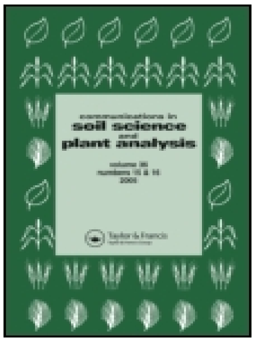

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Maize Yield Response to Zinc Sources and Effectiveness of Diagnostic Indicators

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ABSTRACT

Maize yield is often limited by zinc (Zn) deficiency. The objectives of this study were to (i) evaluate maize yield response to Zn applied at four different rates, (ii) evaluate the yield response and agronomic efficiency of maize to the application of a complex fertilizer, MicroEssentials SZ (12N–40P–0K–10S–1Zn), compared to different rates of monoammonium phosphate (MAP) + ammonium sulfate (AS) + zinc sulfate (ZnSO4), and (iii) evaluate the association between tissue Zn concentration and soil-test Zn with the maize response to Zn fertilizer. Eleven experiments were carried out during the 2010, 2011, and 2012 growing seasons throughout eight states in the USA. Treatments consisted of four Zn rates of a physical blend of MAP + AS + $ZnSO_4$ (0, 2.24, 4.48, 6.72, and 11.2 kg/ha Zn) and MicroEssentials SZ at a Zn rate of 2.24 kg/ha Zn. Nitrogen, phosphorus (P), and sulfur (S) rates were balanced across treatments (40 kg/ha P, 22 kg/ha S) and fertilizers were broadcast and incorporated immediately prior to planting. Treatment and location main effects were significant ($P < 0.001$) on corn yields, whereas the interaction treatment × location was not ($P = 0.33$). Maize responded positively to Zn fertilization; average yields across locations increased from 10,540 kg ha^{-1} without Zn to 11,530 kg ha^{-1} with 11.21 kg Zn ha^{-1} applied as a physical blend. The yield response and Zn agronomic efficiency of maize with the application of the complex fertilizer at a rate of 2.24 kg Zn ha^{-1} averaged 1004 kg ha^{-1} and 448 kg maize kg Zn^{-1}, respectively, significantly higher ($P < 0.1$) than the yield response and Zn agronomic efficiency with the application of a physical blend with the same Zn rate, which averaged 293 kg ha^{-1} and 131 kg maize kg Zn^{-1}, respectively. The Zn concentration in plant tissue of unfertilized plots varied greatly and was not related to the maize response to Zn fertilizer ($r = 0.01$; $P = 0.98$). With respect to soil Zn, a negative but nonsignificant relationship was found between maize response to Zn fertilizer and soil-test Zn ($r = -0.51$; $P = 0.16$).

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Introduction

Zinc (Zn) is the micronutrient that most commonly limits maize (*Zea mays* L.) yields in North America and worldwide (Alloway 2009); in the USA, for example, maize receives the largest tonnages of Zn fertilizers of any crop (Brown 2008). Zinc removal with the maize grain and harvest index is the largest among all micronutrients (Bender et al., 2013). Bender et al. (2013) reported that 308 g ha^{-1} were removed with the grain and a 62% harvest index on average for six hybrids that yielded 12,000 kg ha^{-1}. Zinc deficiencies began to show up in the mid-20th century in the USA (Thorne 1957; Wear and Hagler 1963), and in 1966, the Trace Element Committee of the Council on Fertilizer Application indicated that Zn-deficient corn was reported in 20 states (Berger 1962),

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resulting from the increased use of macronutrient fertilizers and high corn yields (Alley et al. 1972). More recently, Carsky and Reid (1990) observed significant maize yield responses in 6 out of 7 years in the northeastern United States.

