Field Crops Research 216 (2018) 100–108

Contents lists available at ScienceDirect

Field Crops Research

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

Can optimization of phosphorus input lead to high productivity and high phosphorus use efficiency of cotton through maximization of root/mycorrhizal efficiency in phosphorus acquisition?

Wenxuan Mai[a,b,d,*], Xiangrong Xue[a,b], Gu Feng[c], Rong Yang[a,b], Changyan Tian[a,b]

[a] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[b] State Key Laboratory of Oasis Ecology and Desert Environment, Urumqi 830011, China
[c] College of Resources and Environment, China Agricultural University, Beijing 100083, China
[d] Changji National Agricultural Science and Technology Park, Changji, 831100, China

ARTICLE INFO

Keywords:
Cotton
Root
Phosphorus
Hyphal density
Nutrient uptake

ABSTRACT

Although the root/mycorrhizal processes determine phosphorus (P) uptake by crops and P fertilizer use efficiency, knowledge of the plasticity of cotton root/mycorrhizal processes in response to changes in soil P content is lacking. A field experiment was conducted in 2015 and 2016 to investigate the effects of P fertilizer treatments (0, 75, 150, and 300 kg P_2O_5 ha^{-1}) on root/mycorrhizal processes and P uptake by cotton plants. The main aim was to explore the possibility of achieving high P fertilizer use efficiency and high yield simultaneously by optimization of P fertilizer application. A low P application rate (75 kg P_2O_5 ha^{-1}) not only increased root length and hyphal density simultaneously, but also enhanced the spatial distribution of cotton roots in the soil, thereby also increasing the apparent phosphorus recovery (APR). However, P uptake and cotton yield were highest under treatment with 150 kg P_2O_5 ha^{-1}. Thus, it is difficult to maximize APR and cotton yield simultaneously. If the production target is to obtain a relatively high yield (80–90% of the highest potential yield), then root/mycorrhizal efficiency in P acquisition can be maximized through optimization of the soil available P content. The optimum soil available P content observed in this study was 15–20 mg kg^{-1}.

1. Introduction

Efficient utilization of soil phosphorus (P) has attracted worldwide attention. On the one hand, P is a non-renewable resource, while on the other hand, in intensive agriculture, large amounts of inorganic P fertilizers are applied to overcome soil P deficiency and result in P accumulation in the soil. For example, in China, from 1980 to 2007, the average P cumulative in farmland soil over 242 kg P ha^{-1} and resulting in soil available P content increased from 7.4 to 24.7 mg kg^{-1} (Li et al., 2011). Changes in soil available P content in cotton fields in Xinjiang are similar to those of other crop farmland; in the past 30 years, the soil available P content has increased from 4.8 to 16.8 mg kg^{-1}, equivalent to more than 1.68 million t of pure P in the soil (Chen et al., 2010). Therefore, the soil availability of P in cotton fields in Xinjiang has changed from deficiency to excessive accumulation. However, because of the unique properties of P in soil, such as low solubility, low mobility, and high fixation by the soil matrix, the recovery of applied P by crops in one growing season is often low (Vance et al., 2003). Therefore, enhancing P fertilizer use efficiency (to reduce P fertilizer input), while maintaining high crop yields in sustainable agriculture, has become a focus of soil science research for plant nutrition, agriculture, and crop breeding.

To enhance P acquisition, plants and root-associated microbes have evolved a series of strategies that include modified root growth and functioning, for example, root growth to increase the root:shoot ratio, modified root architecture, decreased root diameter, enhanced specific root length (root length per unit root mass), higher root hair length and/or density, and production of aerenchyma (Haling et al., 2016). These morphological adaptations can greatly enhance the volume of soil exploitable by the roots and/or enable exploitation of P-rich patches. The distribution and dynamics of P in the soil shows considerable spatio-temporal variation. A root architecture that distributes more roots to the location of P resources plays an important role in efficient exploitation of P resources.

In addition to root system architecture and morphology, mycorrhizal symbioses can also increase the spatial availability of P, extending the nutrient-absorptive surface area by formation of mycorrhizal hyphae. Arbuscular mycorrhizal fungi (AMF) form symbiotic

---

[*] Corresponding author at: Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China.
E-mail address: maiwenxuan@sina.com (W. Mai).

https://doi.org/10.1016/j.fcr.2017.11.017
Received 26 September 2017; Received in revised form 15 November 2017; Accepted 15 November 2017

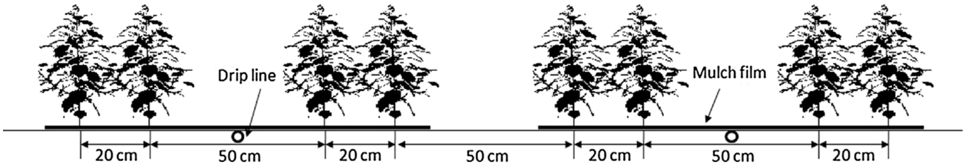

Fig. 1. Plant spacing and irrigation system used in the experiment. Four rows of cotton plants were planted under a mulch film, and an irrigation drip line was laid in the center of the mulch film. All irrigation drip lines in the experimental plot were connected to the main irrigation pipe, and a fertilizer tank, switch and water meter were installed on the main irrigation pipe to control the amount of water and fertilizer applied.

associations with the roots of about 74% of angiosperms (Smithand Read, 2008), including cotton (McGee and Pattinson, 1999). A primary benefit of AMF is the improved P uptake conferred on mycorrhizal plants. In the symbioses, P is transferred to plants by AMF via their extensive mycorrhizal mycelium, while in return the fungi receive carbon from the plant. In low-P soils mycorrhizal plants usually show superior growth to non-mycorrhizal plants as a consequence of enhanced direct P uptake of plant roots via the AMF pathway. A ^{32}P experiment indicated that over 50% of P uptake by wheat plants was absorbed via AMF, even when P was applied (Li et al., 2006). It has been estimated that inoculation with AMF might result in a reduction of approximately 80% of the recommended fertilizer P application rate under certain conditions (Jakobsen, 1995).

