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An overview of rhizosphere processes related with plant nutrition in major cropping systems in China

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Abstract

Rhizosphere processes of individual plants have been widely investigated since 1904 when the term 'rhizosphere" was first put forward. However, little attention has been paid to rhizosphere effects at an agro-ecosystem level. This paper presents recent research on the rhizosphere processes in relation to plant nutrition in main cropping systems in China. In the peanut (*Arachis hypogaea* L.)/maize (*Zea mays* L.) intercropping system, maize was found to improve the Fe nutrition of peanut through influencing its rhizosphere processes, suggesting an important role of phytosiderophores released from Fe-deficient maize. Intercropping between maize and faba bean (*Vicia faba* L.) was found to improve nitrogen and phosphorus uptake in the two crops compared with corresponding sole crop. There was a higher land equivalent ratio (LER) in the intercropping system of maize and faba bean than the treatment of no root interactions between the two crops. The increased yield of maize intercropped with faba bean resulted from an interspecific facilitation in nutrient uptake, depending on interspecific root interactions of the two crops. In the rotation system of rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) crops, Mn deficiency in wheat was caused by excessive Mn uptake by rice and Mn leaching from topsoil to subsoil due to periodic cycles of flooding and drying. However, wheat genotypes tolerant to Mn deficiency tended to distribute more roots to deeper soil layer and thus expand their rhizosphere zones in the Mn-deficient soils and utilize Mn from the subsoil. Deep ploughing also helped root penetration into subsoil and was propitious to correcting Mn deficiency in wheat rotated with rice. In comparison, oilseed rape (*Brassica napus* L.) took up more Mn than wheat through mobilizing sparingly soluble soil Mn due to acidification and reduction processes in the rhizosphere. Thus, oilseed rape was tolerant to the Mn-deficient conditions in the rice-oilseed rape rotation. Oxidation reactions on root surface of rice also resulted in the formation of Fe plaque in the rice rhizosphere. Large amounts of Zn were accumulated on the Fe plaque. Zinc uptake by rice plants increased as Fe plaque formed, but decreased at high amounts of Fe plaque. It is suggested that to fine-tune cropping patterns and optimize nutrient management based on a better understanding of rhizosphere processes at an agro-ecosystem level is crucial for increasing nutrient use efficiency and developing sustainable agriculture in China.

Introduction

Currently, crop production in China is characterized by (i) high inputs including seeds, irrigation and various chemicals, (ii) high outputs in term of grain and fiber yields per unit area but with relatively low quality, and (iii) increasing concerns of environmental problems. At present, arable land areas in China are decreasing due to other land uses for non-agricultural purpose. Meanwhile, the population in China is increasing steadily. It is very important to enhance crop yields to meet the increasing food demands. Sustainable development of agriculture has to be based on the rational exploitation of natural resources with minimal negative impact on the environment. Although fertilizer application has been one of the most important

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measures for crop production for a century, the negative impact of fertilizer use on the environment has been of concern recently for several reasons, including distortion of the quality of food and water and decrease in diversity of the flora and fauna. Increasing use efficiency of resources, especially water and soil nutrients either agronomically or genetically, decreasing inputs of chemicals in agriculture has become a worldwide trend.

China is a traditional agricultural country; it supports over 22% of the world population with less than 9% of the world arable land. At present, about 70% of farm-products are attributed to the improved multiple cropping systems. Besides seed and chemical inputs, traditional multiple cropping systems including rotations, intercropping and other cropping systems have contributed greatly to grain production in China agriculture (Liu, 1994; Tong, 1994). China is expecting an annual increase of 10 million populations and an annual decrease of 350,000 ha cultivated land. To support the already large and increasing population with limited and decreasing cultivated land area, China needs to develop sustainable agricultural production systems through optimizing inputs for agricultural production, making efficient use of the limited land resources, improving soil fertility and productivity, increasing farming profitability and improving cropping systems. Optimizing traditional cropping systems and hence enhancing use efficiency of soil nutrients with minimal inputs of chemicals provide an alternative and potential way to develop the sustainable agriculture yet to keep high yields (Zhang and Shen, 1999a). This paper presents several case studies of the plant nutrition problems related to rhizosphere interactions in Chinese cropping systems and assesses potential approaches to deal with these problems based on a better understanding of rhizosphere processes and management.

