu 16 Zn	0.37	0.40	0.35	0.37 a
P Main Effect	0.39 A	0.36 A	0.40 A	

TABLE 89

Earleaf Ca Concentration at Silking as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.54	0.54	0.61	0.56 a
2	0.49	0.57	0.62	0.56 a
4	0.68	0.49	0.52	0.56 a
8	0.52	0.60	0.58	0.56 a
16	0.44	0.53	0.72	0.56 a
32	0.49	0.50	0.63	0.54 a
0 Cu 16 Zn	0.51	0.47	0.54	0.51 a
P Main Effect	0.52 A	0.53 A	0.60 A	

TABLE 90

Ca Uptake into Corn Shoots as affected
by P, Zn and Cu Fertilization (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	4.57	4.56	4.01	4.38 a
2	4.19	4.58	4.87	4.55 a
4	4.82	3.69	5.41	4.64 a
8	5.28	4.74	5.07	5.03 a
16	3.56	4.11	6.34	4.67 a
32	3.64	5.92	5.85	5.14 a
0 Cu 16 Zn	3.39	5.52	4.74	4.55 a
P Main Effect	4.21 A	4.73 A	5.18 A	

TABLE 91

Mg Concentration in Corn Shoots at Tasseling as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.50	0.49	0.47	0.50 a
2	0.46	0.48	0.50	0.50 a
4	0.49	0.41	0.52	0.47 a
8	0.55	0.45	0.48	0.49 a
16	0.45	0.45	0.48	0.46 a
32	0.48	0.50	0.51	0.49 a
0 Cu 16 Zn	0.43	0.46	0.53	0.48 a
P Main Effect	0.48 A	0.46 A	0.50 A	

TABLE 92

Earleaf Mg Concentration at Silking as affected by P, Zn and Cu Fertilization (%)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	0.34	0.46	0.51	0.44 a
2	0.34	0.40	0.52	0.42 a
4	0.50	0.44	0.46	0.46 a
8	0.38	0.46	0.50	0.45 a
16	0.32	0.37	0.49	0.39 a
32	0.39	0.42	0.45	0.42 a
0 Cu 16 Zn	0.34	0.36	0.58	0.43 a
P Main Effect	0.37 A	0.41 A	0.50 A	

TABLE 93

Mg Uptake into Corn Shoots as affected by P, Zn and Cu Fertilization (kg/ha)

Zn/Cu Rate kg/ha	P Rate kg/ha			Zn/Cu Main Effect
	0	25	100	
0	5.36	6.60	4.88	5.61 a
2	5.75	6.94	5.88	6.19 a
4	5.44	4.77	6.75	5.65 a
8	7.27	6.63	7.14	7.01 a
16	4.20	5.51	6.77	5.49 a
32	5.03	8.56	6.73	6.77 a
0 Cu 16 Zn	4.15	6.71	7.19	6.02 a
P Main Effect	5.31 A	6.53 A	6.48 A	

(2) Enns and Nikkels Sites

Micronutrient Concentrations

The levels of Zn in both earleaves and total plant shoots harvested at the initiation of tasseling were increased by Zn fertilization (Tables 94, 95, 96 and 97). However, the increase in the earleaf Zn concentration at Nikkels site was not significant. The levels of Zn in the earleaves at both sites were low when compared to the critical level of 15 ppm suggested by Melsted, et al. (1969). This includes even the treatments that received 16 kg Zn/ha.

Responses to added Zn were expected, particularly at Nikkels where the DTPA plant available Zn was also low. Despite the increase in Zn concentration in the plant, Zn fertilization was not effective in increasing dry matter yields. These results are similar to those obtained at the Macgregor site.

Earleaf Cu concentrations at the Enns site were low according to the critical level of 5 ppm reported by Melsted, et al. (1969). At Nikkels the corn was likely not Cu deficient according to this critical level. The higher Cu content in the earleaves from Nikkel's site as compared to Enn's site is not consistent with the soil available Cu extracted by DTPA which showed that the level at Enns was almost three times higher.