Zinc is commonly applied to maize crops in physical blends with phosphorus (P) or potassium (K) fertilizers. Zinc sulfate is the most commonly used Zn source (Alloway 2009) and is typically applied in physical blends, such as a mixture of monoammonium phosphate (MAP), ammonium sulfate (AS), and zinc sulfate ($ZnSO_4$). However, these granulated Zn materials, when mixed into the soil, only treat small zones within the soil mass. The volume of soil treated with granular materials is usually insufficient to supply the requirements of the growing corn plant (Brown and Krantz 1966). Complex fertilizers contain nutrient compounds that originate from chemical reactions. They are the most homogeneous type of fertilizer because all the nutrients are uniformly distributed in each granule (Rodríguez 2007). Complex fertilizers provide a practical solution to physical blends not only because nutrient distribution is more uniform but also because fertilizer handling is simplified both at the dealer and farmer levels. Complex N-P-S-Zn fertilizers also minimize segregation, which is critical for micronutrients (Zn in this case) that are typically applied at a low rate.

Diagnostic tools are important to decide which nutrients should be applied to a particular crop. A good diagnostic tool not only reduces costs when fertilization is not necessary but also avoids nutrient overapplication. Both plant tissue Zn concentration and soil Zn have been related to corn response to Zn fertilization. The Zn tissue sufficiency concentration for the whole plant at the early growth stage ranges from 20 to 70 mg/kg (Camberato and Maloney 2012). Critical soil levels of 1.5 have been observed for the diethylene triamine pentaacetic acid (DTPA) extraction method, between 0.8 and 1.17 mg/kg for ethylenediaminetetraacetic acid (EDTA)–extracted soil Zn, and 1 mg/kg for 0.1 N hydrogen chloride (HCl), respectively (Zare et al. 2009; Alley et al. 1972).

Objectives

The objectives of this study were to (i) evaluate maize yield responses to Zn applied at four different rates, (ii) evaluate the yield response and agronomic efficiency of maize to the application of a complex fertilizer compared to different rates of MAP + AS + ZnSO4, and (iii) evaluate the association between tissue Zn concentration and soil Zn with the maize response to Zn fertilization.

Materials and methods

The experiments were carried out during the 2010, 2011, and 2012 growing seasons throughout 11 locations across USA with different agroecological environments, corresponding to the states of Indiana, Louisiana, Minnesota, Nebraska, Ohio, South Carolina, South Dakota, and Wisconsin.

Management practices conformed to local cropping procedures. Nitrogen, P, and S rates were balanced across treatments (40 kg/ha P, 22 kg/ha S) and fertilizers were broadcast and incorporated immediately prior to planting. Treatments consisted of four rates of a physical blend of MAP + AS + $ZnSO_4$ (0, 2.24, 4.48, 6.72, and 11.2 kg/ha Zn) and MicroEssentials SZ at a Zn rate of 2.24 kg/ha Zn (224 kg/ha MicroEssentials SZ). MicroEssentials SZ (12N–40P–0K–10S–1Zn) is an ammoniated phosphate N-P-S-Zn complex fertilizer manufactured by the Mosaic Company. The experiment was a randomized complete block design with four replications. Whole plants were harvested at the eighth leaf stage, dried, ground, and analyzed for Zn concentration by digestion in a microwave with hydrogen peroxide and nitric acid [method AOAC 975.03B(b)] and read on a Thermo Scientific iCAP 6500 inductively coupled plasma (ICP) instrument (AOAC 2012).

Soil samples were taken before planting and analyzed according to NCR (2012) methods for soil organic matter (OM), soil pH, available P, potassium (K), and Zn. Organic matter was analyzed by the loss on ignition (360 °C) method (Nelson and Sommers 1996), regressed to Walkley-Black equivalent; soil pH was performed on a 1:1 soil to water extract; soil P was analyzed by the Bray P1

Table 1. Soil properties of the studied sites except SC (empty cells represent missing values).

Year	2010	2010	2011	2011	2011	2012	2012	2012	2012	2012
State	LA	MN	IN	MN	SD	IN	WI	NE	MN	OH
OM (%)		3.5	2.2		3.2	2.1	2.5	3		3.2
pH	7.3	5.9	5.9		5.5	6.3	7.2	6.8		5.9
P[a](mg kg−1)	37	8	21	13	21	11	23	25	15	29
K(mg kg−1)		98	160	70	235	82	69	767	72	128
Zn (mg kg−1)	1.5	0.91	0.9	1	1.4	0.9	2.9	2.3	1.21	

[a] Extractant for soil P is weak Bray P except for LA, where it is Mehlich 1.

method in all locations except LA where the Mehlich III extraction method was used; and soil K was analyzed by the Mehlich III extraction method (Mehlich 1984), regressed to ammonium acetate equivalent, and read on a Thermo Scientific iCAP 6500 ICP. Soil Zn was analyzed by the Mehlich III extraction method, regressed to 0.1 molar HCl equivalent, and read on the same ICP. Soil properties for the different locations and years are detailed in Table 1.

