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Zinc accumulation and remobilization in winter wheat as affected by phosphorus application

Wei Zhang[a], Dunyi Liu[a], Chao Li[a], Zhenling Cui[a], Xinping Chen[a], Yost Russell[b], Chunqin Zou[a,b,*]

[a] Key Laboratory of Plant–Soil Interactions, Ministry of Education; Center for Resources, Environment and Food Security, China Agricultural University, Beijing 100193, PR China
[b] Department of Tropical Plant and Soil Science, University of Hawai'i at Manoa, Honolulu, HI 96822, USA

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ABSTRACT

Although the interaction between phosphorus (P) and zinc (Zn) in crop production has long been a focus of plant nutrition research, the effects of P on the Zn content of cereal crops remains unclear, especially in intensive agricultural systems with high rates of P application and low levels of available Zn. The current study of a high-yielding winter wheat system on the North China Plain compared the effects of P application (0, 25, 50, 100, 200, and 400 kg ha^{-1}) on yield, biomass accumulation, Zn accumulation, Zn uptake during all crop stages, and Zn remobilization. In two growing seasons (2011–2012 and 2012–2013), the results indicated that P application significantly increased wheat grain yield and shoot biomass. Phosphorus application also significantly increased the P concentration and decreased the Zn concentration in shoots. Phosphorus application increased P accumulation (kg ha^{-1}) throughout the growing season but the effect of P application on Zn accumulation (g ha^{-1}) depended on crop stage. Zn accumulation increased with increasing P application rates at the jointing stage. Zn accumulation at the flowering and maturity stage increased with application of 25 and 50 kg P ha^{-1} but decreased with application of 100–400 kg P ha^{-1} in both cropping seasons. The Zn harvest index and the ratio of pre-anthesis to post-anthesis Zn accumulation were not greatly affected by P application rate. Zn remobilization into grain increased with application of 0–50 kg P ha^{-1} but then decreased with the further application of 50–400 kg P ha^{-1} in both cropping seasons. Overall, the effects of P application on Zn nutrition depended on P rate and crop stage. Lower P application rates (<50 kg ha^{-1}) increased Zn accumulation especially after the flowering stage and increased Zn remobilization to grain. High rates of P (>50 kg ha^{-1}), in contrast, significantly decreased Zn accumulation and remobilization in this high-yielding winter wheat system. The results indicate that optimal P management in intensive agricultural systems is needed to ensure both high wheat yields and high levels of Zn in grain required for human nutrition.

1. Introduction

Zinc (Zn) is required for the health of crops and humans. Although Zn supplementation in foods is commonly recommended to prevent Zn deficiency (Gibson, 2012; Cakmak, 2009; Singh and Prasad, 2014), Zn deficiency is still common in humans (Hotz and Brown, 2004; White and Broadley, 2009). Zinc deficiency is especially common among those humans who rely on cereals as a staple food (Cakmak et al., 1996; Rengel et al., 1999; Li et al., 2003; Ryan et al., 2008; Cakmak and Hoffland, 2012).

As one of the "big three" cereal crops worldwide, wheat critically determines human nutrition (Shewry, 2009). In China, about 70% of wheat is produced on the North China Plain (NCP) where the soils have high levels of available phosphorus (P) (Liu et al., 2010) and where food products based on wheat provide more than 20% of the daily Zn intake, especially in rural areas (Ma et al., 2008). Zinc supplementation through wheat crops can, therefore, be critical to reducing human Zn deficiency on the NCP.

Although the application of P is required to achieve high wheat yields (Cordell et al., 2009; MacDonald et al., 2011; Gemenet et al., 2015), excessive P fertilization can lead to surplus levels of P in croplands (MacDonald et al., 2011) and then to reduced environ-

* Corresponding author at: Key Laboratory of Plant–Soil Interactions, Ministry of Education; Center for Resources, Environment and Food Security, China Agricultural University, Beijing 100193 PR China. Fax: +86 10 62731016.
E-mail address: zcq0206@cau.edu.cn (C. Zou).

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mental quality and food security (Cordell et al., 2009). Moreover, the overuse of P fertilizer affects the Zn nutrition of crops. Numerous reports indicate that P application reduced the concentrations of Zn in the shoots and even in the grain of cereal crops (Buerkert et al., 1998). Furthermore, the Zn content in shoots greatly affects the accumulation of Zn in the grain of cereal crops (Cakmak et al., 2010). Some reports have indicated that P fertilizer application can decrease the total Zn content in rice plants (Haldar and Mandal, 1981; Guo et al., 2005). It is therefore important to clarify how Zn accumulation in wheat shoots is affected by P application in the field.

Although the effect of P application on Zn accumulation has been quantified a number of times (Kizilgoz and Sakin, 2010; Yang et al., 2011; Zhang et al., 2012; Huang et al., 2013), the results have been inconsistent. Kizilgoz and Sakin (2010), for example, reported that Zn content in the shoots of wheat and maize seedlings growing in pots decreased with increasing P fertilizer application. Zhang et al. (2012) found that P application did not affect Zn accumulation in shoots of mature winter wheat in the field. Huang et al. (2013), however, reported that P fertilization enhanced Zn accumulation in shoots and roots of *Sedum alfredii*, L. growing in pots. In all three reports, results were from a specific plant growth stage rather than from the entire crop cycle. Increasing our understanding of the influence of P application on Zn accumulation will require the quantification of Zn accumulation over the entire developmental cycle of the crop in question.

