Root/Rhizosphere Management for Improving Phosphorus Use Efficiency and Crop Productivity

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J. Shen Image

Field performance of maize based on rhizosphere nutrient management.

The rhizosphere (root-soil interface) is the most important area for plant-soil-microorganism interactions, and is the hub for controlling nutrient transformation and plant uptake (Zhang et al., 2010), particularly for P due to its high fixation, low mobility, and low bioavailability in soil. Although the rhizosphere is often conceptually considered to be a thin layer of soil surrounding the root, the rhizosphere is actually a wider, interactive dynamic zone affected by various soil physical, chemical, and biological processes (York et al., 2016). Plants are able to sense changes in their surrounding environment and optimize the absorption of water and nutrients by modifying rhizosphere processes. Keeping an appropriate supply intensity of nutrients in the root zone can promote root growth and enhance rhizosphere processes, but a limited or oversupply of nutrients can repress these positive effects. Although plants have developed adaptive mechanisms to their environmental conditions through evolution, it is important that we maximize beneficial rhizosphere processes to take full advantage of the biological potential of roots to improve nutrient use efficiency and crop productivity in farming systems.

Rhizosphere Management Strategies

Rhizosphere management is defined as the manipulation of different components of the rhizosphere ecosystem, based on a better understanding of rhizosphere processes, to optimize plant root-soil-microbial interactions and achieve sustainable, positive effects (Zhang et al., 2010; Shen et al., 2013). The efficiency of rhizosphere processes is highly dependent on the combined influence of a soil's inherent fertility and the input of external nutrient resources, and is greatly reduced if root growth and expansion are limited by soil nutrient deficiency. With increasing nutrient supply, the efficiency of rhizosphere processes can be increased. However, excessive application of fertilizers may lead to high concentrations of soluble nutrients in the root zone, which can also restrict root growth and rhizosphere efficiency

SUMMARY

Rhizosphere processes affect soil P availability and efficient use of P by plants. This paper summarizes the principles of root/rhizosphere management, and highlights case studies on how to exploit root-soil-microbe interaction processes to improve crop productivity and P use efficiency.

KEYWORDS:

root zone, rhizosphere processes, localized nutrients, intercropping, plant-microbe interactions

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus; AMF = arbuscular mycorrhizal fungi; PGPR = plant growth-promoting rhizobacteria; ACC = aminocyclopropane carboxylic acid