Thus, arbuscular mycorrhizal plants have two pathways for P uptake from soil, namely direct and AMF P-uptake pathways. Root architecture and mycorrhizal hyphae growth play important roles in maximization of P acquisition because root and mycorrhizal systems with a higher surface area are able to explore a given volume of soil more effectively (Lynch and Ho, 2005). Therefore, P uptake by plants is predominantly controlled by spatial availability and acquisition of P as determined by plant root architecture as well as mycorrhizal association.

Plants show plasticity in root growth in response to P application (Lynch, 2011). P deficiency causes reduced growth of primary roots and enhanced length and density of root hairs and lateral roots in many plant species (Doerner, 2008; López-Bucio et al., 2003), and increases the exploited soil space and root–soil contact to increase P uptake (Schachtman et al., 1998; Wang et al., 2016). Application of phosphate fertilizer has a significant influence on the growth of AMF, although P fertilizer may inhibit the colonization rate of mycorrhizal fungi (Smith and Read, 2008). Thus, even in a high-input intensive crop production system, the role of mycorrhizal fungi in P resource acquisition and utilization cannot be ignored (Grigera et al., 2007).

Maximization of the efficiency of root and mycorrhizal pathways in P acquisition for high-yield and high-efficiency sustainable cotton production by optimization of P nutrient input is important. The aim of the present study was to determine the effects of P fertilizer application on the spatial distribution of cotton roots, mycorrhizal growth, and P uptake by cotton plants, and to determine the optimum P nutrient input, so as to attain high cotton productivity and high P use efficiency through maximization of root/mycorrhizal efficiency in P acquisition.

2. Materials and methods

The field experiment was carried out at the Xiaoguai Experimental Station of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, in Urumqi, China, during the 2015 and 2016 cropping seasons. The site has an arid climate typical of the area, with average annual rainfall of 105.3 mm, annual evaporation of 2692 mm, 2705 annual sunshine hours, accumulated temperature $\geq 10\,^{\circ}C$ of 3760 °C, and 232 frost-free days per year.

The soil type at the study site is a gray desert soil typical of the region. The soil was analyzed before sowing. The chemical properties of the 0–30 cm soil layer were as follows: extracted mineral nitrogen $16.7\ mg\ kg^{-1}$, pH (H_2O) 8.1, soil density $1.33\ g\ cm^{-3}$, Olsen P $11.2\ mg\ kg^{-1}$, NH_4OAc-extracted potassium $208.9\ mg\ kg^{-1}$, and organic matter $5.3\ g\ kg^{-1}$.

2.1. Experimental design

The experiment included four P treatments (0, 75, 150, and 300 kg $P_2O_5\ ha^{-1}$, defined as P0, P75, P150 and P300 respectively) applied during two cropping seasons (2015 and 2016). A randomized block design with three replicates was used. There were 12 plots in total, and the area of each plot was 6 m × 5.6 m. Border plots were included on the margins of the experimental field to eliminate border effects. Weed growth within the plots was controlled with pre-emergence herbicides.

Seeds of cotton (*Gossypium hirsutum*) 'XinLuZao50' were obtained from the Xinjiang Academy of Agricultural Sciences, China, and sown on 4 May 2015 and 28 April 2016 at an identical density of 220,000 plants ha^{-1}. Two rows (20 cm apart) were sown on either side of an irrigation drip line, with 50 cm spacing between the first row and the drip line, and spacing of 10 cm between plants within a row, mulch film covered the soil surface of the two rows on each side of the drip line (Fig. 1).

The rates and timing of water and fertilizer application were consistent with the local cotton agronomic practices. The total volume of water supplied was $4000\ m^3\ ha^{-1}$.

The four P fertilizer (superphosphate) treatments and 150 kg $K_2O_5\ ha^{-1}$ (potassium chloride) were applied before sowing as a basal dressing. In addition, urea as a nitrogen fertilizer was applied at the rate of 350 kg N ha^{-1}, of which 20% was applied before sowing as a basal dressing, and the remainder was applied with irrigation. The specific water and fertilizer applications in each treatment are summarized in Table 1.

2.2. Plant harvest

2.2.1. Shoots

Plants were harvested at the peak bolling stage at 118 and 123 days after sowing in 2015 and 2016, respectively. Four plants were harvested from each plot (two plants each from adjacent rows). The shoots were divided into leaves, stems, and reproductive organs. All samples were killed at 105 °C for 30 min, then dried at 70 °C until a constant weight was attained. The dry weight was recorded and subsamples were taken to measure the P content using the standard vanado-

Table 1
Water and nitrogen fertilizer applications with the drip irrigation under mulch film (DI) system. Note: '–' indicates no nitrogen application.

Total water and nitrogen			Date of application										
		2015	5 May	17 May	29 May	10 Jun	22 Jun	4 Jul	14 Jul	24 Jul	4 Aug	14 Aug	26 Aug
		2016	29 April	12 May	24 May	6Jun	17Jun	1Jul	12Jul	20Jul	1Aug	12Aug	23Aug
Water($m^3\ ha^{-1}$)	4000		200	200	300	400	400	500	500	500	400	300	300
Nitrogen(kg N ha^{-1})	270		–	–	–	20	30	40	40	50	50	40	–