REGULAR ARTICLE

Integrated soil and plant phosphorus management for crop and environment in China. A review

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Abstract

Background Crop production in China has been greatly improved by increasing phosphorus (P) fertilizer input, but overuse of P by farmers has caused low use efficiency, increasing environmental risk and accumulation of P in soil. From 1980 to 2007, average 242 kg P ha^{-1} accumulated in soil, resulting in average soil Olsen P increasing from 7.4 to 24.7 mg kg^{-1}. China is facing huge challenges to improve P use efficiency through optimizing corresponding technology and policies. The problem is exacerbated because people have been shifting their diet from plant-based to animal-enriched foods. This results in higher P load in the food chain and lower P use efficiency.

Scope A multidisciplinary approach has been used to improve P management at the field and national level in China. Management strategies based on the soil and on the plant rhizosphere have been developed to increase efficient use of P. A national soil testing and fertilizer recommendation program has been used since 2005 to control build-up and maintenance of P levels. Interactions between root growth and the rhizosphere have been manipulated in intercropping systems and plant genetic traits have been exploited. Phosphorus surplus is highly associated with animal concentrated feed.

Conclusions The P-saving potential by the integrated P management strategies of P flow reaches 1.46 Mt P in 2050 compared to 2005.

Keywords Building-up and maintenance · Environmental risk · Nutrient management · Phosphorus accumulation and flow · Phosphorus use efficiency · Rhizosphere management

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Introduction

China's population was 1.3 billion in 2008 (19.8% of the world population, FAO Resource STAT 2008), but China has only 7% of the arable land in the world (530 million ha, FAO Resource STAT 2006)., The consumption of Phosphorus (P) fertilizer reached up to 5.3 million metric tonnes (Mt) P in 2006. (The Yearbook of China Statistics 2007). In contrast, only 1.8 Mt P fertilizer were consumed by USA as P on 411 million ha arable land (FAO Resource STAT 2006). Nowadays, excessive P input by farmers occurs in most regions of China. In the North China Plain, one of the major areas for intensive crop production, the total P input was 92 kg ha^{-1} year^{-1}, and the total P agronomic output was 39 kg ha^{-1} year^{-1}, and then the net P input was 53 kg ha^{-1} year^{-1} (Vitousek et al. 2009). This

contrasts with Midwest U.S.A (total P input: 14; total P agronomic output: 23; net P input: −9 kg ha^{-1}year^{-1}). In China, only 15–20% of the P applied was taken up by plants in the growing season (Zhang et al. 2008), and the rest accumulated in the soil P pools. The potential accumulation of P in soil as a result of fertilizer applications to all arable land in China, from 1980 to 2007, was more than 242 kg P ha^{-1}as determined from the balance of P inputs and outputs.

Increases in soil Olsen-P (mg kg^{-1}) (Olsen et al. 1954) per 100 kg ha^{-1} P surplus in the top layer (0–20 cm) were: 1.44 for the Grey Desert soil (Aridisols in ST) in Xinjiang province; 1.60 for Fluvo aquic soil (Inceptisols in ST) in Beijing and Henan province; 2.60–2.75 for Red soil (Ultisols in ST) in Hunan province, 3.53 for Loess soil (Mollisols in ST) in Shaanxi province, 4.44 for Purplish soil (Inceptisols in ST) in Chongqiong city; and 5.74 for Black soil (Udic Mollisoils) in Jilin province (Cao 2006). The differences were caused by different application rates and by different soil types. Application of animal manure accelerated the increase of soil Olsen-P with a rate almost 3 times higher than when only chemical fertilizer at the same amount of P were applied (Li et al. unpublished), which was due to desorption of P from soil minerals caused by manure. From 1980 to 2006, the increase in average rate of P application rate was 5% per year in China. In 1980, the national average for soil Olsen-P was 7.4 mg/kg and on 79.4% of the arable land it was less than 10 mg kg^{-1}. The highest level was 10.3 mg kg^{-1} for the black soil area in Northeast China (Fig. 1a). In the North China Plain, soil Olsen P was only 6.4 mg kg^{-1}, which is much lower than the optimal level for crop growth (20 mg kg^{-1}). In 2006, the average soil Olsen P was 20.7 mg/kg, almost three times as high as in 1980 (Fig. 1b). The increase of soil Olsen P occurred in all agroecological regions of China, ranging from 17.5 mg kg^{-1} in the middle-lower Yangtze plain to 25.4 mg kg^{-1} in South China. Soil Olsen P exceeded 40 mg kg^{-1} on 9.3% of the arable land. At that level, there is a risk of P leaching for many soil types in China (Zhong et al. 2004).