The statistical analyses were performed using mixed models in SAS 9.2 (2008), where blocks nested within location-year were considered random and treatments were considered fixed effects. Location-year was treated as one factor (from now on named "location") because some experiments were performed during one year in one location (such as LA 2010, SD 2011, NE 2012, OH 2012, SC 2011, and WI 2012). Experiments in MN and IN were performed during three and two years, respectively, on different fields. Differences among means were analyzed by the least significant differences (Fisher's LSD). A Pearson's correlation was used to find the relationship between maize response to Zn fertilization and tissue Zn, and between the former variable and soil Zn.

Results and discussion

Treatment and location had a significant effect on corn yields ($P < 0.001$), whereas the interaction treatment × location effect was not significant ($P = 0.33$), indicating that there was a consistent response to Zn across locations. Average maize yields across locations ranged from 6900 (WI 2012) to 15,000 kg ha^{-1} (MN 2012). On average across all locations, maize yields increased from 10,540 kg ha^{-1} without Zn to 11,530 kg ha^{-1} with 11.21 kg Zn ha^{-1} applied as a physical blend (Figure 1). The relationship between maize yields and the Zn rate with $ZnSO_4$ (physical blend) was

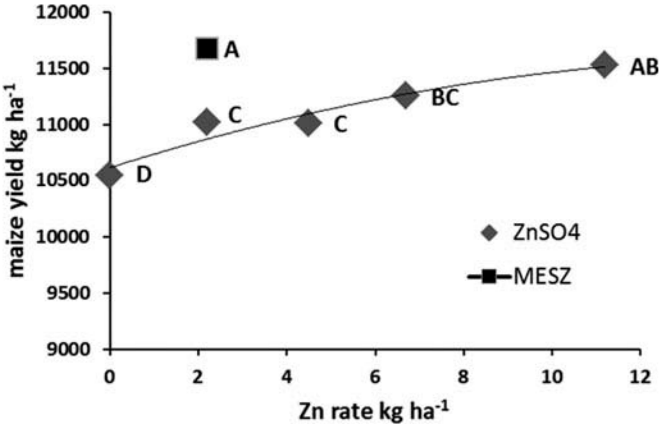

Figure 1. Average maize yields for different Zn rates as MicroEssentials SZ (MESZ) or $ZnSO_4$ from trials across 8 states and 3 years (n = 11). All fertilized treatments were balanced for N, P, and S with ammonium sulfate and monoammonium phosphate to match the rates applied with MicroEssentials SZ. Different letters indicate significant differences with the LSD mean separation method at α = 0.05 (420.6 kg ha^{-1}).

best described by a quadratic equation: $y = 10613 + 124.86x - 3.9749x^2$ ($R^2 = 0.93$), where x represents the Zn rate in kg ha^{-1} and y represents corn yield in kg ha^{-1}. The greatest yield (11,680 kg ha^{-1}) was obtained with complex MicroEssentials SZ at a rate of 2.24 kg Zn ha^{-1}, which was significantly ($P < 0.05$) greater than the yields obtained with the 2.24, 4.48, and 6.72 kg Zn ha^{-1} rates applied as a blend (Figure 1). The greatest Zn rate of 11.2 kg ha^{-1} with the physical blend was necessary to match the yields obtained with the complex fertilizer. The yield response of maize to the application of 2.24 kg Zn ha^{-1} averaged 293 kg ha^{-1} for the physical blend and 1004 kg ha^{-1} for the complex fertilizer. The Zn agronomic efficiency averaged 448 kg maize kg Zn^{-1} for MicroEssentials SZ and 131 kg maize kg Zn^{-1} for the physical blend. The complex fertilizer MicroEssentials SZ was therefore at least three times more agronomically efficient as a Zn source than the physical blend of MAP + AS + $ZnSO_4$. On the other hand, 11.2 kg Zn ha^{-1} of the physical blend were necessary to match the yields obtained with only 2.24 kg Z ha^{-1} of the complex fertilizer. The partial productivity factor was therefore 1029 kg maize kg Zn ha^{-1} for the physical blend and 5214 kg maize kg Zn ha^{-1} for the complex fertilizer.