Tissue Fe was not influenced by Zn fertilization at either site. However, the Fe levels were far higher at the Nikkels site compared to Enns although the levels of DTPA Fe at both sites were almost the same. It is evident that considerably more research is needed to determine if the DTPA test is a reliable indicator of plant available soil micronutrient levels.

In contrast to Fe, shoot Mn concentration at the Enns Site was decreased by added Zn. However, earleaf Mn content was not affected while at Nikkels neither total plant nor earleaf Mn was affected by Zn fertilization. As with Fe the level of Mn in the earleaves were higher at the Nikkels than at Enns or Macgregor sites. But, the level of DTPA extractable Mn was also highest at Nikkels.

The concentrations of both Fe and Mn were higher than the critical level of 15 ppm suggested by Melsted, et al. (1969).

Macronutrient Concentrations

The concentrations of N, P, K, S, Ca and Mg were not influenced by added Zn at either site. Similar results were obtained at the Macgregor site. Phosphorus concentrations in the earleaves were higher at the Enns site than at the other two sites, suggesting that P fertilization was likely more effective at this site. According to Melsted, et al. (1969) the levels of P in the earleaves at Nikkels were low but at Enns the levels were close to the critical level of 0.25% suggested. Both K and S were marginal to low at both sites while N was deficient at Enns but not at Nikkels. Both sites received similar amounts of fertilizer to supply the essential nutrients.

TABLE 94

Influence of Fertilizer Zn upon Nutrient Concentrations in Corn Shoots at Tasseling

Enns

kg/ha Zn	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	% P	% S	% Ca	% Mg	% K
0	7.3	2.7	38.2	30.4	0.16	0.08	0.22	0.55	0.89
16	10.7	2.7	27.9	25.2	0.17	0.08	0.22	0.57	0.84
t(0.05)	*	NS	NS	*	NS	NS	NS	NS	NS

TABLE 95

Influence of Fertilizer Zn upon Earleaf Nutrient Concentrations

kg/ha Zn	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	% P	% S	% Ca	% Mg	% K	% N
0	7.7	4.1	32.0	35.6	0.21	0.10	0.32	0.76	0.75	2.5
16	9.5	4.3	25.4	34.2	0.22	0.11	0.31	0.73	0.82	2.6
t(0.05)	*	NS	NS	NS	NS	NS	NS	NS	NS	NS

TABLE 96

Influence of Fertilizer Zn upon Nutrient Concentrations in Corn Shoots at Tasseling

Nikkels

kg/ha Zn	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	% P	% S	% Ca	% Mg	% K
0	10.2	3.7	96.4	27.1	0.24	0.07	0.38	0.43	0.93
16	12.2	3.6	78.0	24.6	0.23	0.08	0.39	0.43	0.96
t(0.05)	*	NS	NS	NS	NS	NS	NS	NS	NS

TABLE 97

Influence of Fertilizer Zn upon Earleaf Nutrient Concentrations

kg/ha Zn	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	% P	% S	% Ca	% Mg	% K	% N
0	10.5	5.7	71.9	58.6	0.17	0.09	0.37	0.48	0.89	2.7
16	12.0	5.0	90.7	57.1	0.19	0.10	0.37	0.42	0.89	2.6
t(0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

IV. SOIL VOLUME EXPERIMENT

Results from previous experiments showed that responses to micronutrient fertilization were far more prevalent in the growth chamber than in the field. Some workers suspected that the smaller soil volume used in pot experiments was likely the main cause of the more frequent responses obtained in the growth chamber or greenhouse (McKenzie, 1980 and Stevenson, 1967).

Corn dry matter yield in the Zn growth bench experiment was significantly increased by Zn fertilization (Table 2). But no yield responses were obtained when Zn was applied to corn in the field although the experiment was located in the same general area on the same soil association (Almasippi), and contained similarly low DTPA extractable Zn (0.52 ppm Zn as opposed to 0.51 ppm in the growth bench zinc experiment.

The soil volume experiment was conducted to determine the effect of soil volume upon dry matter yield, nutrient concentration and uptake by corn and upon response in dry matter yield, nutrient concentration and uptake to Zn fertilization.