Clearly, food P cost has changed significantly in last two decades, and our comprehensive analysis of the food chain indicate that the mean input of P required to produce 1 kg of P in food in China was 5 kg in 1980 and 13 kg in 2005 (Ma et al. 2010). The low P use efficiency partly resulted from the behavior of fertilizer application by farmers, who often input more P than crops need. China faces two challenges to improve P management. We need to find how to best manage soil fertility and fertilizer P, and we need to find how to make better use of P accumulated in soil by crops and cropping systems. The objectives of this paper are to give an overview of the historical development of phosphorus dynamics at the soil, plant and crop level and options in China, to introduce current management problems, to discuss possible reasons for low phosphorus use efficiency, to give two successful cases, and then to offer a perspective for sustainable phosphorus management strategies in China.

Strategies for maximizing P use efficiency

In order to cope with the challenges, two strategies for P management have been developed in Chinese agricultural production.

1. Soil-based P management strategies

   A. Traditional approach: Yield response to fertilizer dose

      A yield response approach has been widely used in China since 1980s (Huang et al. 1982; Zhu 1984; Lv et al. 1989). The analysis of yield response to fertilization of P is based on field experiments and statistical methods. No chemical or physical means need be used to reveal the soil nutrient supply, crop nutrient requirement, fertilizer use efficiency or other properties. A yield response curve for nutrients can be obtained by linear, quadratic or multiple regression equations. Then, the maximum and economically optimum fertilizer rates can be estimated from the regression equation of yield response to fertilization. The method describes the crop fertilizer response for different soil fertility conditions. This approach has helped to secure high crop yields and to optimize fertilizer use at a large scale by considering macroeconomic management and distribution of fertilizers. In addition, China has been able to lift and stabilize crop yield, keep fertilizer use within a relative rational range, and environmental problems associated with excessive fertilization have been reduced. For

Fig. 1 Soil P availability of China in 1980 (**a**) and 2006 (**b**). Different colors indicated different levels of soil P availability. The number on the map was the average soil P availability (Olsen P) of the ecological zones located by them
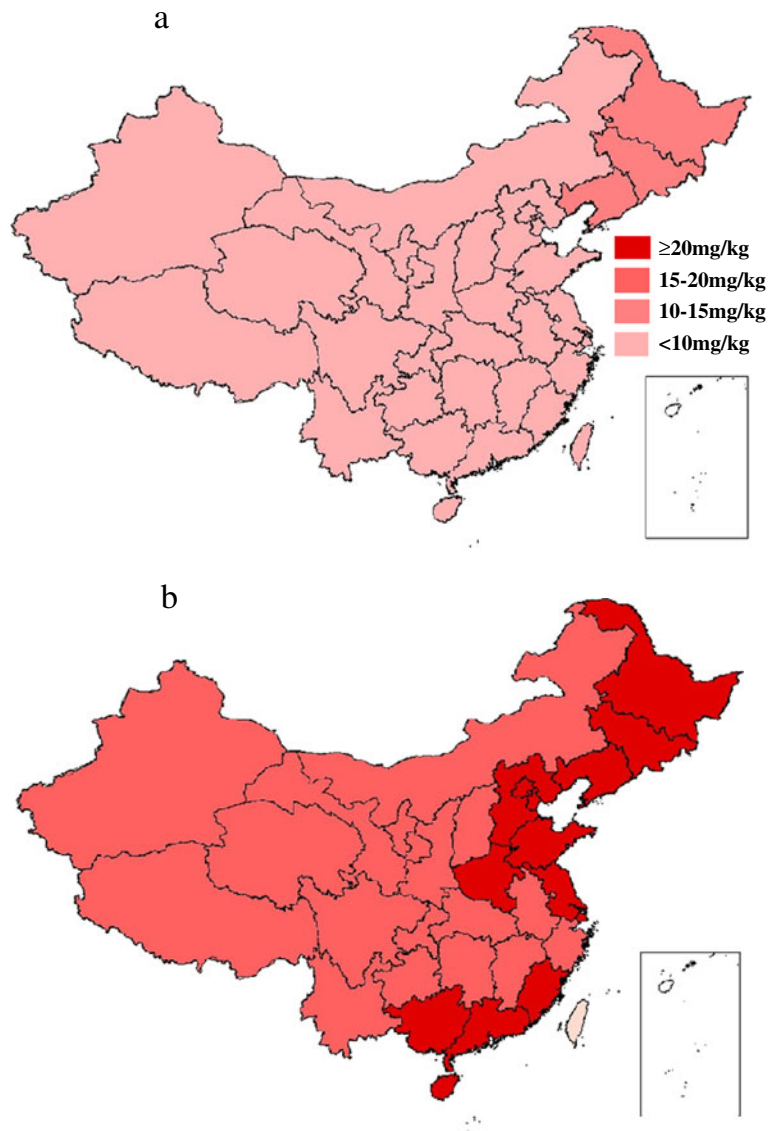
example, implementation of the technology reduced P-fertilizer use in North China Plain by 10–30% compared to farmer practice, without yield loss (Chen et al. 2003).