Improvement of iron nutrition in peanut by the intercropped maize through rhizosphere interaction

Iron chlorosis is one of the most common yield-limiting nutrient problems in calcareous soils for many crops. The response mechanisms of 'Strategy I' plant species to Fe deficiency are characterized mainly by increased reductase activity and enhanced proton release, as well as exudation of reductants from roots (Marschner et al., 1989). Strategy II plant species are characterized by a higher Fe acquisition efficiency through the excretion of phytosiderophores into the rhizosphere (Römheld, 1991). High pH, and high levels of bicarbonate and buffering capacity in calcareous soils impede rhizosphere acidification, Fe^{III} reduction and subsequently Fe uptake. Soil amendments and foliar applications of Fe fertilizers are usually ineffective or uneconomical for correcting Fe chlorosis. Therefore, there is considerable interest in devising practical methods for avoiding or correcting Fe deficiency of crops in Chinese agriculture. A field observation in Henan Province provides a good example. It showed that chlorosis in peanut was much less pronounced when the crop was intercropped with maize than in the monoculture (Zuo et al., 2000). The extent of improvement in the Fe status of the intercropped peanut, represented by chlorophyll and active Fe concentrations in young leaves, increased as the distance between the peanut plants and the associated maize plants decreased (Figure 1).

It is well known that peanut and maize have distinctly different response mechanisms to Fe deficiency. Peanut is classified as a 'strategy I' plant species, while maize belongs to the 'strategy II' group. Thus maize plants have a high resistance to Fe deficiency compared with peanut plants in calcareous soils. Enhancement of Fe nutrition in Fe-inefficient dicots by phytosiderophores excreted by Fe-efficient graminaceous species was previously shown in solution culture experiments (Bryan and Hopking, 1992; Hopking et al., 1992; Römheld, 1991).

Both rhizobox and field experiments were conducted to further investigate nutritional interactions between peanut and maize in intercropping systems. In the rhizobox experiment, neighboring roots of maize and peanut were either allowed to intermingle with each other or were separated by inserting a solid plate between the root systems. As a result, intermingling of peanut and maize roots enhanced the concentrations of HCl-extractable Fe and chlorophyll in young and primary leaves of peanut after 3 months growth (Table 1). These results were further confirmed by a field experiment. The field experiment examined four cropping treatments: peanut monoculture, peanut/maize intercropping, peanut/maize intercropping with plastic plates between their root systems, and peanut/maize intercropping with 30 μm nylon mesh between the root systems. The chlorophyll and active Fe concentrations in young leaves of peanut were higher in the intercropping system with free intermingling of peanuts with maize roots than those in

Table 1. Effect of intercropping peanut with maize on the concentrations of HCl-extractable Fe (mg kg^{-1} DW) and chlorophyll (mg g^{-1} FW) in young and primary leaves of peanut plants. Plants were grown in pots with soil and harvested after 3 months (means ± SD)[a]

Treatment	HCl-extractable Fe (mg kg^{-1}DW)		Chlorophyll (mg g^{-1} FW)	
	Young leaves	Primary leaves	Young leaves	Primary leaves
No root interactions	21.6 ± 5.7	45.2 ± 4.9	1.5 ± 0.5	5.8 ± 1.2
With root interactions	42.3 ± 4.6	58.6 ± 5.1	4.8 ± 1.1	6.2 ± 1.0

[a]Modified from Zuo et al. (2000).

monoculture (Figure 1). Moreover, the chlorophyll and active Fe concentrations in young leaves of peanut decreased significantly with increase in distance from maize row when roots were intermingled between peanut and maize crops. The results suggested that the improvement of Fe nutrition in peanut intercropped with maize is mainly attributed to the rhizosphere effect of maize (Zuo et al., 2000). The excretion of phytosiderophores by maize into the rhizosphere may play an important role in improving Fe nutrition of peanut crops intercropped by maize crops. Investigations of the qualitative role of root exudates of maize in improving Fe nutrition in peanut are still in progress.

Improvement of nitrogen and phosphorus nutrition in intercropping systems through interspecific rhizosphere interactions

The use efficiency of natural resources can be increased through intercropping of different species. Most studies on the advantages of intercropping in terms of interspecific interactions have been mainly focused on interspecific competitions for light, heat, time and space (Bohringer and Leihner, 1997; Braconnier, 1998; Dauro and Mohamedsaleem, 1995; Dupraz et al., 1998; Helenius and Jokinen, 1994; Piepho, 1995; Jolliffe and Wanjau, 1999; Vandermeer, 1989). Although interspecific facilitation (or positive interactions) in which one plant species enhances the survival, growth, or fitness of another has been demonstrated in many natural plant communities (Callaway and Pugnaire, 1999), there have been few studies on facilitation (especially of nutrient uptake) in intercropping systems. The facilitation in P and N nutrition under intercropping has been reported by Horst and Waschkies (1987) and Ae et al. (1990). White lupin (*Lupinus albus* L.) was shown to increase P uptake by wheat (*Triticum aestivum* L.) (Horst and Waschkies, 1987). Pigeon pea (*Cajanus cajan* L.) enhanced P uptake by sorghum (*Sorghum bicolor* L.) (Ae et al., 1990). In both cases, the observed effect was attributed to the ability of the legume crops to release considerable amounts of organic acids and consequently increased availability of soil phosphorus in the rhizosphere. In addition, the cereals obtained a part of the N from the associated legumes in the intercropping systems between cereals and legumes (Midmore, 1993; Stern, 1993). As a result of the competition for N by cereals, N in the rhizosphere of the legumes was depleted, which subsequently stimulated N_2 fixation by the legumes (Boucher and Espinosa, 1982).