https://doi.org/10.24047/BC103136

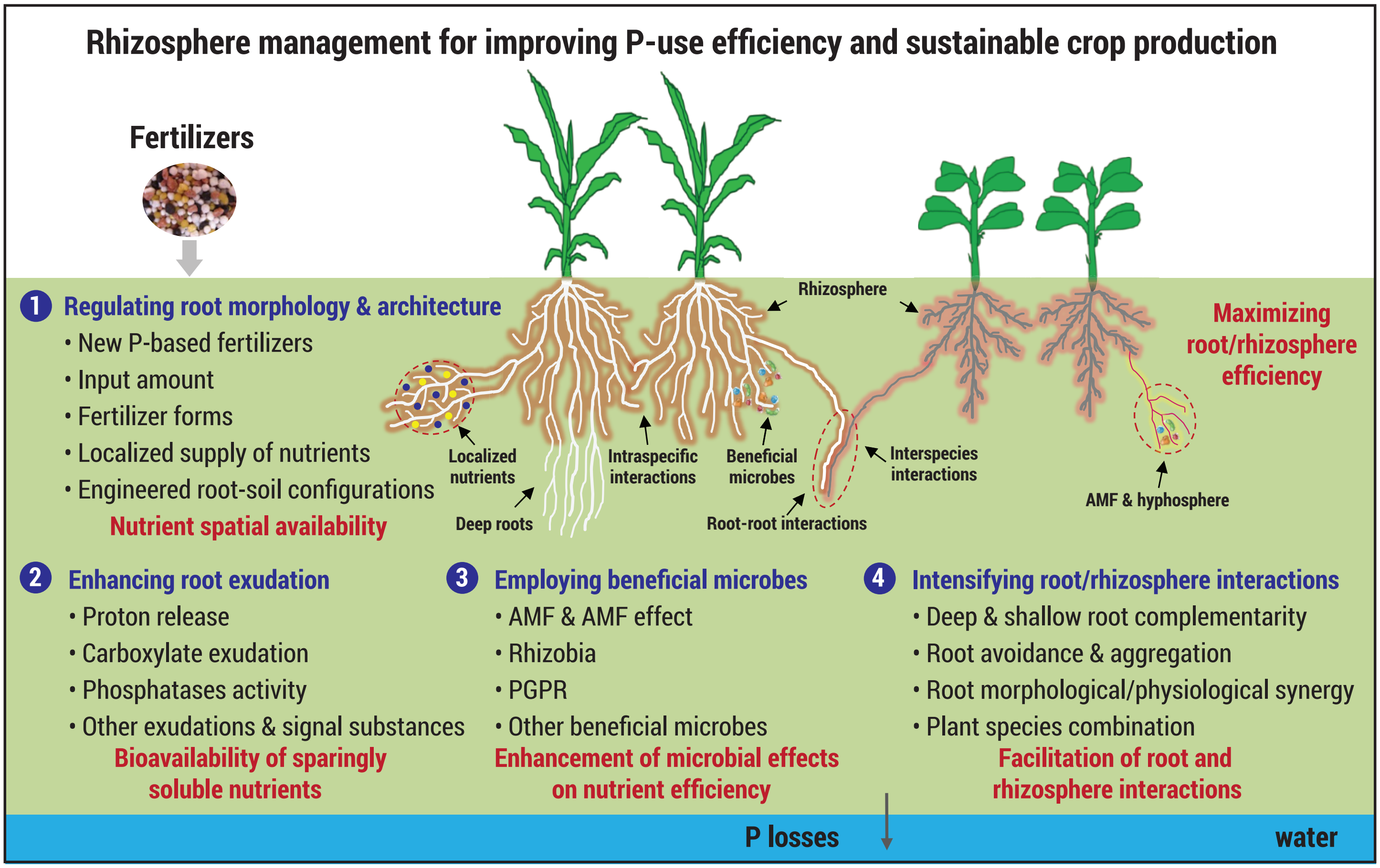

Figure 1. Rhizosphere management strategies for sustainable P use in cropping systems.

(Shen et al. 2011). The regulation of root growth by nutrient supply intensity in the root zone is closely related to crop growth stage. For example, spring maize root systems are very small and soil P availability is relatively low due to low temperature during their early growth stages, but seedlings have a high P requirement. To tackle these incongruities, precision regulation of rhizosphere and root zone nutrients is needed. Therefore, the alteration of root growth and rhizosphere processes can provide an effective approach to improve nutrient use efficiency and crop productivity.

Rhizosphere management strategies emphasize maximizing the efficiency of root and rhizosphere processes involved in nutrient mobilization, acquisition, and use by crops, rather than relying solely on the high use of mineral fertilizers in intensive farming systems (Shen et al., 2013; Jiao et al., 2016). Rhizosphere management strategies include: 1) regulating root morphology and architecture by adjusting the quantity, composition and manner of nutrient supply; 2) increasing the bioavailability of sparingly soluble nutrients by manipulating root exudation; 3) improving the uptake of immobile nutrients by employing mycorrhizal fungi and other beneficial microorganisms; 4) intensifying rhizosphere interactions through interspecies interactions by intercropping (**Figure 1**). The overall goal of rhizosphere management is to increase nutrient use efficiency, improve crop yields, optimize mineral fertilizer inputs, and achieve sustainable crop production by optimizing and integrating a range of beneficial rhizosphere interactions.

Case Studies on Rhizosphere Management for Improving Phosphorus Use Efficiency

1. Root Zone Nutrient Management by Localized Nutrient Supply

Plants can acquire P from soils, which is essential for their growth. Plant roots can influence the processes occurring at the root-soil interface through physiological metabolic activities, to improve the bioavailability of soil P. Studies have shown that plants can efficiently obtain soil P by changing root morphology and physiological characteristics. For example, P-efficient maize roots can occupy greater soil volumes by increasing the density and length of lateral roots under conditions of P deficiency. The intensity of P supply regulates root growth and modifies the chemical and physiological processes in the rhizosphere. A study in the North China Plain showed that maize maintained optimal root efficiency in terms of mycorrhizal infection, root surface area, and root growth vitality at a topsoil (0 to 20 cm) Olsen-P of 5 to 10 mg/kg, and at the same time maintained the maximum yield (Deng et al., 2014). The results showed that maintaining the correct P supply intensity in the root

Figure 2. The responses of root morphology and physiology to P supply. (a) Roots and root hairs of maize proliferated in P-banding zone. (b) Purple color indicated rhizosphere alkalization (+P, 250 µmol/L P) and yellow color indicated rhizosphere acidification (-P, 0 µmol/L P) of alfalfa. (c) Yellow color indicated rhizosphere acidification of maize in P-free nutrient solution.

zone can enhance P use efficiency by crops.

