Field Crops Research 209 (2017) 1–9

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Short Communication

Arbuscular mycorrhizal fungal colonization is considerable at optimal Olsen-P levels for maximized yields in an intensive wheat-maize cropping system

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ARTICLE INFO

Keywords:
Calcareous soil
Critical Olsen-P levels
Rotation
P management

ABSTRACT

The occurrence and significance of arbuscular mycorrhizae (AM) are incompletely known in intensive cropping systems with high inputs of phosphorus (P). In this two-year study of an intensive wheat-maize rotation system on calcareous soil, we investigated plant growth and root colonization by indigenous AM fungi as affected by varied P application rates at different growth stages. Wheat growth was more responsive than maize to increasing P supply, but AM fungal colonization was greater for maize. Linear-plateau relationships were obtained between soil Olsen-P and plant growth and AM fungal colonization, through which critical Olsen-P values for optimum plant growth and AM fungal colonization inhibition were quantified. For both crops, the critical Olsen-P levels for AM fungal colonization inhibition (30.7 mg kg^{-1} at the jointing stage and 24.1 mg kg^{-1} at the flowering stage for wheat, 22.3 mg kg^{-1} at the 12-leaf stage and 11.0 mg kg^{-1} at the flowering stage for maize) were higher than those for optimum plant growth (21.8 mg kg^{-1} at the jointing stage and 21.9 mg kg^{-1} at the flowering stage for wheat, 6.2 mg kg^{-1} at the 12-leaf stage for maize). Considering the whole system, maintaining soil Olsen-P levels around 22 mg kg^{-1} is optimal for best yields. Under such conditions, wheat and maize maintained relatively high status of AM fungal colonization, especially for maize, indicating AM might still play an efficient role for both crops.

1. Introduction

Intensive agriculture, currently the main food production system, is characterized by high resource input and high productivity. Typically, intensive cropping systems usually use substantial phosphorus (P) fertilizers (Tilman, 1999; Childers et al., 2011; Li et al., 2011). Sustainable management of P is now urgently needed, however, because of scarcity of phosphate rock, a non-renewable resource of P fertilizers (Neset and Cordell, 2012; Ober, 2016; Sattari et al., 2016), and the negative effects of extensive P fertilization on the environment (Sharpley et al., 1994; Conley et al., 2009). Phosphorus use efficiency may be increased and dependent on P fertilizers thereby decreased by maximizing root/rhizosphere efficiency to improve P acquisition, which highlights the significance of plant and microbial strategies to efficiently acquire P (Lynch, 2007; Ramaekers et al., 2010; Shen et al., 2013).

Arbuscular mycorrhizae (AM), symbioses between AM fungi and more than 80% terrestrial plants, have been well known for their multifunctionality in both natural and agricultural ecosystems, especially facilitating P uptake (Newsham et al., 1995; Smith and Read, 2010). Nonetheless, the benefits generated by AM symbioses have usually been reported in natural ecosystems or in low-input or organic agricultural systems (Plenchette et al., 2005; Gosling et al., 2006; Mahmood and Rizvi, 2010). In intensified farming systems, only a few in-situ field studies have been made to indicate the importance of interactions between AM fungi and plants (Covacevich et al., 2007; Grigera et al., 2007; Wang et al., 2015; Zhang et al., 2016). As reported, colonization of roots by AM fungi (and perhaps the consequent benefits to host plants) generally decreases with increasing P supply (Jensen and Jakobsen, 1980; Al-Karaki and Clark, 1999; Kahiluoto et al., 2001), P fertilization and subsequently high soil P status in intensive cropping systems is often considered detrimental to activity and functions of AM fungi (Ryan and Graham, 2002; Plenchette et al., 2005). However, increased abundance of AM fungi and facilitation of P uptake was discovered during the reproductive stages in high-yielding maize systems with medium to high soil P availability, suggesting that AM

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http://dx.doi.org/10.1016/j.fcr.2017.04.004
Received 23 January 2017; Received in revised form 5 April 2017; Accepted 7 April 2017

fungi might still play an efficient role for such intensified cropping systems (Grigera et al., 2007). Researches concerning the effects of soil P availability on AM formation and functioning have usually been conducted by biologists or microbiologist, in which the extreme conditions of P starvation versus P sufficiency in laboratory or glasshouse have been mostly used. As a consequence, understanding of in-situ AM formation and functioning under the range of soil P levels typical of intensive agriculture is relatively limited.

Agronomists working in intensive cropping systems are mostly concerned about good crop growth response through P fertilization, whereas agricultural environmentalists are working on solving the environmental problems caused by soil P accumulation through excessive fertilization (Sharpley and Wang, 2014). Thus to maximize crop yield without environment damage, a ‘building-up and maintenance’ approach for soil P management has been developed and used in most intensive cropping systems in developed countries and some fast developing countries, e.g. China (Sharpley et al., 2003; Li et al., 2011). This approach aims at adjusting soil available P status from those threatening P deficiency (very low P-status) or environment pollution (very high P-status) to the level of ensuring stable crop yield (medium or optimum P-status), which is higher than the critical value needed to sustain high crop yield and lower than soil P leaching level (Li et al., 2011). This approach does not focus on annual soil P change and influence on roots and microbial mechanisms for efficient P uptake, which might hide the importance of plant and microbial strategies in P utilization, especially for the accumulated P in soil after fertilization (Withers et al., 2014). For AM, it is under the agronomic optimal soil P supply that knowledge of formation and functioning is needed.