Soil Characteristics

Soil was collected from the field site near Macgregor (SE 19-11-9 W) where no response to Zn fertilization in either dry matter yield taken at the initiation of tasseling or final grain yields was obtained. The physical and chemical characteristics of the soil are presented in Table 98. The soil was low in DTPA available Zn according to the critical level of 0.8 ppm suggested by Lindsay and Norvell (1978) for corn. Unfortunately, the DTPA extractable Zn level was not

TABLE 98

Soil Characteristics for the Soil Volume Experiment

Soil Name	Almasippi
Textural Class	Loamy fine sand
pH	7.7
Conductivity (mmhos/cm)	0.2
$CaCO_3$ (%)	2.7
Organic Matter (%)	2.07
NO_3-N (ppm)	3.2
PO_4-P (ppm)	8.4
Exch. K (ppm)	115
SO_4-S (ppm)	5.2
DTPA Cu (ppm)	0.20
DTPA Zn (ppm)	0.77
DTPA Fe (ppm)	7.45
DTPA Mn (ppm)	10.55
F.C. Moisture content (%)	28.6

as low as those in the zinc and copper experiments or in the field experiment.

General Crop Appearance

The corn plants were generally healthy in all the treatments although Zn deficiency symptoms were exhibited. The symptoms were not as severe as those observed in the zinc experiment particularly where P accentuated Zn deficiency. Symptoms similar to Fe deficiency were also observed. These involved alternating green veins with yellow stripes between the veins, particularly in the younger leaves.

The time to silking varied slightly among treatments. When Zn was not added there was generally no marked difference in days to silking among the soil volumes. But, when Zn was added, silking took place about ten days earlier in the largest pots compared to the smallest ones. When similar soil volumes are considered silking was about five days earlier in the treatments that received Zn, except the smallest pots where silking was delayed by five days when Zn was added.

Dry Matter Yield

Dry matter yield of corn shoots was significantly increased by Zn fertilization. These results were consistent with those in the growth bench zinc experiment. However, corn grown on the same soil in the field did not respond to Zn fertilization.

Dry matter yield was also increased as soil weight was increased from 5 kg to 20 kg (Table 99). The lowest yield was obtained in the smallest soil volume. The shape of the pots also affected dry matter yield. Lateral expansion of soil volume (10H) resulted in higher dry matter yield than the depth expansion (10V). It is likely that the differences were caused by differential availability of nutrients.

There was no significant soil volume x Zn interaction in dry matter yield. Dry matter yield increased with increasing soil volume in the same way with no Zn as when Zn was added.

As in the zinc experiment, the response to Zn was expected since the level of DTPA extractable Zn in the soil was low. Nevertheless, deficiency symptoms similar to the mild Zn deficiency symptoms reported by Bates and Johnstone (1975) were observed even in the treatments that received Zn. The symptoms were different from those obtained in the zinc experiment. Instead of broad chlorotic bands on both sides of the midrib, these were narrow interveinal chlorotic stripes and the plants were not stunted. The lack of severity might have been caused by change in variety, slightly warmer temperature or the slightly higher level of soil available Zn. However, since Zn levels in the plant were quite high, particularly where Zn was applied, it is possible that the symptoms were not those of Zn deficiency. Since the symptoms were also quite similar to Fe deficiency it is possible that the corn was Fe deficient and/or that the striping was simply a varietal characteristic.

Plant Zn Concentration and Uptake

Zinc concentration in earleaves of corn receiving no Zn were usually above the critical level of 15 ppm suggested by Melsted, et al. (1969). It is not surprising that the increases in dry matter yield as a result of Zn fertilization were relatively small. Earleaf Zn concentrations of corn receiving Zn were always higher than the critical level. This suggests that the apparent Zn deficiency symptoms may have been caused by some other factor(s).