Most areas of northwestern China have a relatively short cropping season for two crops yearly because of low temperature in the winter season. Several intercropping patterns have been widely used with an attempt to maximize crop yields. Effects of intercropping on soil nutrient uptake and interspecific interactions have been investigated in different intercropping systems such as wheat (*Triticum aestivum* L.)/maize, wheat/soybean (*Glycine max* Merr.), maize/faba bean (*Vicia faba* L.) and wheat/faba bean (Li et al., 1999, 2001). In the wheat/maize and wheat/soybean intercropping systems, growth and yield of intercropped wheat in the border row and inner rows were increased compared with the sole wheat system. Wheat showed a higher competitive ability than maize or soybean for nutrients. The significant interspecific facilitation was observed in the maize/faba bean and wheat/faba bean systems. Our results indicated some beneficial effects of maize and faba bean intercropping on crop yields, and suggest that the beneficial effects resulted mainly from the rhizosphere interactions between the two crop species (Li et al., 1999).

Field experiments were conducted to examine the interspecific facilitation and competition of maize and

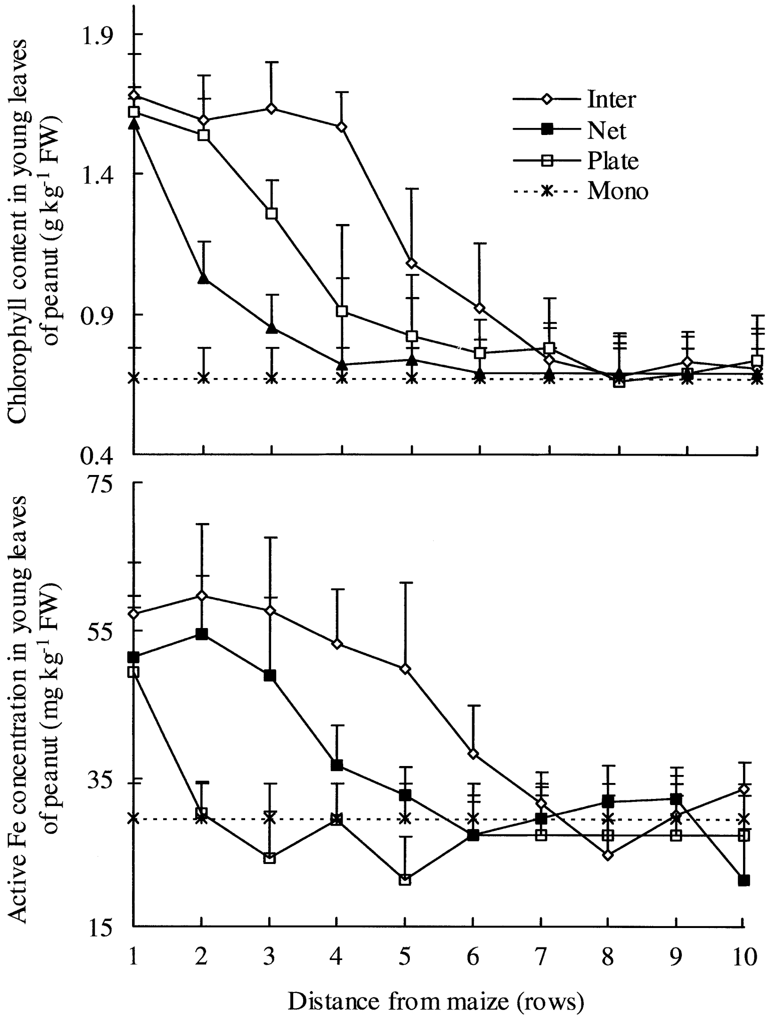

Figure 1. The effects of monocropping and different intercropping treatments on chlorophyll and HCl-extractable Fe concentrations in young leaves of peanut at the flowering stage in field experiment. Values are means of four replicates; bars represent standard deviation. Inter refers to no root barrier between peanut and maize where the roots of maize and peanut were intermingled. Net and Plate refer to a nylon mesh root barrier and solid plastic-plate root barrier inserted between maize and peanut, respectively. Mono refers to monocropped peanut (Calculated from Zuo et al. 2000).