To better use the resources, many intensive cropping systems adopt crop rotation. Soil P status required for best yield are likely to differ depending on the plant species in the rotation (Föhse et al., 1988). In a maize-soybean rotation system, for example, the optimum soil P supply for soybean is lower than that for maize (Dodd and Mallarino, 2005; Howard, 2006), because rhizosphere acidification and consequent P availability is greater with soybean as a result of nodulation (Hinsinger et al., 2003). Wheat and maize are two gramineous crops often rotated (Berzsenyi et al., 2000; Cui et al., 2010), but maize usually produces its maximum yield at lower soil P availability and is less responsive to P fertilization than wheat (Tang et al., 2009). Both crops can develop association with AM fungi although maize is often regarded to have higher AM dependency (Habte and Manjunath, 1991; Tawaraya, 2003). As soil P level influences both plant growth and AM fungal colonization, it is desired to know how much difference exists between the two crops in growth and AM fungal colonization in response to different soil P supply, and thus to guide P management in such rotation system for better formation and functioning of AM.

In the present study, a two-year field research was carried out in a wheat-maize rotation cropping system on calcareous soil of the North China Plain, which is a main area of intensive agriculture in China (Meng et al., 2012). We hypothesized that AM fungal colonization could maintain considerable under the agronomic optimal soil P levels for production, and maize would have a lower requirement of optimum soil P supply for best growth with higher AM fungal colonization than wheat. Thus, the objectives of the study were to (1) quantify the relationships between soil and plant P status, plant growth and root colonization by indigenous AM fungi at different growth stages for both plants, and to (2) further determine the optimal soil P supply for both crop growth and AM fungal colonization.

2. Materials and methods

2.1. Site description

The experimental site is located at the Quzhou Experimental Station of the China Agricultural University, Quzhou County, Hebei Province, China (36°52′N, 115°02′E). Quzhou County is a typical area of intensive agriculture on calcareous soil of the North China Plain, and more than 80% of the agricultural fields in the county follow a wheat-maize rotation. The annual mean temperature is 13.2 °C, and the mean annual precipitation is 494 mm, with about 30% of the precipitation occurring during the wheat growing season. The soil is an alluvial loam, with basic soil properties as follows: pH7.3 (water:soil ratio 2:1), organic matter 10.3 g kg^{-1}, total N 0.67 g kg^{-1}, available P (Olsen-P) 7.0 mg kg^{-1}, and exchangeable K 74 mg kg^{-1}.

2.2. Experimental design

The field study was conducted from October 2009 to October 2011 based on a P fertilization experiment starting from October 2008. In the following text, 2009–2010 and 2010–2011 cropping year are recorded as 2010 and 2011, respectively. Before the establishment of the experiment, this field was under wheat-maize rotation cropping for two years without fertilization. In each rotation year, wheat was sown in early October and harvested in mid-June of the following year; maize was then immediately planted and harvested at the beginning of October. To quickly build up the range of soil available P levels, the P application rates were used as follows: 0, 25, 50, 100, 200 and 400 kg P ha^{-1} for wheat, 0, 12.5, 25, 50, 100 and 200 kg P ha^{-1} for maize, respectively. Each treatment had four replicate plots, with each plot having an area of 43.2 m^2 (5.4 m × 8 m). Each plot was treated with the same relative level of P in each season; for example, the plots treated with the highest level of P in wheat season were also applied the highest application in the following maize season. Same varieties of wheat (Kenong 9204) and maize (NE15) were planted during the two years.

After straw was cleared at the end of a growth season but before the next crop was sown, the following fertilizers were broadcast and mixed into the topsoil by plowing: all P treatments in the form of calcium superphosphate, 75 kg N ha^{-1} as urea, and 50 kg K ha^{-1} as potassium sulfate. As in conventional practice, 150 kg N ha^{-1} as urea was top-dressed at the jointing stage for wheat and at the 12-leaf stage for maize, respectively. To compensate for low precipitation in growing season, wheat was flood irrigated three times (50 mm of water each time) at the pre-wintering, jointing and flowering stages. Maize was flood irrigated with 50 mm of water once at sowing. Pesticides and herbicides were applied as needed and according to conventional practice.

2.3. Sampling and analysis

In each growth season, samples of shoot, root and soil were taken at the jointing and flowering stages for wheat, and at the 12-leaf and flowering stages for maize, respectively. At each sampling time, all wheat plants were sampled along a 0.5-m length of each of two rows per plot, and three maize plants were sampled per plot. Plant samples were separated into shoots and roots. Shoot samples were oven-dried at 60 °C, weighed for shoot dry weight, and then milled for determination of shoot P concentration. Roots were sampled at 0–20 cm depth and were washed clean for analysis of AM fungal colonization. Soil cores (0–20 cm depth) were taken at five locations between plant rows and mixed to yield one sample for each plot; the soil samples were air-dried, ground, and passed through a 2-mm sieve before analysis of available P. At maturity, plants in the center of each plot were harvested to determine grain yield.

Shoot P concentration was measured by the molybdo-vanadophosphate method after samples were digested in concentrated H_2SO_4 and H_2O_2 (Shi, 1986). Soil available P level was determined as Olsen-P using the molybdo-vanadophosphate method by extracting soil samples with 0.5 M $NaHCO_3$ at pH8.5 (Pierzynski, 2000). Root AM fungal colonization was measured according to Phillips and Hayman (1970) with some modification. Root samples were cut into 1-cm pieces, cleared with 10% KOH in a 90 °C water bath for 1 h, rinsed with water,