Diffusion and interception are the mechanisms by which Zn comes into contact with plant roots (Marschner and Rengel 2012). The reason for the greater agronomic efficiency with the complex fertilizer compared to the physical blend is that Zn availability is greater with the complex fertilizer due to the larger number of granules with Zn and the greater Zn uniformity throughout the soil. Assuming a normal granule size of a physical blend, broadcast at 2 kg Zn/ha (heptahydrate), 22 granules containing Zn would be distributed per square meter of soil. Plant availability with such few granules is extremely limited. In contrast, assuming a normal granule size of a complex fertilizer with 1% Zn, about 500 granules containing Zn would be distributed per square meter of soil. In fact, Brown and Krantz (1966) compared powdered and granulated $ZnSO_4$ and observed that when ZnSO4 was granulated, even with mixing in the soil, only a few small zones within the soil mass were actually treated with the Zn fertilizer, producing insufficient availability for the needs of the growing maize plant.

Plant tissue Zn concentration of unfertilized plots varied greatly across locations and years (9.1 mg kg^{-1} for LA 2010 to 66.5 mg kg^{-1} for IN 2012), and increases in plant Zn concentration due to Zn fertilization occurred in only two locations (LA 2010 and MN 2010). The Zn concentration in plant tissue of unfertilized plots was not related to the maize response to Zn fertilizer ($r = 0.01$; $P = 0.98$). Similarly, Carsky and Reid (1990) analyzed whole-plant tissue Zn in 3- to 6-week-old plants and observed that tissue Zn concentration explained only 21% of the variability in grain yields. Maize Zn content at the eighth leaf stage represents less than 10% of the total Zn uptake at maturity (Bender et al., 2013), which explains the relative weakness of tissue testing as a Zn diagnostic tool. In another study that related tissue Zn concentration in 6-week-old plants to its available supply, Hiatt and Massey (1958) observed that plants showing severe deficiency symptoms were stunted and had a relatively high Zn concentration, while lowest tissue Zn concentrations occurred when maize deficiency symptoms were mild and plants grew more. Plant tissue Zn concentration does not appear to be a reliable diagnostic tool for Zn fertilization in maize.

Available soil Zn values ranged from 0.9 (IN 2011) to 2.9 mg kg^{-1} (WI 2012). A negative relationship was found between the relative maize response to Zn fertilization and soil Zn concentration, but the association was not significant ($r = -0.51$; $P = 0.16$), probably due to the soil and climate variability among locations, affecting not only Zn availability but also the response to Zn fertilization. Carsky and Reid (1990) also associated the relative maize yield to extractable soil Zn and observed that soil Zn explained only 25% of the variability in maize yield response to Zn fertilization. Further studies will probably increase the significance of this relationship. Tissue Zn was not a good indicator of the response of corn to Zn fertilization, whereas soil Zn showed a weak association to this variable.

Conclusions

Maize responded positively to Zn fertilization; yields increased from 10,540 kg ha^{-1} without Zn to 11,530 kg ha^{-1} with 11.21 kg Zn ha^{-1} applied as a physical blend. The yield response of maize to the application of the complex fertilizer MicroEssentials SZ at a rate of 2.24 kg Zn ha^{-1} averaged 1004 kg ha^{-1}, significantly higher than the yield response to the application of a physical blend with the same Zn rate, which averaged 293 kg ha^{-1}. The Zn agronomic efficiency therefore averaged 448 kg maize kg Zn^{-1} for the complex fertilizer and 131 kg maize kg Zn^{-1} for the physical blend. The maize yield response to Zn fertilization was poorly associated to tissue Zn concentration and showed a stronger negative but nonsignificant relationship with soil Zn. Greater maize responses and agronomic efficiencies were obtained with a complex fertilizer compared to a physical blend.

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