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Contribution of interspecific interactions and phosphorus application to sustainable and productive intercropping systems

Hai-Yong Xia[a,c], Zhi-Gang Wang[a], Jian-Hua Zhao[b], Jian-Hao Sun[b], Xing-Guo Bao[b], Peter Christie[a,d], Fu-Suo Zhang[a], Long Li[a,*]

[a] Key Laboratory of Plant and Soil Interactions, Ministry of Education, Center for Resources, Environment and Food Security, China Agricultural University, Beijing 100193, China
[b] Institute of Soils, Fertilizers and Water-Saving Agriculture, Gansu Academy of Agricultural Sciences, Lanzhou 730070, China
[c] Crop Research Institute, Shandong Academy of Agricultural Sciences, Jinan 250100, China
[d] Agri-Environment Branch, Agri-Food and Biosciences Institute, Newforge Lane, Belfast BT9 5PX, UK

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ABSTRACT

Rational soil/rhizosphere-plant phosphorus (P) management strategies in intercropping systems are poorly understood. Three years of field experiments with different rates of P fertilizer (0, 40 and 80 kg ha^{-1}) as main effects and maize (*Zea mays* L.) intercropping with oilseed rape (*Brassica napus* L.), turnip (*Brassica campestris* L.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.) and soybean (*Glycine max* L.) with the respective monocultures as subplot effects were carried out to study the influence of fertilizer P application on productivity, shoot P content, apparent recovery of fertilizer P and soil Olsen-P in intercrops and monocultures. Average total grain yields and shoot P contents of maize/turnip, maize/faba bean, maize/chickpea and maize/soybean intercropping increased by 30.7%, 24.8%, 24.4%, and 25.3% and by 44.6%, 30.7%, 39.1%, and 28.6%, respectively, compared with the weighted means of the corresponding monocultures, and were highest at 40 kg P ha^{-1}. Moreover, the average apparent recovery of fertilizer P of the intercropping systems increased from 6.1% to 30.6% at 40 kg P ha^{-1} and from 4.8% to 14.5% at 80 kg P ha^{-1} compared with overall monoculture systems on average over three years. The results indicate that intercropping and a rational P application rate (e.g. 40 kg P ha^{-1}) maintained maximum total grain production and shoot P content, P balance of inputs/outputs and soil Olsen-P at an appropriate level (21.3 mg kg^{-1}), and maximum apparent recovery of fertilizer P (30.6%) through exploitation of the biological potential for efficient acquisition of P and other resources by interspecific interactions toward a sustainable and productive agricultural system.

1. Introduction

As agriculture intensifies phosphorus (P) is of increasing concern as it is a limited and non-renewable resource (Cordell et al., 2009; Gilbert, 2009) and this calls into question the sustainability of current P fertilizer use in developed and emerging countries (Hinsinger et al., 2011). Crop production in China has been greatly increased with the help of increasing P fertilizer inputs but overuse of P by farmers has led to low P use efficiency and increasing environmental risk and accumulation of P in soils (Ma et al., 2010; Ma et al., 2011). On the North China Plain, one of the major areas of intensive crop production, the total P input is 92 kg ha^{-1} yr^{-1} and the total P agronomic output is 39 kg ha^{-1} yr^{-1}, so that the net P input is 53 kg ha^{-1} yr^{-1} (Vitousek et al., 2009). This contrasts with the midwestern USA where there are 14 kg ha^{-1} yr^{-1} of total P input, 23 kg ha^{-1} yr^{-1} of total P agronomic output and –9 kg ha^{-1} yr^{-1} of net P input (Li et al., 2011a).