There are some disadvantages associated with the use of yield functions alone for managing fertilizer input. When nutrients are deficient, crop yields increase with increases in fertilizer application. However, the yield increment per kg fertilizer and the economic benefits of fertilization decrease with improving soil fertility and the economic benefits decline to zero when the value of increase

yield equals the costs of the fertilizer application (line A in Fig. 2). The results from fitted quadratic models (Table 1), indicated that higher amounts of phosphorus fertilizer were required for optimum yield than the P-demand of plant growth alone. Although this is not unusual on soils that have high P sorption capacity, it could also arise from over application of P fertilizer as a result of not updating the fertilizer requirements of crops on soils where soil fertility was rising. It is therefore necessary to continually update yield response functions to determine the appropriate
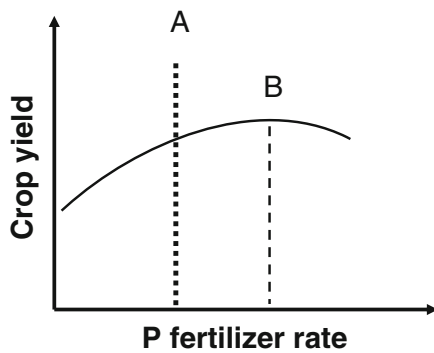
Fig. 2 Theoretical model of yield response approach

amounts of fertilizer that need to be applied. The yield response to fertilizer is based on field experiments and is only applicable to the region where the field experiments were conducted.

It is difficult to overcome the impact of climate differences at different locations on fertilizer requirements. As the method is based on field experiments and requires statistical analysis, it is mainly suited for the agricultural technicians, researchers and government policy-makers, rather than farmers. As a large amount of data is required from the treatments, this approach is more feasible for cereal crops but not vegetables.

B. New approach for P management: Building-up and maintenance

The building-up and maintenance approach was first presented by Wang et al. (1995), and fully developed by Zhang et al. (2008) during

Table 1 Amount of phosphorus fertilizer recommend by yield response approach

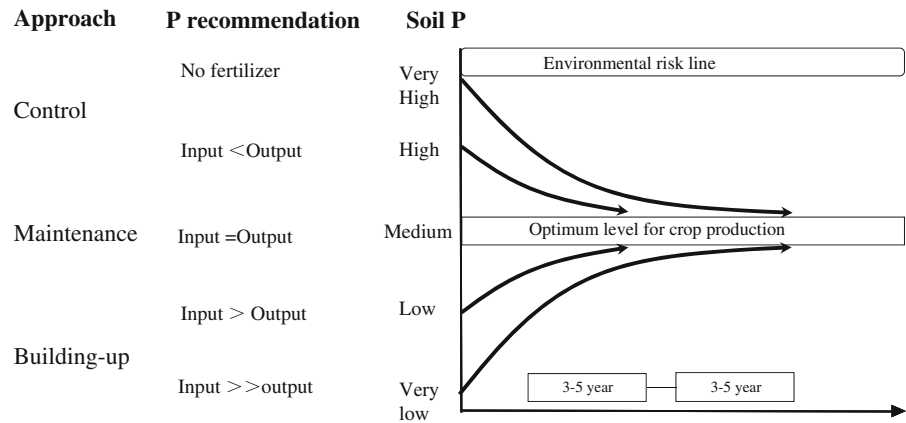| Crop	Location	P recommend (kg ha^{-1})	P uptake (kg ha^{-1})	References
Wheat	Beijing	59	36	Huang et al. (1982)
Wheat	Henan	126	69	Zhu (1984)
Wheat	Shanxi	113	37	Lv et al. (1989)
Maize	Henan	180	44	Wu et al. (1990)
Rice	Liaoning	150	23	Yang and Wang (1985)