Plant roots have high plasticity to the heterogeneous distribution of nutrients in soils (**Figure 2**). Drew (1975) showed that localized supply of nitrate (NO_3^-) or P increased the number of lateral roots in barley. The nutrients serve as signals to stimulate root development and growth. Studies suggested that localized supply of superphosphate combined with ammonium-N (NH_4^+-N) significantly stimulated root proliferation, especially of fine roots, and thus improved maize growth in a calcareous soil. The supply of NH_4^+-N promoted H^+ release from the roots and thus decreased rhizosphere pH, resulting in increased P bioavailability (Jing et al., 2010). Further studies indicated that localized supply of P and NH_4^+-N at both seeding and later growth stages increased maize yield by 8 to 10%, P uptake by 39 to 48%, and localized increases in root density and length of 50% (Ma et al., 2013). Compared with conventional nutrient management in an intensive, high input-high output system having excessive amounts of fertilizer being broadcast on the soil surface, this strategy fully considers soil conditions and the biological potential of roots, enhancing nutrient use efficiency by fertilizing roots, not the soil, to maximize root/rhizosphere efficiency.

2. Rhizosphere Interactions in Intercropping

Intercropping systems can improve nutrient use efficiency and crop productivity (Zhang et al., 2010). Most studies on intercropping have focused on aboveground interactions. However, underground interactions can affect the spatial distribution of roots, the morphological characteristics of roots, and physiological processes in the rhizosphere. In maize/fababean intercropping systems, fababean increases P uptake and growth for both itself and neighboring maize plants by secreting organic acids and H^+ into the rhizosphere, thus mobilizing sparingly soluble P (Li et al., 2014). Optimizing nutrient supplies in intercropping systems, as described in the previous section, can further improve nutrient use efficiency and crop yield. Localized supply of P and NH_4^+-N was shown to promote the uptake and use of P in a maize/fababean intercropping system. Root/rhizosphere interactions in maize/fababean were also promoted by having a localized P supply and neighboring crop (Zhang et al., 2016). Exploring root/rhizosphere interactions in cropping systems can greatly reduce P fertilizer input requirements by effectively using P that is already present, but bound, in the soil.

3. Plant-Microbe Interactions in the Rhizosphere

The root-microbe interactions in the rhizosphere are important for plant growth, nutrition, and health (Zhang et al., 2017). Arbuscular mycorrhizal fungi (AMF) help more than 80% of terrestrial plants to acquire P from the soil. Rhizobia can fix N, while P-solubilizing bacteria can increase the amount of available P for plants and assist roots to take-up these nutrients. Plant growth-promoting rhizobacteria (PGPR; e.g., *Variovorax paradoxus 5C2*) can reduce the ethylene content in roots and promote root growth by decomposing the ethylene precursor aminocyclopropane carboxylic acid (ACC) (Belimov et al., 2009). Root exudates play an important role in root-microbial interactions, and

TAKE IT TO THE FIELD

Phosphorus use efficiency can be improved by root zone nutrient management through adopting localized nutrient supplies (subsurface band placement), enhancing root/rhizosphere interactions with intercropping, and manipulating beneficial rhizosphere microorganisms.

