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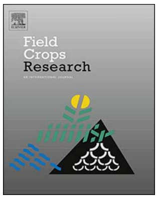

Short Communication

The role of phosphorus supply in maximizing the leaf area, photosynthetic rate, coordinated to grain yield of summer maize

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ABSTRACT

Understanding the responses of the leaf area index (LAI) and photosynthetic rate to phosphorus (P) fertilization is important for optimizing P management and obtaining high grain yield for summer maize. A field experiment with six rates of P application (0, 12.5, 25, 50, 100, 200 kg ha^{-1}) was conducted in a maize field in 2014 and 2015. P application significantly increased the soil Olsen-P concentration, and the critical level of soil Olsen-P concentration for maximal shoot P concentration was 20.5 mg kg^{-1}. As the shoot P concentration increased to 2.01 g kg^{-1} in 2014 and 2.40 g kg^{-1} in 2015, the LAI and net photosynthetic rate got maximum but then plateaued at higher shoot P concentration. The highest grain yield (11.6 Mg ha^{-1}) was attained when the critical LAI and net photosynthetic rate was 4.85 m^2 m^{-2} and 28.5 μmol CO$_2$ m^{-2} s^{-1}, respectively. The length of barren ear tips was reduced by optimizing the P application rate then increased grain yield. By properly managing P fertilization, maize growers can maximize the LAI and net photosynthetic rate and thereby attain high grain yields without applying excessive P.

1. Introduction

Cereal grains are a common staple food because of their diverse functionality as food for both humans and animals (Nuss and Tanumihardjo, 2010; Prasanna et al., 2001). Although the average maize yield in China has increased from less than 1 Mg ha^{-1} in 1949–6 Mg ha^{-1} in 2013 (Qin et al., 2016), yields per ha may need to be further increased because cropland is decreasing and food demand is increasing (Zhang et al., 2013).

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, especially phosphorus (P), nitrogen (N), and potassium (K) fertilizer (Stewart et al., 2005). The maize grain yield is also determined by the accumulation of shoot biomass (Wu et al., 1962; Echarte et al., 2008), and the leaf photosynthetic rate is the ultimate source of biomass production in plants (Beadle and Long, 1985; Long et al., 2006; Zhu et al., 2010). Because the leaf photosynthetic rate is determined by the available light energy and by the efficiency of light capture (Long et al., 2006), the optimization of the leaf area index (LAI) should maximize light interception and thereby increase biomass production (Beadle and Long, 1985). Excessive LAI, however, can cause leaf shading and reduce the photosynthetic rate in maize (Vos et al., 1998). A previous report indicated that increases in soil P were positively correlated with LAI (Plénet et al., 2000). Another study documented a decrease in photosynthesis under P deficiency conditions (Kirschbaum and Tompkins, 1990). Little information is available, however, about the effects of P application on the relationships between leaf photosynthetic rate, LAI, and grain yield. Such information is needed to improve P fertilization management.

The objectives of the current study were (1) to determine how soil Olsen-P concentration and shoot P concentration are related to LAI and the photosynthetic rate in maize, and (2) to quantify the relationship between LAI, photosynthetic rate, and maize grain yield as affected by P application.

2. Materials and methods

2.1. Field location

A field experiment was conducted at the Quzhou Experiment Station in Hebei Province, China. Data for yield, P concentration in soil and plant, LAI, and photosynthetic rate were collected in 2014 and 2015. The experiment was part of a winter-wheat and summer-maize crop rotation system. In both two years the experiment was conducted on a

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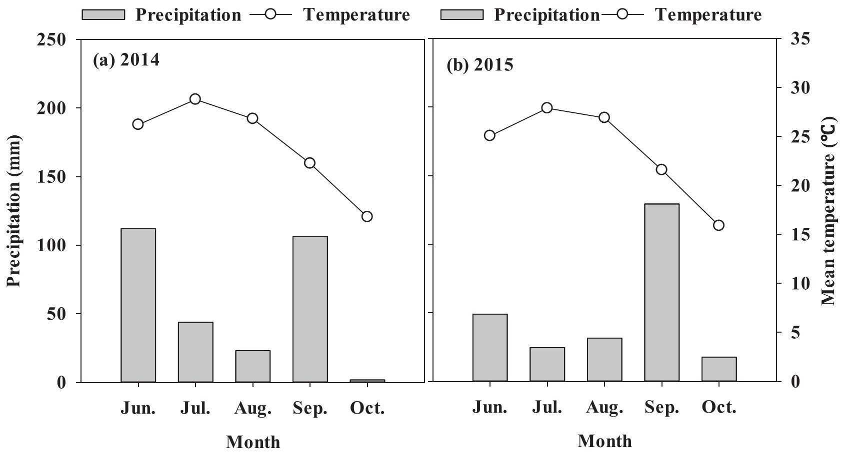