faba bean in the maize/faba bean intercropping. On average, LERs [land equivalent ratio, defined as sum of the ratios of yields of each intercropped and sole crop in a specific intercropping system (Vandermeer, 1989; Willey, 1979)] were 1.21–1.24 for shoot biomass and 1.13–1.43 for grain yields when faba bean and maize were intercropped. Clearly, there was a significant intercropping advantage in this intercropping system. A more detailed experiment with root barrier between faba bean and maize root systems illustrated the mechanisms of interactions of root systems between these two species. There were four treatments in the experiment: (i) a plastic sheet partition inserted into the ground between maize and faba bean to prevent interspecific root interactions, (ii) a 30 μm nylon net partition inserted into the ground between the two species to prevent direct root contacts but allow interactions by mass flow and diffusion, and (iii) a control treatment with no partition between the two crop species to allow complete intermingling of their root systems. The results demonstrated that the advantage of intercropping was mainly derived from interaction of root systems in faba bean/maize intercropping (Table 2). This interaction resulted from intermingling of their root systems (direct root-to-root contact) as well as rhizosphere interactions between

Table 2. Yield advantage of intercropping, nitrogen and phosphorus uptake by intercropped faba bean and maize in the treatments of complete (without root barrier), partial (nylon mesh barrier) and no interspecific interactions (solid barrier) between faba bean and maize root systems under the field condition. Modified from Li et al. (1999) and Li et al. (2003)

Extent to root interactions	LER[a]		N uptake (mg N m^{-1} per 2 rows)			P uptake (mg P m^{-1} per 2 rows)		
	Grain yield	Biomass	Maize	Faba bean	Maize+Faba	Maize	Faba bean	Maize+Faba
No	1.19 b[b]	1.06 b	14.2 b	24.0 b	38.2 b	2.78 c	1.19 b	3.97 c
Partial	1.26 ab	1.12 b	14.6 b	23.3 b	37.9 b	3.25 b	1.32 ab	4.57 b
Complete	1.34 a	1.21 a	17.3 a	28.8 a	46.1 a	3.58 a	1.46 a	5.03 a

[a]Land equivalent ratio (LER), an index of intercropping advantage, is defined as sum of the ratios of yields of each intercropped and sole crop in a specific intercropping system (Vandermeer, 1989; Willey, 1979). If LER is greater than 1.0, there is an advantage of intercropping.
[b]Within each column, means followed by the different letters are significantly different according to a LSD test at 0.05 level.

the two species. Nutrient uptake in the treatment of nylon net partition was intermediate between those of plastic sheet partition and no partition, indicating that the effect of intercropping was due to root exudates (Li et al., 2003). Moreover, the rhizosphere of the two species can be overlaid with each other due to intermingling of their root systems, causing more intense rhizosphere effect. However, quantitative contribution from root exudates to interspecific facilitation still needs further investigation.

Interspecific complementary interactions for nitrogen and phosphorus uptake between maize and faba bean in the intercropping system were also investigated. Nitrogen uptake by intercropped faba bean was 20% higher than that by sole faba bean during early-growth stages and at maturity (Table 2). Nitrogen uptake by intercropped maize was 22% higher than that by sole maize at maturity. Maize and faba bean root intermingling was advantageous to nitrogen uptakes by both faba bean and maize (Li et al., 2003).

Intercropping also improved phosphorus nutrition in both maize and faba bean. Phosphorus concentrations of the intercropped maize shoot were not higher than those in the sole maize during the early-growth stages, but were significantly higher in the later growth stages and at maturity. Intercropping also increased phosphorus uptake by faba bean at the flowering and maturity stages (Table 2). Phosphorus uptake in faba bean and maize increased by 23% and 29%, respectively, when their roots were allowed to interact freely in the treatment of no root barrier. The P uptake only increased by 11% and 17%, respectively, when their roots had a partial interaction in the treatment of nylon mesh barrier compared with P uptake of the plants with plastic plate barrier. Clearly, interactions of root systems or rhizosphere between maize and faba bean played an important role in interspecific facilitation of phosphorus uptake (Figure 2) (Li et al., 1999, 2003; Zhang et al., 2001; Zhang and Li, 2003). These results suggest once more a rhizosphere effect that is likely to be related to root exudation and increased phosphate mobilization.