implementing in China. The approach aims at maintaining the soil Olsen P at the optimal level for plant growth by fertilizer application management. The optimal level is more than the critical concentration of soil Olsen P needed to sustain high crop yield and less than P leaching level. The critical level for crop yield depends on the characteristics of the different plant species and cropping systems, and can be found through long-term fertilizer experiments or many-year field experiments. The critical level for maize (Zea mays L.) ranged from 12.1 to 17.3 mg P kg^{-1} and for winter wheat from 12.5 to 19.0 mg P kg^{-1} based on three 15 years long-term fertilizer experiments (Tang et al. 2009). Zhang et al. (2008) found that the critical levels ranged from 10 to 20 mg P kg^{-1} for rice (Oryza sativa L.) in south China, 20–60 mg P kg^{-1} for vegetable in north China, 13–30 mg P kg^{-1} for cotton (Gossypium hirsutum L.) in Xinjiang province and 16–25 mg P kg^{-1} and rape (Brassica napus L.) in central China. This approach helps keep soil P at an optimal level, meets the needs of crops, increases profitability and achieves maximum economic efficiency, and reduces environmental risk of P leaching.

The principle of building-up and maintenance based on a nutrient balance approach and soil P test is illustrated in Fig. 3. The objective is to move from the environmental risk level (very high P-status) or P deficient level (very low P-status) to the level of ensuring stable crop yield (medium P-status). When soil Olsen P is too high, either no P fertilizer or the amount of 50–70% take up by the crops should be applied to reduce excessive soil P reserves. When soil Olsen P is at an optimal level, the amount of P-fertilizer equals to crop removal to maintain soil P level. In China, the 20 mg kg^{-1} was regarded as the minimum limit of the optimal soil Olsen P for crop growth, over which most crops can reached the high yield, in contrast, over 40 mg kg^{-1}, a large amount of soil types faces soil P leaching risk (Zhong et al. 2004). Under severe P deficiency, the amount of P-fertilizer approaches 130–170% or even 200%

Fig. 3 Theoretical model of building-up and maintenance approach

of the amount of taken up by the crops in order to build-up soil P supply capacity. In this approach, the P-fertilizer applications should be adjusted according to the soil fertility level every 3–5 years.

Fertilizer P continued to react with soil as a result of which added phosphorus become ever more slowly available to plants (Barrow 1980). In order to maintain soil Olsen P at a range of 20–40 mg kg^{-1}, more than P output should be added every year from a scientific viewpoint. In the practice, the slow reaction between P and soil can be neglected because that if soil Olsen P become less than 20 mg kg^{-1}, the decrease can be detected in the routine measurement, and soil P can be replenished by P fertilizer application.

This strategy can harmonize crop yield, fertilizer efficiency and soil fertility, which is conducive to sustainable development of agriculture. This approach does not focus on the precise measurement of the annual soil P change at each field; thus simplifying the farm management, improving resource use efficiency. This strategy has a potential for broad application, because of its simplicity and feasibility. As an example the P fertilizer recommendations for winter wheat in the North China Plain, based on building-up and maintenance approach are shown in Table 2 (Zhang et al. 2010). In Shandong Province, only 27% of the soil with soil Olsen P content was less than the optimum levels in 61130 soil samples (<14 mg kg^{-1}). As a result, the average P fertilizer recommendation amounted to

31.4 kg P ha^{-1} year^{-1} compared to a recommended dosage of 52.4 kg P ha^{-1} year^{-1} based on a single-season crop P fertilizer response function. Potentially, 0.14 Mt of P can be saved in Shandong Province by using this strategy only (Zhang et al. 2008).

The building-up and maintenance approach has been used in the National Soil Testing and Fertilizer Recommendation Program in China, which started in 2005. In 2009, 2498 counties were covered and a total of 42 billion RMB (1=0.15 US Dollars) have been invested, and 7.2 million soil samples have been measured. In 2010, the program plans to offer the service of Soil Testing and Fertilizer Recommendation to 160 million farmer families freely and will extend the technology up to 700 million ha.

