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Contribution of interspecific interactions and phosphorus application to increasing soil phosphorus availability in relay intercropping systems

Xiaochun Wang[a], Xiaoyan Deng[a], Tian Pu[a], Chun Song[b], Taiwen Yong[a], Feng Yang[a], Xin Sun[a], Weiguo Liu[a], Yanhong Yan[c], Junbo Du[a], Jiang Liu[a], Kai Su[a], Wenyu Yang[a,d,*]

[a] *College of Agronomy, Sichuan Agricultural University, Chengdu, China*
[b] *College of Environment, Sichuan Agricultural University, Chengdu, China*
[c] *College of Animal Science and Technology, Sichuan Agricultural University, Chengdu, China*
[d] *Key Laboratory of Crop Ecophysiology and Farming System in Southwest, Ministry of Agricultural, Chengdu, China*

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ABSTRACT

Maize-based intercropping, especially with legumes, can result in increased yields of the whole cropping system and lead to efficient utilization of soil phosphorus (P). Field experiments were conducted for two consecutive years to investigate the mechanisms behind the increased yields of maize by increasing soil P availability in intercropping systems and how P application and companion crops influenced the process. The planting patterns and P fertilizer application rates significantly affected P taken up by maize. The increased yields of maize – average increases of 22.67 and 12.60% for maize (*Zea mays*)/soybean (*Glycine max*) and maize/sweet potato (*Dioscorea esculenta*)intercropping, respectively; and 12.60 and 7.17% for maize/soybean and maize/sweet potato after P fertilization, respectively – indicated that the interspecific stimulation of P uptake may be a general phenomenon controlled by soil P availability and crop species. Under the maize/soybean intercropping system, considerable facilitation was observed when roots were not kept separate; suggesting that selective enrichment of competent species may be responsible for increased P uptake during intercropping. Positive interactions were supported by soil P activation processes that increased P availability, such as pH changes and acid phosphatase activity. In the intercropping of maize/soybean, acid phosphatase activity was significantly higher than that of maize/sweet potato. In accordance, soil acidification increased with root interaction. Soil acidification increased in maize/soybean intercropping with root contact as did acid phosphatase activity especially in P-deficient soil, which enhanced soil P availability. It was concluded that there was indeed P activation when maize grew with root interactions in the maize/soybean and maize/sweet potato systems. However, the facilitation was stronger in P-deficient soil. Interspecific interactions and P application together contributed to the yield advantage of intercropping.

1. Introduction

Phosphorus (P), a necessary nutrient for plants and animals, is a major limiting factor for crop yield. Farmers in many areas of China have resorted to using higher than the recommended levels of fertilizer to achieve higher yields. During 1981–2009, net anthropogenic P input had an upward trend across mainland China, with P input for 1981, 1990, 2000 and 2009 of 190, 295, 415 and 465 kg P ha^{-1} yr^{-1}, respectively (Han et al., 2013). Most P fertilizer is produced from phosphate rocks, and these fertilizers have contributed greatly to increased crop yields in recent decades, but the reserves of phosphate rock are finite. Recent estimates of the reserves suggest that at the current rate of use this resource will be exhausted within some hundreds of years (Dawson and Hilton, 2011).

The intensive and excessive use of P fertilizers has resulted in low P use efficiency and increased environmental risks. The P seasonal utilization efficiency is only 15–25% (Yang et al., 2012), leading to high P concentrations in soilsand eutrophication of surface water (Haynes and Williams, 1992; Liao et al., 2008; Thuynsma et al., 2013). The rapid increase in human mobilization of P has

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[*] Corresponding author at: College of Agronomy, Sichuan Agricultural University, Chengdu, China.
E-mail address: wenyu.yang@263.net (W. Yang).

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raised concerns over its supply security(Suh and Yee, 2011). Over the last 20 years, crop yield has not increased proportionately with increasing fertilizer inputs (Zhang et al., 2010). Since there is a large P accumulation in soils, improving crop utilization of native soil P is necessary and could reduce agricultural demand for non-renewable mineral phosphates and increase sustainability of Chinese intensive agriculture. Achievement of high P use efficiency is an approach to mitigate the negative impacts associated with P consumption.

Therefore increasing the utilization rate of P fertilizer is quite necessary. Two main strategies have been investigated to improve plant utilization of P: (i)rational fertilization, particularly for P is one of the most important measures to improve crop yield and simultaneously protect the environment from surface water eutrophication(Li et al., 2011);and (ii)crops that can efficiently access native or residual-fertilizer Pin soils may require fewer external P inputs, thereby reducing the loss of nutrientsand consumption of non-renewable mineral phosphates in agricultural systems (Li et al., 2013; Nyfeler et al., 2011). Increasing P uptake without further increasing P inputs requires greater exploration and exploitation of accumulated P fertilizer in the soil and current P fertilizer application.