Only 15–20% of the P applied in China is recovered by plants during the current growing season (Zhang et al., 2008a,b) and the remainder accumulates in soil P pools. A net input of 242 kg P ha^{-1} on average, based on the values of P inputs from fertilizer P and outputs from crop harvest, accumulated in the soils during the 27-year period from 1980 to 2007, leading to an average of 24.7 mg kg^{-1} of soil Olsen-P in 2007 from an average of 7.4 mg kg^{-1} in 1980 (Li et al., 2011a). Current soil Olsen-P ranges from 17.5 mg kg^{-1} in the middle-lower Yangtze plain to 25.4 mg kg^{-1} in South China and can exceed 40 mg kg^{-1} on 9.3% of the arable land (Li et al., 2011a). At 40 mg kg^{-1} soil Olsen-P there is a risk of P leaching in many Chinese soil types (Zhong et al., 2004). In most parts of northwest China, although there have been somewhat lower P inputs than in other parts of the country, it has been estimated that P over-fertilization has still occurred and has led to relatively high Olsen-P

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[*] Corresponding author. Tel.: +86 10 62734684; fax: +86 10 62731016.
E-mail address: lilong@cau.edu.cn (L. Li).

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concentrations ranging from 15 to 20 mg kg^{-1} in 2007 from a value of < 10 mg kg^{-1} in 1980 according to Li et al. (2011a).

It is therefore important to increase P use efficiency through optimizing fertilizer P application for the current growing season and to devise ways of better utilizing the P that has accumulated in the soil by exploiting the biological potential of plants in cropping systems.

Increasing shoot P content of crops without further increasing P inputs requires greater exploration and exploitation of accumulated P fertilizer in the soil and current P fertilizer application. Scientists are trying to achieve this by breeding cultivars that are more P-efficient and will make better use of soil P through altered root architecture and rhizosphere-related traits (Vance et al., 2003; Lynch, 2007). However, this may take a considerable amount of time. Another option may be ecological intensification of agricultural ecosystems (Cassman, 1999) by using crop diversity where there is niche complementarity and interspecific facilitation between crop species to enhance productivity and P utilization (Fridley, 2001; Li et al., 2007; Zhang et al., 2010).

Intercropping enhances crop diversity (which has been declining as development of modern intensive agriculture has proceeded) and also increases utilization of resources i.e. land, light, water and nutrients (Francis, 1985; Vandermeer, 1989; Li et al., 2001; Zhang et al., 2008a,b; Mao et al., 2012). In the last few decades some intercropping systems in China, notably wheat/maize, wheat/soybean, and maize/faba bean intercropping, have been investigated, especially with respect to the advantage of phosphorus uptake (Li et al., 2001, 2003a,b, 2007). However, most studies have focused on understanding the mechanisms behind shoot P content facilitation in these intercropping systems, for instance maize/faba bean and maize/chickpea intercropping in terms of complementarity and facilitation and have provided convincing evidence of specific rhizosphere processes (Li et al., 2003c, 2004, 2007; Zhou et al., 2009; Hinsinger et al., 2011). These studies have explained the enhanced shoot P content of P efficient species and P inefficient species grown together. However, to our knowledge, there are fewer data available on optimizing fertilizer P application, P accumulation in soil and the recovery of P fertilizer in intercropping systems under field conditions over periods of several years.

The objective of the present study was to test the hypothesis that intercropping suitable crop combinations at a rational P application rate will maximize productivity and also enhance the apparent recovery of P fertilizer through increasing shoot P content by interspecific interactions in the quest toward sustainable and productive maize-based intercropping systems under field conditions over a period of several years.

2. Materials and methods

2.1. Site description

The field experiments were conducted in 2009, 2010 and 2011 at Baiyun Experimental Station, Institute of Soils, Fertilizers and Water-Saving Agriculture, Gansu Academy of Agricultural Sciences, Gansu province (38°37′N, 102°40′E), located 15 km north of Wuwei City, Gansu province, at an altitude of 1504 m above sea level. Annual mean temperature is 7.7 °C. Cumulative temperatures 0 and 10 °C is 3646 and 3149 °C, respectively. The frost-free period is 170–180 days. Total solar radiation is 5988 MJ m^{-2} yr^{-1}. Annual precipitation is 150 mm and potential evaporation is 2021 mm. The area is classified as having a typical arid climate and the soil at the site is classified as an Aridisol (serozem). At the start of the present study in 2009 the soil pH (water) was 8.0, the soil contained 19.1 g organic matter, 1.08 g total N, 20.3 mg Olsen-P, and 233 mg exchangeable K per kilogram of dry soil in the top 20 cm of the soil profile. Bulk density was determined in six 20-cm depth categories using the cutting ring method (Blake and Hartge, 1986) and was 1.40 g cm^{-3} (0–20 cm), 1.40 g cm^{-3} (20–40 cm), 1.40 g cm^{-3} (40–60 cm), 1.30 g cm^{-3} (60–80 cm), 1.25 g cm^{-3} (80–100 cm), and 1.20 g cm^{-3} (100–120 cm).