Improvement of manganese nutrition in rice-wheat or rice-oilseed rape rotation systems by rhizosphere processes

The rice-wheat rotation system accounts for 27 million ha and feeds more than 1 billion people around the world (Timsina and Connor, 2001). In south Asia, the sustainability of rice-wheat system is low due to a number of problems, particularly the gradual decline of soil fertility and productivity (Harrington, 2000; Kumar and Yadav, 2001). In China, however, the rice-wheat rotation system has been practiced for more than a millennium and has made great contribution to meeting the food requirement since around 900 AD (Ellis and Wang, 1997). Many studies have shown the advantages of this rotation on agricultural resource utilization, soil quality, and high yield under integrated nutrient management (Aulakh, et al., 2001; Gami et al., 2001; Singh et al., 2000). Few studies, however, were focused on the nutrient improvement through rhizosphere interactions in the rice-wheat rotation systems (Wang, 2001). Manganese deficiency in wheat is a typical nutritional disorder in rice-wheat rotation particularly on coarse-textured soils, resulting in the reduction of wheat yield by 30–50% (Lu, 1992; Nayyar et al., 1985). Periodic change in soil water conditions, as one of the most important characteristics in rice-wheat rotation, greatly alters the availability of soil Mn, and further affects Mn uptake by rice and wheat crops (Ponnamerperuma, 1972; Liu, 1997). Leaching of Mn in soil profile particularly from topsoil and luxurious Mn uptake by rice during sub-

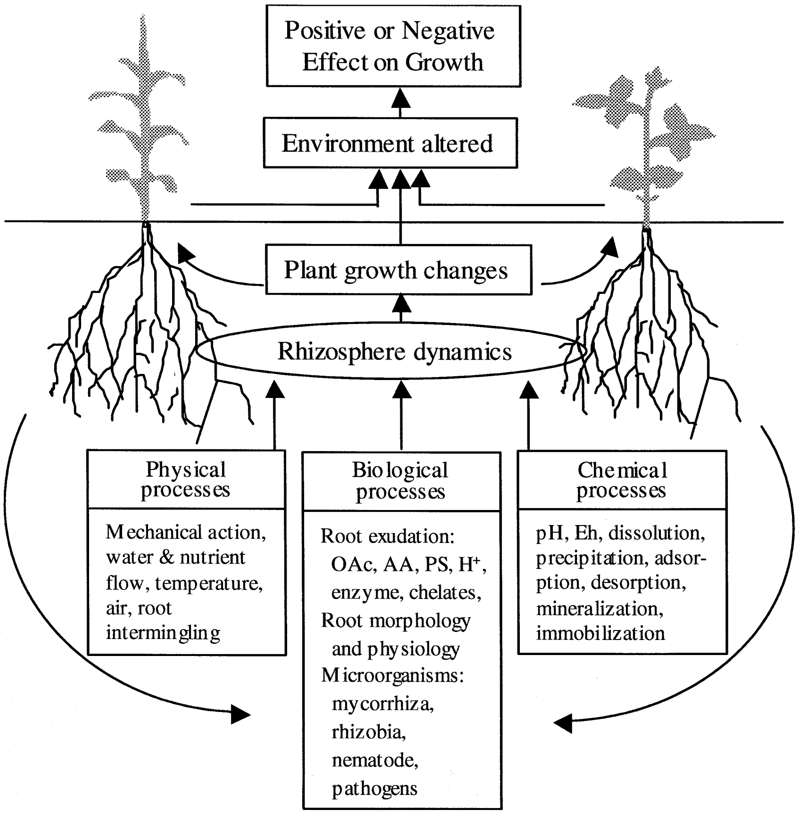

Figure 2. Rhizosphere processes and interactions between two species of crops. Rhizosphere processes include physical, chemical and biological processes, by which interactions of root system between two species of crops occur. Integrated interactions involving above- and underground parts between two species of crops result in positive or negative effect on crop growth in the intercropping systems. The abbreviations represent: OAc, organic acids; AA, amino acids; PS, phytosiderophores; H^+, protons.

mergence of soils in traditional flooded season are the main reasons for the low availability of soil Mn to wheat (Liu et al., 1999a). In addition, in the wheat phase of the rotation, Mn is strongly adsorbed by the freshly precipitated Fe oxides. Wheat crops are inefficient at absorbing Mn, particularly at low temperature, resulting in Mn deficiency. A soil-column experiment was set up to compare the effects of wetting (no water layer covering soil) and continuous flooding on Mn availability in sandy and clay loam soils. Flooding significantly increased the concentrations of water soluble and exchangeable Mn, and led to the leaching losses and excessive removal of Mn by rice in both soils (Table 3). Manganese distribution in the soil profile changed significantly with long-term rice-wheat rotation (Liu et al., 2002). Both total and available Mn contents were very low in the topsoil but increased substantially in the subsoil. The spatial distribution of Mn in soil profiles, caused by the alternate cycles of flooding and drying, led to Mn deficiency in the successive wheat crops in the rotation (Lu et al., 2004). Interestingly, under the same field conditions, oilseed rape (*Brassica napus* L.) crops did not develop Mn deficiency.