Intercropping, an important agricultural system for meeting local food demand and ensuring food security in China, can enhance agro-biodiversity in farms and also increase utilization of resources due to below-ground root interactions between intercropped species (Inal and Gunes, 2008; Xiao et al., 2010). Resources may be used more efficiently than in corresponding monocultures and overyielded compared with monocropping and also maintained the stability of most of the soil chemical and enzyme activities relative to monocropping(Yang et al., 2013; Wang et al., 2015). Beneficial effects of intercropping on nutrient uptake, especially with respect to P have been widely investigated in many studies on different cropping systems, notably soybean/sorghum (Ghosh et al., 2009), wheat/maize (Knörzer et al., 2011), maize/peanut (Xiong et al., 2013) and cucumber/onion (Zhou et al., 2011). The usual explanation is that the two intercropped species do not compete for exactly the same resource niche, and so tend to use resources in a complementary way – provided that they have, for example, contrasting nitrogen (N) or P utilization efficiencies.Both niche complementarity and interspecific facilitation contribute to increased P acquisition in cereals/legumes intercropping systems (Xue et al., 2016). As discussed by Latatiet al. (2016), common bean–maize intercropping can enhance N and P nutrition and increase resource use in P-deficient soil resulted in improved grain yield.Another explanation is that P-efficient species may increase P mobilization in the rhizosphere by acidification. This may then increase P availability for less P-efficient crops. Compared with corresponding sole crops, yield advantages have been recorded in many legume/non-legume intercropping systems, which are known to show increased yields due to legume N fixation, including maize/faba bean. Applying above- and below-ground partitions indicated that component crops usually compete intensely for soil resources (Li et al., 2007). However, most studies have focused on understanding the mechanisms behind shoot P content facilitation in intercropping systems (e.g. maize/faba bean and maize/chickpea) in terms of complementarity and facilitation and have provided convincing evidence of specific rhizosphere processes. To our knowledge, most attention in intercropping studies has been on explaining the enhanced shoot P content of P-efficient and P-inefficient species grown together. There are fewer data available on optimizing fertilizer P application and P accumulation in soil and crop rotations to enhance soil P availability in intercropping systems.

Quantifying the beneficial or competitive effects of soil resources, particularly nutrient use in intercropping is an important research issue. The legume/non-legume intercropping system is still not understood adequately as compared to sole cropping. Fertilizer schedules are mainly determined for sole cropping and may not meet the nutrient demand of component crops in an intercropping system, because competition between component crops for nutrients may be more pronounced for intercropping.

We conducted a field experiment and a root-partition pot experiment on maize-based intercropping systems with soybean and sweet potato respectively, for two years to investigate the effects of different application rates of fertilizer P and crop rotation on yield advantage, maize growth and the possible physiological mechanisms involved in the utilization of P in rhizosphere soil, with regard to the complementary and competitive interactions between maize and soybean (or sweet potato) plants. The physiological mechanisms tested were available P concentration, changes in pH and acid phosphatase (APase) activity in rhizosphere soil. Our hypotheses were that facilitation would be greater under low P conditions, and that maize/soybean intercropping was an efficient cropping system in southwest China.

2. Materials and methods

2.1. Site description and soil properties

The field and pot experiments were conducted in 2012–2013 at Ya'an (29°98′N, 103°0′E) experimental site of Sichuan Agricultural University, located in Sichuan Province, China. The trail soil is classified as a Purple soil (Luvic Xerosols, FAO classification). At the start of the study the soil pH (water) was 6.59, organic mattercontent 29.2 g kg^{-1}, available N 60.1 mg kg^{-1}, Olsen-P 26.0 mg kg^{-1},exchangeable K 99.6 mg kg^{-1} of dry soil in the top20 cm soil layer.

2.2. Experimental set-up and plant growth

2.2.1. Field experiment

The field experiment was a split–split design. The main plot treatment was either maize/soybean or maize/sweet potato relay strip intercropping, and the subplot treatment was P application rates of maize at 0 (P_0), 35 (P_{35}), 70 (P_{70}), 105 (P_{105}) or 140 (P_{140}) kg/ha P_2O_5, applied as superphosphate. Each treatment had three replicates with area of each individual plot being 4.0 m × 5.0 m. Maize and soybean (or sweet potato) occupied 50% of the intercropped area respectively. The ratio of maize:soybean (or maize:sweet potato) was 2:2. Maize and soybean were planted in alternating 2 m wide strips, including 1-m wide for two rows of maize with 0.4 m inner-row distance and the next 1 m width for two rows of soybean (or sweet potato) also with 0.4 m inner-row distance. In the second year, the experiment was rotated according to strips, which meant that the two intercropped crop strips were exchanged, such that maize was grown on strips that had soybean (or sweet potato) in the previous year, and similarly for soybean (or sweet potato). Inter-plant distance within the same row was 0.38 m for maize and 0.17 m for soybean (or sweet potato). Each treatment consisted of two strips: one used to collect samples for biomass and measurement and analysis of nutrient concentration during growth and the other for harvest yield at maturity. All plots received N fertilizer at 240 kg/ha as nitrate N and potassium (K) fertilizer at 90 kg/ha K_2O to eliminate N and K limitations. All P and K fertilizer and a half of N were applied and incorporated into the top 20 cm of the soil before sowing of maize, and the other half of N fertilizer was applied as panicle fertilizer. In the two years, dates of sowing were 7 April and 5 April for maize, and 12 June and 7 June for soybean (or sweet potato) respectively. Dates of harvesting were 4 August and 2 August for maize, and 25 October and 22