China's Phosphorus Fertilizer Demand was forecasted by the building-up and maintenance approach in Cao's PhD thesis (2006). On average, soil Olsen-P represented about 3.1%

Table 2 Phosphorus fertilizer recommendation for winter wheat in the north China Plain based on "Building-up and maintenance method"

Soil fertility	Soil Olsen-P (mg kg^{-1})	Recommend P rate (P kg ha^{-1})
Very high	>40	0
High	30~40	17.5
Medium	14~30	35
Low	7~14	48
Very low	<7	61

of the accumulated P in the arable areas in China. The P balance sheet for arable land in China showed an increase of about 392 kg ha^{-1} from 1980 to 2003. The present soil Olsen-P of arable land is estimated at about 19 mg kg^{-1} at the national level. If the soil Olsen-P is to be increased to 40 mg kg^{-1}, the maximum level without environment risk, during the next 30 years, the demand for phosphorus fertilizer as P per year should be 4.6 to 5.5 Mt. After 2035, the soil Olsen-P level should be kept at 40 mg kg^{-1}, and the demand of phosphorus fertilizer per year would then be around 4.6 Mt.

2. Plant/rhizosphere-based P management

A. Case 1: manipulating root morphology and physiology by managing rhizosphere processes.

Proliferation of lateral roots was greatly stimulated by localized supply of high nitrate or P in barley (Hordeum vulgare L.) (Drew 1975). Cluster roots of white lupin (Lupinus albus L.) were found to be concentrated in the organic matter profile where nutrients and water were normally rich (Li et al. 2010a). Assimilation of ammonium in roots produces similar amount protons, which can release into rhizosphere (Marschner 1995). Rhizophere acidification improved bioavailability of soil P in calcareous soil (Hinsinger 2001). The modifications of root morphology and physiology caused by nutrient supply in soil under low-P stress makes rhizosphere management feasible. The manipulation of rhizosphere processes by localized application of P and ammonium improved P uptake and growth of maize in an intensive farming system in North China (Jing et al., 2010). Localized supply of P plus ammonium significantly increased chlorophyll content and leaf area, leading to increased dry weight of shoots by 18%–77% at early growth stages in N_LP_L (localized application of both P and N) than N_BP_B (both N and P broadcast) or N_BP_L (localized P application with N broadcast) treatments . The acquisition of N and P by plants was markedly improved by modification of rhizosphere processes including stimulating root proliferation (especially of

fine roots) and rhizosphere acidification (by 2–3 units in the fertilized zone) caused by localized supply of P plus ammonium. In the calcareous soil of North China, it is feasible to improve nutrient use efficiency and plant growth through an effective management strategy, such as localized application of P in combination with ammonium.

B. Case 2: Rhizosphere interactions are important for increasing nutrient use efficiency of P and maximizing crop productivity.

Individual plants may modify the rhizosphere in ways that facilitate nutrient adsorption by roots. This may benefit plants of the same, or of different, species. For many years, Chinese farmers have used intercropping systems to increase productivity and profitability per unit of land. In the past decades, some intercropping systems were widely investigated, especially with respect to the advantage of phosphorus uptake (Li et al. 2001, 2003, 2007).

Maize/faba bean intercropping

Maize/faba bean (Vicia faba L.) intercropping systems have a long history in the irrigated areas of the Hexi Corridor in Gansu province, China, where climatic conditions allow only one cropping season annually (Li et al. 2001). The sowing date for maize was the middle of April, which was 3 weeks later than faba bean sowing. Faba bean and maize was harvested at the end of July and September, respectively (Li et al. 2003). There was a significant intercropping advantage on crop yield and phosphorus adsorption for intercropped maize and faba bean compared with mono-cropped plants. On a low-phosphorus but high-nitrogen soil, over 4 years of field experiments, the yield of maize and faba bean was 43% and 26% higher in intercropping than monocropping (Li et al. 2007). Intercropped maize and faba bean also had a greater P uptake by 28% and 29% than monocropped plants (Li et al. 2003). The increase in uptake was attributed to rhizosphere interactions between maize and faba bean (Li et al. 2007). Faba bean acidified its rhizosphere via proton exudation from roots in calcareous soil and alkalized the rhizosphere in an acidic soil (Li et al. 2007; Li et al. 2010b).