2.2. Experiment design and crop management

The experiment was a split-plot design with three replicates. The main plot treatments comprised a zero P control and two application rates of P (40 and 80 kg P ha^{-1}, applied as triple superphosphate) and the sub-plot treatments consisted of maize (*Zea mays* L. cv. Zhengdan no. 958) intercropping with oilseed rape (*Brassica napus* L. cv. Longyou no. 1), turnip (*Brassica campestris* L. cv. Gannan no. 4), faba bean (*Vicia faba* L. cv. Lincan no. 5), chickpea (*Cicer arietinum* L. cv. Longying no. 1), soybean (*Glycine max* L. cv. Huaxia no. 1), soybean (*G. max* L. cv. Wuke no. 2) and the corresponding monocultures. Because maize intercropped with rape in 2009 showed a significant yield decrease, turnip was substituted for rape in both 2010 and 2011, and because soybean cv. Huaxia no. 1 failed to produce pods (with a consequent absence of seeds) in 2009, it was replaced by soybean cv. Wuke no. 2) in both 2010 and 2011.

All intercropped and monocropped plots were planted in an east–west row orientation. The area of each individual plot was 4.0 × 5.5 m^2 for monocropped maize, turnip, rape, faba bean, chickpea and soybean, and 5.6 × 5.5 m^2 for the intercropping systems. Each intercropped plot consisted of four strips in which the width of each strip was 1.4 m, and two rows of maize alternating with three rows of beans, turnip or rape were planted in each strip; the inter-row distance was 40 cm for monocropped and intercropped maize and 20 cm for monocropped and intercropped beans, turnip and rape and there was a 30-cm-wide gap between maize rows and associated crop rows in the intercropping systems. The inter-plant distance was 20 cm for maize and legumes; turnip and rape were planted by broadcast sowing in each row. The spacing was specifically designed to represent typical intercropping practices in the region. Maize occupied 57% of the intercropped area and the other crop occupied 43%. To compare intercropping with monoculture, the density of maize or other crops in the intercropped plots was designed to be equal to that in the monoculture, based on the overall proportional density of each crop species.

Legumes, rape and turnip were given an identical N application rate of 112.5 kg ha^{-1} as urea, which was 50% of the total N fertilizer application for maize. All the P fertilizer and 112.5 kg ha^{-1} of the N were evenly broadcast and incorporated into the upper 20 cm of the soil prior to sowing. The other half of the N fertilizer for maize was divided into two portions applied with irrigation at the maize stem elongation stage and the pre-tasseling stage. No K or organic manure was applied. During the growth period all plots were adequately irrigated and weeded manually. No fungicides were applied to either crop. At the peak flowering stage omethoate (2-dimethoxyphosphinoylthio-*N*-methylacetamide) (Dazhou Xinglong Chemical Co., Ltd., Dazhou, China) was used as a foliar spray to control aphids on faba bean in all three years.

The sowing dates were 27 March in 2009, 28 March in 2010, and 22 March in 2011 for faba bean, chickpea, turnip and rape; and 20 April in 2009, 26 April in 2010 and 28 April in 2011 for maize and soybean. The harvest dates were 28 June in 2010 and 30 June in 2011 for turnip, 29 July in 2009, 28 July in 2010 and 30 July in 2011 for faba bean and chickpea, 7 August in 2009 for rape, 31 August in 2009 and 2010 and 2 September in 2011 for soybean, and 5 October in 2009, 8 October in 2010 and 14 October in 2011 for maize. The sowing dates of maize and soybean were almost one month later than rape, turnip, faba bean and chickpea and the harvest dates of maize were almost three months later than turnip, two months