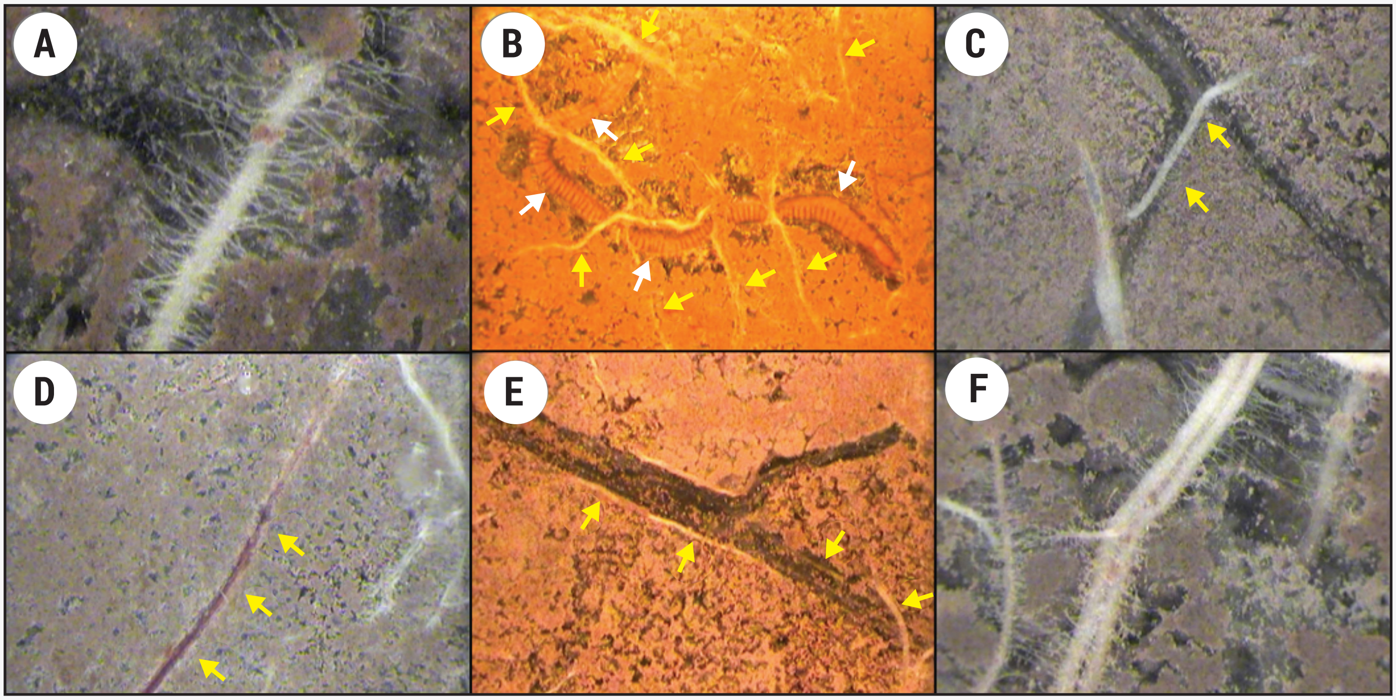

Figure 3. Images showing root-soil-microbial interactions. (a) Maize root hairs and hyphae attach plants to soil particles. (b) Maize roots grow around earthworm and earthworm burrow. (c) Maize root grows along soil pore at an appropriate angle. (d) A biopore formed after a root death. (e) Maize root growing along pores formed by dead root. (f) Maize roots clumped in a soil pore with root hairs contacting sides of pore.

even can act as signals to regulate root-microbe interactions. Some plants secrete large quantities of root exudates into the rhizosphere, which are 'exchanged' for soil nutrients mobilized by soil microbes (Werner et al., 2014). The composition and amount of root exudates affect the composition of microbes in the rhizosphere, and the structure of the rhizosphere microbiome, affecting plant growth and nutrient uptake. For precision rhizosphere management, plant-microbe interactions must be finely tuned to improve P use efficiency by crops (**Figure 3**).

Concluding Remarks

Maintaining crop production with high P use efficiency and low environmental impact to feed a growing global population is a great challenge. Better root/rhizosphere management has been shown to be an effective way of ensuring fertilizer P is efficiently absorbed and used by plant roots. Theoretically, fertilizer P should be applied into the rhizosphere rather than to the whole soil profile, but technically it is hard to achieve this. Precise management of root/rhizosphere processes and interactions can play an important role in the development of effective solutions for the sustainable use of P, given the success of root/rhizosphere-based P management in China. The complexity of root-soil-microbe interactions limits the predictability of impacts of practices like inoculation and other manipulations intended to enhance the benefits. Optimizing root/rhizosphere management and better matching nutrient supply with crop demands to maximize root/rhizosphere interactions are potentially an important way of improving the sustainable use of P in agriculture. **BC**

Acknowledgement

This study was supported by the National Natural Science Foundation of China (31330070, 31772402, 30925024), and the National Key Research and Development Program of China (2017YFD0200200). We thank Dr. Martin Blackwell (from Rothamsted Research, UK) and Prof. Caixian Tang (from University of Western Australia) for helpful revisions and suggestions on this manuscript.

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