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Change in phosphorus requirement with increasing grain yield for Chinese maize production

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ABSTRACT

By understanding the relation between maize (*Zea mays* L.) grain yield and phosphorus (P) uptake requirements it is possible to reduce both cost and environmental impact of maize production. The goal of this study was to determine P uptake requirements and patterns of P accumulation, pre- and post-silking, at different maize grain yield levels. A database comprising measurements in 955 plots in 44 on-farm and research station experiments during the period 2000–2012 on the North China Plain was used for the analyses. The P requirement ($P_{req.}$, the P content Mg^{-1} grain yield on the basis of 155 g kg^{-1} moisture content) increased significantly from 2.84 kg in the P < Opt. treatment to 3.44 kg in the P > Opt. treatment. In the Optimal P treatment, average $P_{req.}$ values were 3.41, 3.15, 3.09, and 2.94 kg for grain yields ranging from <8.0, 8–10, 10–12, and >12.0 Mg ha^{-1}, respectively. The decrease in $P_{req.}$ values with increasing grain yield was mainly attributable to the increase in the harvest index from 0.47 to 0.53 and the decrease in grain P concentrations from 2.73 to 2.42 g kg^{-1}. A larger proportion of the P was accumulated post-silking when grain yields were higher than 10 Mg ha^{-1} (48%) and 8–10 Mg ha^{-1} (44%) than when yields were less than 8 Mg ha^{-1} (35%). Using this knowledge of P uptake requirements should improve assessments of global P balance, and help optimize P management, especially in high-yielding maize system.

1. Introduction

Phosphorus (P) as a primary component of DNA, RNA and ATP plays an important role in the carriers of genetic information and intracellular energy transfer within living cells and is also the key limiting nutrients for supporting plant growth (Marschner, 2012). Achieving high maize yields requires adequate soil P concentrations in the root zone (Bai et al., 2013; Li et al., 2011). However, high soil P accumulation also increases the risk of P loss through erosion, overland flow and leaching, which leads to serious environmental problems such as eutrophication of surface waters (Diaz and Rosenberg, 2008; Conley et al., 2009; Le et al., 2010; Xu et al., 2010; Bai et al., 2013). Matching P supply with P uptake requirements of maize (*Zea mays* L.) grain yield without excess or deficiency is important for crop yield and mitigation of environmental risks (Li et al., 2011; Zhang et al., 2012a; Shen et al., 2013).

Previous studies have reported wide variation in the grain yield–P uptake relationships over regions (environments), genotypes, and P management strategies (Liu et al., 2006; Setiyono et al., 2010; Bender et al., 2013; Ning et al., 2013; Qi et al., 2013; Xu et al., 2013; Zhang et al., 2012b). For example, Setiyono et al. (2010) reported that the average P requirement Mg^{-1} grain ($P_{req.}$) for maize was 2.8 kg in Nebraska, USA, compared with 2.5 kg in Southeast Asia; Xu et al. (2013) reported that the simulated $P_{req.}$ by the QUEFTS model was different between summer maize (4.4 kg) and spring maize (3.5 kg); Zhang et al. (2012b) found that $P_{req.}$ for spring maize increased with the P supply. Different studies have reported large variations in $P_{req.}$ for maize, which underscores the need for a better understanding of the factors that influence variation in P requirements and determine the degree of influence that occurs.

Abbreviations: Preq., the phosphorus requirement megagram^{-1} grain yield; HI, harvest index; PHI, phosphorus harvest index; DM, dry matter; NCP, North China Plain.

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Previous studies that estimated the P requirements of maize have often been on-site-specific field experiments, and very few attempts have been made to investigate physiological P requirements in terms of yield relationships across a wide range of farming environments of high yield potential. In this study, we collected data in 955 plots in 44 field experiments from 2000 to 2012 on the North China Plain (NCP).The objectives of this study were to investigate P uptake under different P management strategies, quantify the P requirement Mg^{-1} grain produced for different yield levels under optimal P application conditions, and evaluate pre-silking and post-silking patterns of dry matter (DM) and P accumulation for different yield levels.

2. Materials and methods

2.1. Data collection

The data were collected from on-farm and research station experiments conducted in 44 locations during 2000–2012 on the North China Plain (NCP). Measurements were conducted in 955 plots in total. Measured variables were maize yield (155 $g\,kg^{-1}$ moisture content), total dry matter (DM), and phosphorus (P) concentrations in both stover and grain at physiological maturity. Two types of field experiments were used for the investigation. (1) P dose experiments were conducted at 29 locations. All sites included an optimal P rate (Opt.) based on soil testing or agronomists' recommendations, which was compared with 3–5 sub- and superoptimal rates including, e.g. farmers' practices, no P as a control, and 50%, 150%, 200% and 300% of the considered optimal P dose. (2) Demonstration experiments with optimal NPK rates for different tillage managements and fertilizer types were conducted at 15 locations. Specific detailed information of these on-farm studies is not reported here. We collected data on DM and P uptake at the R1 and R6 stages from 123 plots with optimal P doses.