Modification of the rhizosphere pH improved soil P bio-availability in both calcareous and acidic soils (Lindsay 1979). More than 400 nmol citrate g^{-1} soil was present the rhizosphere of faba bean (Li et al. 2010b), which desorbed phosphate anion from Al- and Fe- bound phosphorus in soil. P mobilized by modification of the rhizosphere of faba bean facilitated P uptake by the neighboring maize in the intercropping system. Moreover, the improvement of intercropped maize's yield is also partly due to higher soil N availability from N_2 fixation of faba bean (Fan et al. 2006). Faba bean yield also increased because of competition alleviation in P uptake resulted from different root distribution between two plant species (Li et al. 2006), and because of enhanced nitrogen fixation (Fan et al. 2006).

Maize/wheat intercropping

Maize/wheat (Triticum aestivum L.) is popular in the irrigated areas of the northwest China, and produces a combined yield of more than 12,000 kg ha^{-1} (Li et al. 2001). Sowing date were the middle of March for wheat and April for Maize. Harvesting date were the middle of July for wheat and the end of September for Maize. The individual intercropped wheat had a higher yield by 74% than monocropped wheat. For intercropped wheat in the border rows, the increase was 56–92% compared with monocropped wheat; for the inner rows the increase was 22% (Li et al. 2001). Maize had a greater yield by 19–33% when intercropped in different P fertilizer application rates. Intercropped combined crop took up 28–41% more P than the weighted mean of monocropping with P fertilizer application (Li et al. 2001). The advantage to wheat of intercropping was due to higher competitive ability than that of neighbor maize because of larger root system (Li et al. 2003). In the early stage, the rates of dry matter accumulation of intercropped maize was 10–20 g m^{-2} day^{-1}, which was significantly lower than for monocropped maize (17–35 gm^{-2} day^{-1}) (Li et al. 2003). After wheat harvest, maize had a compensatory growth of 59 to 70 gm^{-2} day^{-1}, which was around double the rate of the monocropped plant, and offset the impairment of early growth (Li et al. 2003). The process was summarized as the 'competition-recovery production principle'. Recovery resulted from diminished interspecific competition.

C. Case 3: exploitation of plant genetic potentials.

(1) Plant species shows different responses to P on acid and alkaline soils.

Many strategies have been evolved by different plant species to acquire soil P (Raghothama 1999; Hinsinger 2001; Vance et al. 2003; Raghothama and Karthikeyan 2005). These include release of protons, exudation of carboxylates and secretion of phosphatases. Even in the same type of soil, different plant species used different strategies (Li et al. 2007; Li et al. 2008, 2010b). Faba bean had a strong ability to acidify the rhizosphere and to exude carboxylates in calcareous soil, whereas large root biomass and length facilitated P uptake efficiently in maize (Li et al. 2007). Li et al. (2010b) showed faba bean greatly alkalized the rhizosphere to acquire P from the acidic soil. Common bean and wheat used different behaviors on utilization of different P fractions (Li et al. 2008). Phosphorus is usually concentrated in the topsoil and decreases with depth due to P fertilizer application or returning P to surface in leaf litter in unfertilised soils. Common bean (Phaseolus vulgaris L.) and soybean (Glycine max (L.) Merr.) adapt to low P availability by allocating roots to shallow horizons (Liao et al. 2001; Rubio et al. 2003; Liao et al. 2004; Lynch 2011).

The morphological and physiological adaptation to soil P supply of five plant species, including white lupin, maize, soybean, faba bean and rape, was estimated recently by Lv and Shen (2010) in both calcareous soil and acidic soils. Maize, soybean and rape were strongly responsive to P addition, and P supply increased the shoot dry mass 1–4 times in the calcareous soil compared with the no P treatment. In contrast, white lupin and faba bean were relatively insensitive to P application, with only around 30% higher yield with P application. High acid phosphatase activity

occured inthe rhizosphere of white lupin and faba bean in this study. Li et al. (2010b) also found modification of rhizosphere pH and high carboxylate exudation of these plants. There rhizosphere processes were responsible for high P use efficiency. Maize, soybean and rape showed inefficient adaptation to soil P deficiency. In contrast, faba bean and white lupin highly relied on a physiological adaptation of root exudation from roots to P deficiency.