The different responses to Mn deficiency by wheat and oilseed rape mainly resulted from the difference in root distribution and rhizosphere interactions between the two crops (Fang, 1998; Lu et al., 2002). First, the wheat cultivars (N02 or 942) used in the studies of Fang (1998) and Lu (2002) had a high-yielding potential but were sensitive to Mn deficiency. Oilseed rape responded to a pretreatment of Mn starvation by increasing Mn uptake by 4–6 folds (Table 4). In contrast, the wheat cultivars N02 and 942 showed little response. The wheat cultivar 80-8 was more tolerant to Mn deficiency. After a 2-week pretreatment of Mn starvation, there was a clear reduction-color in the agar sheet along the roots of the wheat genotype 80-8 and a significant increase in the Mn concentration in the shoots, suggesting a clear rhizosphere effect related

Table 3. Effect of water conditions (flooding and wetting) on soil available Mn, leaching of Mn and plant Mn nutrition during rice growing season in two alluvial soils. Flooding represents continuous water layer (2–3 cm depth) covered on soil and wetting represents no obvious water layer on soil. Results are the means (± SD) of three replicates (modified from Liu et al., 1999a)

Water condition	Readily reducible Mn (mg kg^{-1})	Exchangeable Mn (mg kg^{-1})	Mn leached (mg column^{-1})	Mn uptake by rice (mg column^{-1})	Rice dry matter (g column^{-1})
			Sandy loam		
Flooding	40.5 ± 7.2b[a]	14.7 ± 2.3a	37.8 ± 10.7a	4.2 ± 1.0a	14.3 ± 0.2a
Wetting	84.8 ± 5.4a	8.5 ± 1.2b	5.9 ± 2.2b	0.8 ± 0.1b	12.5 ± 2.6a
			Clay loam		
Flooding	145.2 ± 7.4b	69.7 ± 8.1a	15.0 ± 5.3a	24.1 ± 7.8a	34.4 ± 2.5a
Wetting	193.0 ± 4.6a	28.0 ± 5.5b	0.7 ± 0.3b	3.9 ± 0.5b	33.6 ± 2.3a

[a] Values with different letters in the same column are significantly different at 0.05 level.

Table 4. Mn concentrations (mg kg^{-1}) in the shoots of wheat and oilseed rape genotypes. Plants were grown in complete nutrient solution for two weeks and then were pre-treated with (+Mn) or without Mn (−Mn) for another two weeks. Afterward, the pre-treated plants were transplanted into agar sheets containing 1 mM $KMnO_4$ and other essential nutrient elements, and colour indicator for Mn reduction. Plants were harvested after 72-h culture. The wheat genotype 80-8 with root distribution in deep soil was tolerant to Mn deficiency, while the genotypes 942 and N02 were sensitive to Mn deficiency. The oilseed rape genotypes CY44 and CY11 were highly tolerant to Mn deficiency (Modified from Fang, 1998)

Pre-treatment in nutrient solution	Mn supply in agar	Wheat genotype			Oilseed rape genotype	
		N02	942	80-8	CY11	CY14
−Mn	1 mM	83a	80a	104a	290a	356a
+Mn	1 mM	81a	79a	75b	48b	72b
Difference[a]		NS	NS	**	***	***

[a] NS, ** and *** represent not significant, significant at 0.05 and 0.001 levels.

with the increased root reduction ability or reductant exudation and Mn mobilization. Second, the shallow root system of wheat in soil profile restricted Mn uptake from Mn-deficient topsoil (Liu, 1997). Third, oilseed rape could mobilize sparingly soluble Mn from soil through acidification and reduction processes in the rhizosphere.

Liu et al. (1999b) reported that deep rooting wheat genotypes (e.g. 80-8) were more tolerant to Mn deficiency, indicating that the penetration of wheat roots or the downward extension of wheat rhizosphere contributed to overcoming Mn deficiency under the rice-wheat rotation. Deep ploughing helped root penetration into subsoil and thus significantly improved shoot Mn nutrition of wheat following rice compared with control (Table 5). In addition, the growth and Mn nutrition of rice and growth of successive wheat could also be improved by injecting Mn fertilizer solution to root zone of rice and thus increasing the availability of Mn in the rhizosphere of rice under non-flooded rice-wheat rotation systems (Table 6).

In summary, the above results suggest that optimizing Mn management based on a better understanding of the rhizosphere processes involved is necessary to improve Mn nutrition of crops in the rice-wheat or rice-oilseed rape rotation systems.