Summer maize was sown in the middle of June and harvested in late September. Annual precipitation in NCP is 500–700 mm, with ~70–80% of the rainfall occurring during the summer maize growing season. As a result, summer maize generally requires very little irrigation. All experimental fields received P applications that ranged from 0 to 300 $kg\,P\,ha^{-1}$ (average 32 $kg\,P\,ha^{-1}$). Nitrogen application rates (averaged 175 $kg\,N\,ha^{-1}$ and ranged from 45 to 376 $kg\,N\,ha^{-1}$) and potassium application rates (averaged 61 $kg\,K\,ha^{-1}$ and ranged from 37 to 318 $kg\,K\,ha^{-1}$) were recommended by agronomists and were based on targeted yield and soil fertility. Nitrogen was broadcast by hand as granular urea $[CO(NH_2)_2]$ with plowing before sowing (30–40% N fertilizer) and deep placement at the 6-leaf stage (60–70% N fertilizer). All plots received P fertilizer as triple superphosphate and K fertilizer as potassium chloride at pre-sowing. No manure was applied. All experiments were managed according to high-yield practices. Commercial hybrids with high yield potential that were considered suitable at each site were used. Plant densities ranged from 70,000 to 75,000 plants ha^{-1}. No obvious water, weed, pest, or disease stresses were observed during the growing season.

2.2. Plant sampling analysis

At the R1 and R6 stages, five consecutive plants of each plot were sampled to determine the aboveground total dry weight and P content. At the R6 stage, plant samples were divided into stover (leaves + stem + cobs + husks) and grain. All plant samples were oven-dried at 70 °C until a constant weight was reached for biomass measurements. The samples were ground to fine powder, and the P concentrations of grain and stover were determined by the molybdate-blue colorimetric method (Murphy and Riley, 1962). The P concentrations of grain and stover were reported as oven-dried values. The maize was hand harvested from 2.5 m × 8 m in each plot and grain yield was reported with 155 $g\,kg^{-1}$ moisture content.

2.3. Data analysis

The data were analysed as three groups, (1) the optimal P dose based on recommendations (P = Opt., 35.7 $kg\,P\,ha^{-1}$ on average), (2) below optimal P doses (P < Opt., 2.1 $kg\,P\,ha^{-1}$ on average), including no P, 50% of P Opt. and some FPP that applied <P Opt. and (3) above optimal P doses (P > Opt., 90.8 $kg\,P\,ha^{-1}$ on average) including 150%, 200%, and 300% of the Opt and some FPP that were >Opt. The relationships between aboveground P uptake and grain yield for these three groups was simulated by linear, quadratic, power, and exponential models using SigmaPlot 12 for Windows (www.sigmaplot.com). The best-fitting power model was selected.

The data for the P = Opt. treatments were split into four groups according to grain yield: <8, 8–10, 10–12, and >12 $Mg\,ha^{-1}$. Experiments with DM and P uptake data collected at the R1 and R6 stages from the P = Opt treatments were also grouped on the basis of grain yield (<8, 8–10, and >10 $Mg\,ha^{-1}$). A one-way ANOVA was used to compare the data means of different P treatments and yield levels based on the least significant difference at a 0.05 level of probability, using SPSS 18.0.

The $P_{req.}$ is defined as the amount of aboveground P needed to produce 1 Mg grain (on the basis of 155 $g\,kg^{-1}$ moisture content). The harvest index (HI) was determined by dividing the grain yield by the total aboveground plant DM (kg grain kg^{-1} total aboveground DM). The P harvest index (PHI) is defined as P accumulation in grain as a proportion of P accumulation in aboveground plant DM.

3. Results

3.1. P requirements for different P management strategies

Considering all 955 observations, summer maize grain yield (at 155 $g\,kg^{-1}$ moisture) averaged 9.0 $Mg\,ha^{-1}$, ranging from 3.1 to 15.2 $Mg\,ha^{-1}$ (Table 1). The HI ranged from 0.28 to 0.65, with an average of 0.50 (Table 1). The grain P concentrations averaged 2.65 ± 0.59 $g\,kg^{-1}$, while the P concentration of stover averaged 1.11 ± 0.50 $g\,kg^{-1}$ (Table 1). Overall, The average $P_{req.}$ was 3.20 ± 0.68 kg and ranged from 1.79 to 5.71 kg.

Overall, the relationship between aboveground P uptake and the grain yield of summer maize in the different P treatments could be described by a positive power function (Fig. 1). An average of 59.9%, 54.1%, and 55.1% of the variation in grain yield was explained by aboveground P uptake for the P < Opt., P = Opt., and P > Opt. treatments, respectively. The curves produced for the P = Opt. treatment were lower than for the P > Opt. treatment, but higher than that for P < Opt. treatments (Fig. 1d), which reflects a more balanced P uptake by maize at similar grain yield. The aboveground P uptake was significantly affected by the P supply (Table 1). There was a significant increase in grain P concentrations with increasing P application doses from the P < Opt. treatment to P = Opt. treatment to P > Opt. treatment (Table 1). Stover P concentrations were significantly increased by P = Opt. treatment compared to P < Opt. treatment, but did not differ significantly from P > Opt. treatment (Table 1). As a result, $P_{req.}$ increased significantly from the P < Opt. treatment to P = Opt. treatment to P > Opt. treatment (Table 1).

3.2. P requirements for different yield levels under optimal P application conditions

Using all of the data for the P = Opt. treatment (n = 673), the average grain P concentrations were gradually decreased with