(2) Gene modification for enhancing P use efficiency

The diversity of root adaptation strategies in different plant species makes improving P acquisition by transgenic techniques feasible. Many researchers have already focused on transgenesis of acid phosphatase (APase) (Yip et al. 2003; Xiao et al. 2006; Wang et al. 2009). An Arabidopsis (Arabidopsis thaliana) purple APase gene *(AtPAP15)* containing a carrot (Daucus carota) extra-cellular targeting peptide in soybean hairy roots was transformed and over-expressed in soybean (Wang et al. 2009). The transgenic lines exhibited a greater activity of APase (by 9.7–33.1%) and phytase (50.1–159.3%) in leaves and root exudates compared to wild-type plants, resulted in 56.5–117.8% increases in plant dry weight and 18.2–90.1% in plant P content. Ma et al. (2010) introduced a phytase gene (MtPHY1) and a purple acid phosphatase gene (MtPAP1) isolated from *Medicago truncatula* into white clover (*Trifolium repens* L.). The threefold activities of phytase or acid phosphatase in root apoplasts of the transgenic plants facilitated higher accumulation of total P (up to 2.6-fold) than the wild-type plants. A number of families of phosphate transporter mediate the transport of phosphate anion transport across plant membranes (Smith et al. 2003). However, some researchers found that increase of phytase release couldn't improve P uptake of plants because of rapid adsorption of phytase by soil minerals (George et al.

2003, 2007). Mobilization of soil organic P by acid phosphatase was strongly depended on soil types. Mitsukawa et al. (1997) enhanced tobacco cell growth under phosphate-limited conditions by over-expression an *Arabidopsis thaliana* high-affinity phosphate transporter gene (*PHT1*). A high-affinity phosphate transporter genes (*OsPT1*) was induced into rice roots and significantly enhanced P acquisition in transgenic rice (Seo et al., 2008). In contrast, Rae et al. (2004) failed to improve P uptake of transgenic barley by over-expression of a high affinity phosphate transporter. Through gene modification to enhance P use efficiency of crop is still a challenge for plant nutrition scientist.

(3) Marker assistant selection (MAS) for enhancing P efficiency

It has been reported in that maize on the genotypic variation in adaptation to low P soil conditions including morphological and physiological response by roots (Hajabbasi and Schumacher 1994; Liu et al. 2004; Hao et al. 2008, Li et al. 2010a, b). Using a MAS on root-related QTLs, we developed a maize inbred L224 with increased root growth and strong rhizosphere acidification. Phenotypic evaluation in the field trials showed that, L224 has a larger root system, higher P uptake and grain productivity in comparison with the recurrent parent (Yuan unpublished). This work highlighted a molecular breeding approach on the development of P-use efficient maize.

Perspectives

Phosphorus is a limited and non-renewable resource, and the remaining accessible reserves of high quality phosphate rock would run out by 2050 in China (Zhang et al. 2008). Phosphorus fertilizer inputs have greatly contributed to increased food production in China in recent decades, but also caused environmental problem (Ma et al. 2010). The

challenge of P management is to harmonize food security, resource limitation and pollution problems at field regional scale. Rapid economic development of China in recent years has shifted diet from plant to animal products (Wang et al. 2010). Phosphorus flow has changed significantly in the last two decades. Firstly, the phosphorus cycle in China agricultural system has undergone an evident change because of diet shift. Secondly, animal production system has been separated from crop production. Thirdly, most of the manure phosphorus entered into the water environment. According to a prediction by the Ministry of Agriculture, by 2050, the national animal products will increase considerably: the nationwide total meat production will increase to 86.0 Mt from current 76.2 Mt; egg production will increase to 32.0 Mt from 27.4 Mt; milk production will increase to 60.0 Mt from 35.2 Mt. Therefore, it can be expected that the total amount of animal manure will also increase by a large margin. In the meantime, there will be even greater pressure on the recycling of animal manure and a decline in mineral P fertilizer availability. Manure P will have an increasing role as fertilizer for crops, with an associated decline in the environmental problems currently linked to their disposal. Prospectively, the research should be from "soil" to "soil-plant-animal-environment".