Effect of iron plaque in rice rhizosphere on nutrient uptake by rice

Oxidation reactions on the root surface due to oxygen release from rice roots is known to result in the formation of Fe plaque in the rhizosphere or on the root surface due to high redox potential along the roots and the high concentrations of Fe^{2+} in the bulk soil (Armstrong, 1967). The effect of Fe plaque in rice rhizosphere on nutrient uptake by rice was examined (Zhang et al., 1998). For example, the amount of Zn accumulated in Fe plaque correlated positively to the amount of Fe plaque. Zinc uptake by rice plants increased as Fe plaque increased to 12.1 mg kg^{-1} root dry weight, but decreased when higher amounts of Fe plaque was formed (Figure 3). Similar results were reported by Kirk and Bajita (1995).

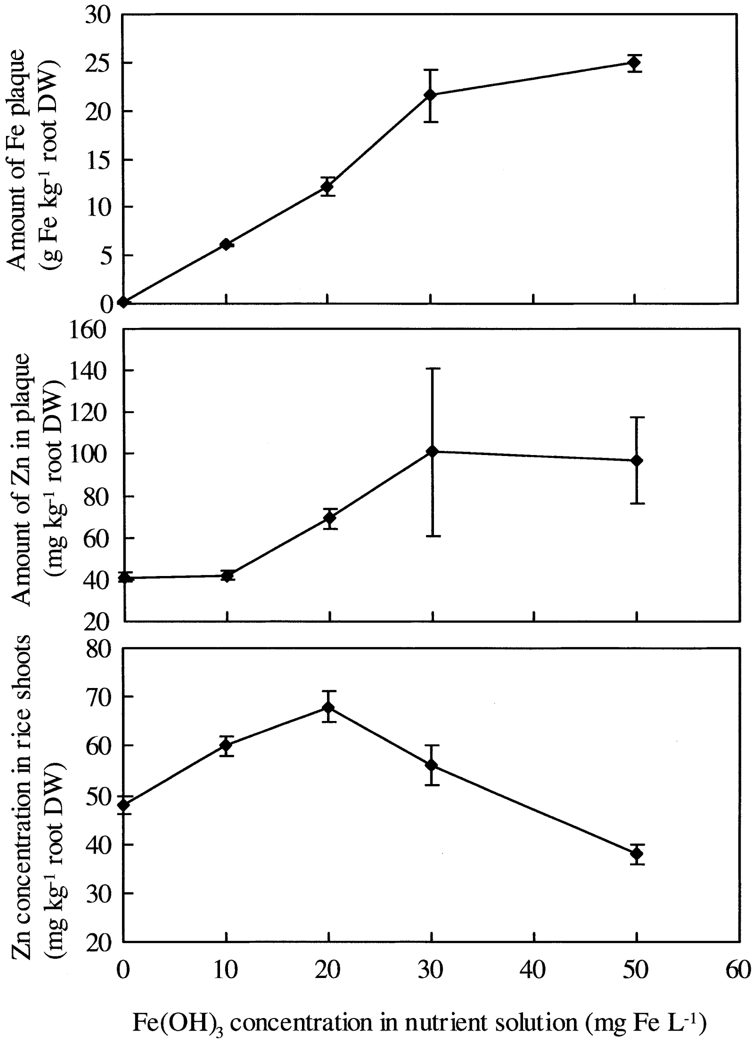

Figure 3. Effect of $Fe(OH)_3$ concentrations in nutrient solution on the amount of Fe plaque on rice root surface, Zn content in Fe plaque and Zn concentrations in shoots of rice plants. Various amounts of Fe plaque were induced by supplying different rate of $Fe(OH)_3$ in nutrient solution for 24 h. The nutrient solution contained 0.065 mg Zn L^{-1}. Bars are the standard errors of the means with three replicates (Calculated from Zhang et al. 1998).

Under Fe deficiency, the increase in Zn concentration in plants could be attributed to phytosiderophores production. The amount of phytosiderophores released from roots of Fe-deficient rice plant was four-fold greater than in Fe-sufficient plants (Zhang et al., 1998). Enhanced release of phytosiderophores by rice plants may mobilize Zn adsorbed to Fe plaque on root surface and enhance Zn uptake. However, when Fe plaque is thick, it inhibits Zn uptake by rice plants because the effective zone of action of root exudates is limited to near root apoplast or in rhizosphere and mean Zn concentration in plaque is diluted. Phytosiderophores rather complex Fe on the root surface and thus decrease Zn mobilization, in which case the Fe plaque becomes a barrier for Zn uptake by rice plants. In addition, ferric hydroxide deposits on the root surface of rice have also been shown to affect the P uptake (Zhang et al., 1999). Iron plaque adsorbed phosphorus from the growth medium, and the amount of phosphorus adsorbed by the plaque correlated with the amount of Fe plaque. The results suggest that Fe plaque formed on the root surface of rice may act as a nutrient pool. Therefore, adjusting rhizosphere processes through optimizing water management and appropriate ploughing in rice production

