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Accumulation, partitioning, and bioavailability of micronutrients in summer maize as affected by phosphorus supply

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ABSTRACT

Decreased micronutrient concentration in cereal grains caused by excessive application of phosphorus (P) fertilizer may contribute to reduce their nutritional quality. To help correct this problem in maize grain, a 3-year field experiment was conducted to determine how P application rate affects micronutrient partitioning in maize shoots and other plant organs and micronutrient bioavailability in grain. Phosphorus application significantly decreased shoot zinc (Zn) and copper (Cu) concentrations at all growth stages but had no effects on shoot iron (Fe) and manganese (Mn) concentrations. As the P application rate increased, shoot Zn and Cu contents decreased, and shoot Fe and Mn contents increased. The ratios of pre-anthesis to post-anthesis mineral contents were not affected by P application rate except Zn. P application increased the percentage of Zn that was allocated to grain and decreased the percentage that was allocated to other tissues, but had no effects on the allocation of other micronutrients among tissues. The bioavailability of Zn, Cu, Fe, and Mn in grain decreased as P application rate increased. Overall, taking account of grain yield and nutrients concentration, P fertilizer rates should range from 12.5 to 25.0 kg P ha^{-1} under the local condition. It can be concluded that not only grain yields, but also nutritional quality, should be considered in assessing optimal P rates in maize.

1. Introduction

Maize (*Zea mays* L.) is one of the world's leading cereal grains and is very popular because of its diverse functionality as a food for both humans and animals (Nuss and Tanumihardjo, 2010). Maize is also a dietary staple for more than 200 million people and it provides around 15% of the protein and 20% of the calories in the world food diet (Brown et al., 1988). As a result, nutrient-biofortification of maize is attracting increasing attention from researchers (Xue et al., 2014). According to recent publications, the target concentrations of zinc (Zn) and iron (Fe) in biofortified maize are 38 mg kg^{-1} and 60 mg kg^{-1}, respectively (Bouis and Welch, 2010), but the concentrations of Zn and Fe in global maize grain are only about 22.0 mg kg^{-1} and 21.0 mg kg^{-1}, respectively (Gibson, 2012; Welch, 2002).

In the intensive cultivation of high-yielding crop cultivars, at least 30–50% of the crop yield is attributable to the application of commercial fertilizers (Stewart et al., 2005). Although phosphorus (P) fertilizer can substantially increase maize grain yield (Banaj et al., 2006), excessive P fertilizer typically does not result in additional yield increases (Bai et al., 2013) but can lead to environmental pollution (Guo et al., 2010; Le et al., 2010) and deficiencies in Zn, copper (Cu), and Fe of maize (Cakmak, 2002; Stein, 2010). In China, for example, approximately 40% of the soils are Zn and Fe deficient, and about 30% are manganese (Mn) and Cu deficient (Liu, 1991). P application can reduce micronutrient concentrations and especially Zn and Cu concentrations in wheat grain (Zhang et al., 2012). It is therefore important to clarify how the micronutrient status in maize grain and stover is affected by P application in the field.

Many studies have reported how the accumulation of minerals in maize shoots is related to maize yields (Bender et al., 2013; Karlen et al., 1988). For instance, maize that yielded 12.0 Mg of grain ha^{-1} accumulated 49.8 kg of P, 0.1 kg of Cu, 1.4 kg of Fe, 0.5 kg of Mn, and 0.5 kg of Zn ha^{-1} (Bender et al., 2013). If the yield increased to 19.3 Mg ha^{-1}, the accumulation of P, Cu, Fe, Mn, and Zn at physiological maturity increased to 69.9, 0.14, 1.9, 0.9, and 0.8 kg ha^{-1}, respectively (Karlen et al., 1988). Furthermore, Xue et al. (2014), who evaluated shoot micronutrient accumulation at different growth stages under different yield and nitrogen levels, found that the reciprocal internal efficiencies (g of micronutrient requirement in plant dry matter per Mg of grain) of Fe, Mn, and Cu were not greatly affected by the yield and N levels. Although researchers have

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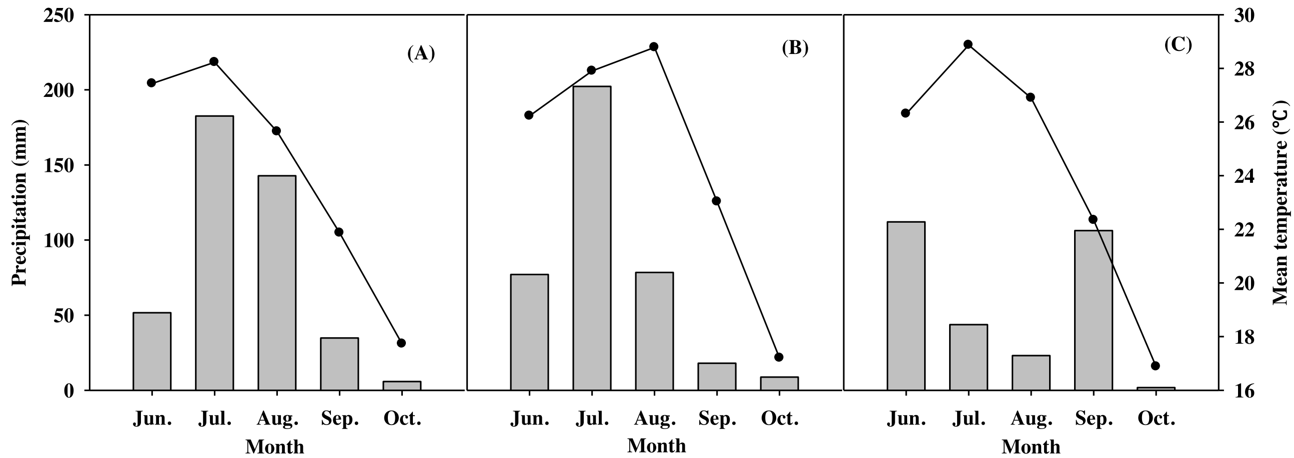