Fig. 1. Precipitation and mean temperature of month in two cropping seasons: 2014 (a), and 2015 (b). The bars indicate the precipitation and the lines indicate mean temperature of month.

same site and the same amount of P fertilizer was applied into soil for each P application rate. The soil at this location is a calcareous alluvial soil which is a typical soil in the North China Plain based on the WRB classification. The loam soil from 0 to 20 cm soil depth had a high pH (8.0, 1:2.5 w/v in water) and a high $CaCO_3$ content ($65\,g\,kg^{-1}$). The initial soil (0–20 cm layer) Olsen-P concentration was $6.4\,mg\,kg^{-1}$ ($0.5\,mol\,L^{-1}$ $NaHCO_3$-extractable). The mean temperature during the maize growing season was 24.3 °C in 2014 and 23.5 °C in 2015. The annual precipitation during the maize growing season was 285.2 mm in 2014 and 256.4 mm in 2015 (Fig. 1a and b).

2.2. Experimental design

Six P application rates were applied to maize: 0, 12.5, 25, 50, 100, and 200 kg P ha^{-1}. Each treatment was represented by four replicate plots (75 m^2 per plot). The plots were arranged in a randomized block design. The summer maize (*Zea mays* L.) cultivar was '*Zhengdan 958*', and the maize density was 67,000 plants ha^{-1} in 2014 and 75,000 plants ha^{-1} in 2015. The row spacing and inter plant distance of maize was 60 cm and 22.2 cm in both cropping seasons. Before sowing in each cropping season, 75 kg of N ha^{-1} as urea (46% N), 60 kg of K_2O ha^{-1} as potassium sulphate, and all P fertilizers as calcium superphosphate were broadcasted then mixed into soil with a rotary cultivator. Another 150 kg of N ha^{-1} as urea was banded applying at the 6-leaf stage (V6). At V6 stage (at July 9th in both cropping seasons), irrigation water of maize was pumped from a well near the field then diverted to all the experiment plots through plastic pipe and calibrated with flow meter. A pre-emergence herbicide and pesticide (i.e., paraquat and omethoate) were used to control weeds and pests. The sowing dates of maize in 2014 and 2015 were at June 12th and June 10th, respectively. Meanwhile, the plant sampling, and measurement of net photosynthetic rate and LAI were all performed at VT stage, which was at August 9th in 2014 and at August 7th in 2015. At maturity, grain harvesting was at October 2th in 2014 and October 1th in 2015, respectively. The standard growth stages of maize in this research were referred to Lancashire et al. (1991).

2.3. Sampling and P analysis

Four maize plants were collected from each plot at the VT stage and at maturity. To reduce sampling variation, the four maize plants were collected from two adjacent rows with uniform height and growth stages which can be the representative of the whole plot. The maize plant was large and the samples with external factor as well as edge maize should be avoided to be collected when sampling. The shoot was divided into stover and grain at maturity. All stover and grain were washed with tap water followed by deionized water and were then dried at 60–65 °C in an oven to a constant weight. Plants samples were ground with a stainless steel grinder for nutrient analysis. To evaluate the maize grain yield, all maize ears in a 7.2 m^2 (3 m × 2.4 m) area in the center of each plot were hand-harvested in both cropping seasons at maturity.

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

The four plants as described above were used to measure the LAI as reported by Yan et al. (2016): at the VT stage, leaf length (L) and width (W) were measured, and leaf area (LA) was calculated as $LA = L \times W \times K$, where $K = 0.75$ for fully expanded leaves and $K = 0.5$ for incompletely expanded leaves (Bertin and Gallais, 2000). LAI was then calculated as the sum of the green leaf area of the four plants divided by the area occupied by those plants. A portable non-dispersive CO_2/H_2O infrared gas analyzer (LC*pro*-SD, ADC BioScientific Ltd. UK) was used to measure the net photosynthetic rate under natural sunlight. Three ear leaves of maize at the VT stage were chosen in each plot to measure net photosynthetic rate. At maturity, 12 consecutive maize ears in the center of each plot were chosen to measure barren ear tip length. At VT stage and maturity, in each plot, six subsamples of soil were collected from 0 to 20 cm depth using a stainless steel auger then composited into a single sample. To reduce the soil sample variation, the soil sampling site was followed as an 'S' route. The soil Olsen-P concentration was measured by the molybdovanado phosphatase method with 0.5 M $NaHCO_3$ at pH 8.5 (Olsen, 1954). The number of kernels was determined in five samples of 200 kernels each.

2.4. Statistical analysis

SAS software (SAS 8.0, USA) was used for the statistical analysis and for fitting data to a linear-plateau model.

3. Results

3.1. Soil Olsen-P concentration, shoot biomass at maturity, kernel number per spike

Soil Olsen-P concentration significantly increased as the P application rate increased (Fig. 2). For maximal shoot biomass, the critical level of P application was 15.3 kg ha^{-1} in 2014 and 18.0 kg ha^{-1} in