TABLE 99

Influence of Fertilizer Zn and Soil Volume upon Dry Matter Yield of Corn Shoots at Silking (g/pot)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	98	110	104 c
10 V	123	129	126 b
10 H	140	150	145 a
20	143	154	149 a
Zn Main Effect	126 B	135 A	

TABLE 100

Influence of Fertilizer Zn and Soil Volume upon Zn Concentration in Corn Shoots (ppm)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	7.7 d	43.0 a	25.4 a
10 V	6.6 d	19.4 b	13.0 b
10 H	5.0 d	22.4 b	13.7 b
20	6.0 d	13.4 c	9.7 c
Zn Main Effect	6.3 B	24.0 A	

TABLE 101

Influence of Fertilizer Zn and Soil Volume upon Zn Concentration in Corn Earleaves (ppm)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	29.6	35.7	32.7 a
10 V	17.7	22.3	20.0 b
10 H	13.2	25.1	19.1 b
20	21.9	18.2	20.0 b
Zn Main Effect	20.6 A	25.3 A	

TABLE 102

Influence of Fertilizer Zn and Soil Volume upon Zn Uptake into Corn Shoots (μg/pot)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	819 e	4676 a	2747 a
10 V	853 e	2503 c	1678 c
10 H	741 e	3358 b	2049 b
20	918 e	2053 d	1486 c
Zn Main Effect	833 B	3148 A	

Plant Zn concentration and Zn uptake were higher in plants grown in 5 kg of soil than in plants grown in 10 or 20 kg of soil. However, this effect occurred only in those plants which had been fertilized with Zn. Soil volume had little or no influence upon Zn concentration and uptake in corn receiving no Zn which led to significant soil volume x Zn interaction in total plant Zn concentration and in Zn uptake (Tables 100 and 102). The decrease in Zn concentration and uptake with increasing soil volume when Zn was applied may have resulted at least partially from decreasing contact between fertilizer Zn and roots active in Zn uptake. It is perhaps reasonable to assume that roots active in Zn uptake grew through the Zn fertilizer reaction zone in the larger pots so that a smaller portion of the total roots were exposed to fertilizer Zn than in the 5 kg soil pots. However, the fact that Na_2ZnEDTA is quite mobile in the soil weakens this hypothesis somewhat. Later it will be noticed that P uptake increased with increasing soil volume. The increasing P uptake may have decreased Zn uptake and/or translocation into shoots.

The failure of soil volume to influence Zn concentration or uptake when Zn was not applied suggests that the smaller soil volumes in pot experiments may not be responsible for the greater frequency of response to Zn fertilization in the greenhouse.

Hedayat (1978) suggested that Zn uptake by blackbeans and barley was proportional to root available soil Zn contact times the concentration of Zn in the soil solution. Using that approach in the present experiment and assuming that Zn concentration in the soil solution was not influenced by soil volume it could be suggested that total root mass did not increase with increasing soil volume when no Zn was applied but remained relatively constant.

It is also reasonable to assume that the increase in dry matter yield with increase in soil volume was likely due to some factors other than Zn supply.

Plant Cu Concentration and Uptake

Copper concentrations in the earleaves were above the critical level of 5.0 ppm suggested by Melsted, et al. (1969). It is unlikely, therefore, that the plants were Cu deficient. The decrease in Cu concentration with increasing soil volume (Tables 103 and 104) was likely due to dilution caused by increasing dry matter yield since Cu uptake

TABLE 103

Influence of Fertilizer Zn and Soil Volume upon Cu Concentration in Corn Shoots (ppm)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	3.4	3.2	3.3 a
10 V	2.4	2.3	2.4 b
10 H	1.9	2.3	2.1 b
20	2.0	2.4	2.2 b
Zn Main Effect	2.4 A	2.5 A	

TABLE 104

Influence of Fertilizer Zn and Soil Volume upon Cu Concentration in Corn Earleaves (ppm)

Soil Weight Kg	Zn Rate ppm		Soil Weight Main Effect
	0	8	
5	16.5	7.8	12.1 a
10 V	12.9	5.9	9.4 a
10 H	6.1	10.6	8.3 a
20	7.3	6.5	6.9 a
Zn Main Effect	10.7 A	7.7 A	