Fig. 1. The precipitation and mean temperature of month in the three years: 2012 (A), 2013 (B), and 2014 (C). The bars indicate the precipitation and the lines indicate mean temperature of month.

reported that high rates of P application can decrease Zn and Cu accumulation in wheat (Kizilgoz and Sakin, 2010), little information is available about how the dynamics of micronutrient accumulation (such as Zn, Fe, Mn, and Cu) in maize are affected by P application rate. Researchers have also reported that the quantity of minerals accumulated before anthesis determined the quantity that is remobilized into grain of wheat (Stomph et al., 2009). Pearson and Rengel (1994) indicated that a high accumulation of available Zn pre-anthesis is the main source for the Zn that is retranslocated to grain. In maize, however, the effect of P application on Zn accumulation pre- and post- anthesis is unclear. Thus, the effect of P fertilizer supply on the accumulation of Zn and other micronutrients pre- and post- anthesis should be evaluated in maize.

Minerals in plants exhibit different degrees of mobility among tissues, especially during the grain formation stage (Hegelund et al., 2012). While P and Zn are highly mobile and begin to translocate to maize grain at the R2 growth stage, Mn, Cu, and Fe have limited mobility (Bender et al., 2013). A previous study found that large proportions of the N and P and a small proportion of K were translocated from other plant parts to developing grain (Hanway, 1962). In another study, about 60% of the Zn, 30% of the Cu, 20% of the Fe, and 15% of the Mn originally in maize shoots had accumulated in grain at maturity (Bender et al., 2013). Potential effects of P application levels on P and micronutrient partition among shoot tissues (i.e., among bract, rachis, grain, stem, and leaf) of maize under field conditions has not been studied. In addition, micronutrient bioavailability has been found to be negatively affected by P application. For instance, Zhang et al. (2012), who used the molar ratio of P to Zn to indicate Zn bioavailability, reported that the increase of P fertilizer rates increased the molar ratio of P to Zn and therefore decreased Zn bioavailability in wheat grain.

The aims of this study were to determine how P application rate affects (1) the temporal dynamics of micronutrient (Zn, Fe, Mn, and Cu) accumulation in maize, (2) the partitioning of P and micronutrients among different maize tissues pre- and post-anthesis, and (3) the micronutrient bioavailability in grain.

2. Materials and methods

2.1. Field location

A long-term field experiment with maize was conducted at the Quzhou Experiment Station (36.9°N, 115.0°E) in Hebei Province of China to determine the effect of P fertilizer application on grain yield and nutrients in grain and straw. The experiment was begun in 2008, and the same plots, treatments, and crops were conducted from 2008 to 2014. In this report, all the data of biomass, yield, and nutrients in grain and straw were collected from 2012 to 2014 cropping years. At the beginning of the experiment, the initial soil Olsen-P concentration in 2008 was 7 mg kg^{-1} (0.5 M $NaHCO_3$-extractable). The average soil DTPA (Diethylene Triamine Pentacetic Acid)-extractable Zn, Cu, Fe, and Mn concentrations before sowing were 0.40, 0.88, 8, and 13 mg kg^{-1}, respectively. The soil micronutrient concentrations were low mainly because the soil was a calcareous alluvial soil with a high pH (8.0, 1:2.5 w/v in water). The soil texture in the location was loam with 140 g kg^{-1} of sand (2–0.05 mm), 605 g kg^{-1} of silt (0.05–0.002 mm), and 255 g kg^{-1} of clay (<0.002 mm) on basis of the American soil particle-size classification standard. Meanwhile, the soil $CaCO_3$ and organic matter content were 65 g kg^{-1} and 10.3 g kg^{-1}, respectively. The monthly precipitation and mean temperature from a meteorological station installed the Experiment Station are presented in Fig. 1 among the three years.

2.2. Experimental design

Six P application rates, which were applied before sowing in each cropping year, were included in the experiment: 0, 12.5, 25, 50, 100, and 200 kg P ha^{-1} (recorded as P0, P12.5, P25, P50, P100, and P200, respectively). Each treatment was represented by four replicate plots, and each plot was 75 m^2 (7.5 m × 10 m). The plots were arranged in a randomized block design. The summer maize (*Zea mays* L.) cultivar was 'Nongda 108′ in 2012 and 2013 and 'Zhengdan 958' in 2014, and the maize density was 67,000 plants ha^{-1}. Before sowing, 75 kg nitrogen (N) ha^{-1} as urea (46% N), 60 kg K_2O ha^{-1} as K sulphate, and P fertilizer as calcium superphosphate (7% P content: 0, 179, 358, 716, 1432, and 2864 kg ha^{-1}, respectively) were applied. Another 150 kg N ha^{-1} as urea (46% N) was supplied at the 6-leaf (V6) stage. The 700 m^3 ha^{-1} irrigations were carried out after sowing and at V6 stage of maize for the three cropping years. Weeds and pests were controlled by standard practices including pre-emergence herbicide (sprays before emergence of seedlings) and pesticide (sprays at 12-leaf stage) to control weeds and aphids. No water, weed, or pest problems were observed during the experiment. In 2012, 2013, and 2014, the maize seeds were sown on June 12, June 15 and June 12, respectively and the grain was harvested on October 5, October 4, and October 2, respectively.