There are two main sources of Zn accumulation in cereal grain: uptake that is concurrent with grain filling and that resulting from post-anthesis remobilization from the Zn stored in source tissue (Stomph et al., 2009; Waters et al., 2009; Hegelund et al., 2012). On the NCP and in other areas concurrent Zn uptake can be limited by stresses during grain filling caused by the following factors: calcareous soil with high levels of $CaCO_3$ and high pH; hot and dry continental wind; high temperature; and drought (Yang et al., 2000; Zhou et al., 2007). Under these stress conditions, uptake of Zn by roots is likely to be limited during grain filling. It follows that, when Zn availability is restricted during grain filling then Zn remobilization is particularly critical for the accumulation of Zn in grain (Kutman et al., 2012).

Some research has indicated that grain Zn accumulation is closely associated with the remobilization of Zn from stem to grain (Erenoglu et al., 2002; Wu et al., 2010). One study reported that from 58 to 60% of the Zn content in grain was provided by Zn remobilization of pre-anthesis Zn uptake in winter wheat (Dang et al., 2010). Another recent study reported that, with optimal N fertilization, from 67 to 100% of the Zn in grain was provided by Zn remobilization of pre-anthesis Zn uptake (Xue et al., 2012). Whether P application affects Zn remobilization and then the Zn content of grain, however, has not been reported.

The aims of this study were (1) to investigate the effect of P application rates on the dynamics of Zn accumulation during the developmental cycle of winter wheat on the NCP, and (2) to compare the Zn remobilization from vegetative tissues to the grains vs. pre-anthesis and post-anthesis Zn uptake as affected by P application rates on the NCP.

2. Materials and methods

2.1. Field location

The field experiment was conducted at the Quzhou experiment station in Hebei province (36.9°N,115.0°E) from October to the following June for two cropping seasons (2011–2012 and 2012–2013) of a winter wheat–summer maize rotation. The experimental site is located in the center of the NCP and had a mean temperature from January to June of 9.8 °C in 2012 and 8.9 °C in 2013. The site has a calcareous alluvial soil. The soil pH (1:2.5 w/v in water) was 8.0, and the initial soil Olsen-P was 6.4 mg kg^{-1} (0.5 mol L^{-1} $NaHCO_3{}^{-}$-extractable). The soil DTPA-extractable Zn concentration before sowing averaged 0.40 mg kg^{-1}.

2.2. Experimental design

The field experiment included of six P application rates: 0, 25, 50, 100, 200, and 400 kg P ha^{-1} (designated as P0, P25, P50, P100, P200, and P400, respectively). Each treatment was represented by four replicate plots. Each plot was 43.2 m^2 (8 m × 5.4 m) and was treated with the same P application rate in both cropping seasons. The winter wheat (*Triticum aestivum* L.) cultivar was Kenong 9204 in 2011–2012 and Liangxing 99 in 2012–2013. The seeding rate was 187.5 kg ha^{-1}. All plots received 225 kg N ha^{-1} as urea (46% N), 60 kg K_2O ha^{-1} as potassium sulphate, and P fertilizer as calcium superphosphate. Potassium and P were applied before sowing. Urea was applied in two applications per crop cycle: the first was applied as 75 kg N ha^{-1} before sowing, and the second was applied as 150 kg N ha^{-1} at the jointing stage. Based on soil water content, irrigation was applied at the pre-wintering stage, the jointing stage, and the flowering stage in both cropping seasons.

2.3. Sample collection and nutrient analysis

Winter wheat shoot samples were collected at the jointing stage (GS31), the flowering stage (GS65), and the maturity stage (GS92). Entire shoots were randomly selected from two 0.5-m lengths of two adjacent rows in each plot at 181 days after sowing (DAS), 212 DAS, and 241 DAS in 2011–2012 and at 181 DAS, 209 DAS, and 241 DAS in 2012–2013. At maturity, all wheat plants in a 6-m^2 (3 m × 2 m) area in the center of each plot were harvested to determine the grain yield, and then the wheat plants were separated into grain and straw. In this report, the term “shoot” refers to all aboveground parts of wheat plants including the straw and grain. The shoot samples were rapidly washed with tap water and then deionized water before they were dried at 60–65 °C to constant weight. All plant samples were ground with a stainless steel grinder (model RT-02A, made in Taiwan) for nutrient analysis.

The plant samples were digested with HNO_3–H_2O_2 in a microwave-accelerated reaction system (CEM, Matthews, NC, USA). The Zn and P concentrations in the digested solutions were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, OPTIMA 3300 DV, PerkinElmer, USA). IPE684 grain and IPE126 straw samples (Wageningen University, Netherlands) were used as reference materials to verify the digestion procedures and to calibrate the ICP-OES.

2.4. Calculations

The parameters in the following calculations are on a per hectare basis.

Shoot Zn content was equal to shoot biomass multiply by shoot Zn concentration.

Post-anthesis Zn uptake was calculated as shoot Zn content at maturity minus shoot Zn content at anthesis.

Zn remobilization to the grain was calculated from the shoot Zn content at anthesis minus straw Zn content at maturity.

Zn remobilization efficiency was then calculated as Zn remobilization divided by shoot Zn content at anthesis.

Pre-anthesis Zn accumulation was reported as a percentage of total Zn accumulation and calculated as shoot Zn content at anthesis divided by shoot Zn content at maturity × 100%.