Table 5. Effect of deep ploughing on Mn concentration in shoots, Mn uptake and grain yield of wheat following rice in a Mn-deficient sandy loam soil. Results are the means (± SD) of three replicates

Treatment	Mn concentration (mg kg^{-1})	Mn uptake (g ha^{-1})	Yield[a] (kg ha^{-1})
	Shooting stage		
Control	14 ± 3 b[b]	18 ± 3 b	1250 ± 210 b
Deep ploughing	27 ± 5 a	44 ± 6 a	1580 ± 340 a
	Harvesting stage		
Control	11 ± 3 b	46 ± 9 b	2160 ± 230 b
Deep ploughing	24 ± 6 a	148 ± 32 a	2930 ± 380 a

[a]At shooting stage, yields represent total biomass of shoots of wheat, and at harvesting stage yields represent wheat grain yields.
[b]Values with different letters in the same column are significantly different at 0.05 level.

Table 6. Effects of Mn fertilizer injected to root zone of rice (rhizosphere) on shoot Mn concentration and grain yield of rice and wheat in non-flooded straw mulching rice-wheat cropping systems

Treatment	Shoot Mn concentration of rice (mg kg^{-1})	Shoot Mn concentration of wheat (mg kg^{-1})	Grain yield of rice (t ha^{-1})	Grain yield of wheat (t ha^{-1})
−Mn	66 b[a]	35 a	4.80 b	5.89 b
+Mn	105 a	38 a	6.01 a	6.52 a

[a]Values with different letters in the same column are significantly different at 0.05 level.

can effectively improve nutritional status of P, Zn, Fe and Mn.

Managing rhizosphere ecosystem toward enhancing crop productivity and nutrient use efficiency

The diversity of cropping systems in China provides a unique field for investigating rhizosphere processes at an agro-ecosystem level. To reveal the mechanisms of rhizosphere interactions in these cropping systems is an important step for better understanding of advantages for efficient resource use in cropping systems and thus fully utilizing these advantages and avoiding disadvantages to optimize crop production. In cropping systems, rhizosphere is not only an interface between root and soil for an individual plant, but also is a center of interaction for plant community (e.g. plant species in intercropping systems), soil, microorganisms and their environment (Marschner, 1995; Zhang and Shen, 1999a, b; Zhang et al., 2002). Therefore, rhizosphere processes should be considered as important ecological processes for a specific crop ecosystem (Rovira, 1991).

Rhizosphere ecosystem can be defined as an ecosystem of energy transfer, matter cycling and information transmission caused by many interactions between plants, soil, microorganisms and their environment (Zhang and Shen, 1999a). According to this concept, the rhizosphere ecosystem is characterized by multi-level components ranging from molecular, individual to community levels. Plants play a dominant role in the interactions between plants, soil, microorganisms and their environment, as proposed by Whipps and Lynch (1986) and Marschner (1995). In the plant-soil system, rhizosphere processes are the linkage between plant processes and soil processes, and to some extent, determine the exchanges of matter and energy between plant and soil and thus affect crop productivity (Zhang et al., 2002). Therefore, it is very important for optimizing crop production to clarify rhizosphere interactions, particularly the mechanisms of nutrient mobilization and utilization related to rhizosphere physical, chemical and biological processes in cropping systems (Figure 2). For these reasons, managing the rhizosphere ecosystem and rhizosphere processes towards sustainable agriculture can be one of the most important ways to enhance nutrient-resource utilization efficiency and crop productivity in main cropping systems in China (Zhang and Shen, 1999a). The roles of rhizosphere microorganisms in the cropping systems are not fully understood and need to be further investigated.

Conclusion

An overview of rhizosphere processes in relation to plant nutrition in the main cropping systems of China has been presented. Rhizosphere processes are significantly modified by the specific cropping patterns of intercropped or rotated plants, which have an important influence on soil nutrient availability. There are clear interspecific rhizosphere interactions in the intercropping systems. More attention should be paid to investigating rhizosphere processes at an ecosystem level, focusing on the interaction processes between plants, soil, microorganisms and their environment at various scales. Managing the rhizosphere ecosystem and regulating rhizosphere processes towards sustainable development may be an effective alternative approach to enhancing nutrient-resource use efficiency and improving crop productivity in various cropping systems.

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