Strategies of soil P management should be based on soil type. Three critical points exist in each soil type: yield and leaching. The critical point for yield is the point above which a crop will maintain 80–100% of the maximum yield and have no significant response to P fertilizer application, and is regarded as 20 mg kg^{-1} (Olsen P) for major crops in China. The critical leaching point was first described by Heckrath et al. (1995) (change-point between soil Olsen P and soil $CaCl_2$-P) in the Broadbalk Experiment at Rothamsted, which is 40 mg kg^{-1} (Olsen P) as temporal index in China. The critical level of yield for each crop and P leaching for each soil type will be specified in further research. The critical level of yield and leaching is in between minimum and maximum line of soil Olsen P in "Building-up and Maintenance" approach at a field level.

Optimizing the soil-plant-animal P nutrient management should involve increasing P uptake efficiency of animals and plants; reducing P fertilizer input in areas of excessive fertilization; and adopting new technology to increase recycling of animal manure. The result would be quite significant: in contrast to 2005, by 2050 the whole system will reduce demand for P fertilizers (P) by 0.51 Mt and 0.48 Mt of animal manure discharge–animal manure will substitute for 1.46 Mt of chemical phosphorus fertilizers (P) (Wang unpublished). A long-term strategy for optimizing P flow in a "soil-crop-animal" system involves multidisciplinary collaboration and this is the future research direction of P management.

Lowering the net P costs of food production requires a food chain approach. Key topics are (1) to increase the understanding of P cycling in the food production—consumption chain, (2) to quantify P use efficiencies in the food chain at regional level in China, and the effects of changes in population, urbanization and diets, and (3) to explore nutrient management options for improving P use efficiencies at regional level, like social and policy issues.

References

Barrow NJ (1980) Evaluation and utilisation of residual phosphorus in soils. In Kasewnah F, Sample G (Ed) The role of phosphorus in agriculture (Eds.). pp. 333–59

Cao N (2006) Phosphorus management in Chinese agro-ecosystem based on forecasting the change of soil phosphorus fertility. Dissertation, Northwest A & F University

Chen X, Zhang F, Jiang R (2003) The technique system of soil/plant quick test and recommend fertilizer (in Chinese). In: Zhang F, Ma W, Jiang F (eds) Integrated management of nutrient resources. China Agriculture Press, Beijing

Drew MC (1975) Comparison of the effects of a localized supply of phosphate, nitrate, ammonium and potassium on the growth the seminal root system, and the shoot, in batley. New Phytol 75:479–490

Fan F, Zhang F, Song Y, Sun J, Bao X, Guo T, Li L (2006) Nitrogen fixation of faba-bean (*Vicia faba* L.) interacting with a non-legume in two contrasting intercropping systems. Plant Soil 283:275–286

FAO Resource STAT 2006

FAO Resource STAT 2008

George TS, Richardson AE, Hadobas PA, Simpson RJ (2003) Rhizosphere limitations to the efficacy of phytase-phytate interactions. In: Rengel Z (ed) Book of abstracts for 2nd ISPDSC. Perth, Australia

George TS, Simpson RJ, Gregory PJ, Richardson AE (2007) Differential interaction of Aspergillus niger and Peniophora lycii phytases with soil particles affects the hydrolysis of inositol phosphates. Soil Biol Biochem 39:793–803

Hajabbasi MA, Schumacher TE (1994) Phosphorus effects on root growth and development in two maize genotypes. Plant Soil 158:39–46

Hao L, Zhang J, Chen F, Christie P, Li X (2008) Response of two maize inbred lines with contrasting phosphorus efficiency and root morphology to mycorrhizal colonization different soil phosphorus supply level. J Plant Nutr 31:1050–1073

Heckrath G, Brookes PC, Poulton PR, Boulding KWT (1995) Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. J Environ Qual 24:904–910

Hinsinger P (2001) Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. Plant Soil 237:173–195

Huang D, Ji H, Xu Q, Wu S, Liu S (1982) Application of yield response approach on amount and ration of NP fertilizer application for wheat (in Chinese). Beijing Agric Sci 4:24–30

Jing J, Rui Y, Zhang F, Rengel Z, Shen J (2010) Localized application of phosphorus and ammonium improves growth of maize seedlings by stimulating root proliferation and rhizosphere acidification. Field Crops Res 119:355–364

Li H, Shen J, Zhang F, Lambers H (2010a) Localized application of soil organic matter shifts distribution of cluster roots of white lupin in the soil profile due to localized release of phosphorus. Ann Bot 105:585–593

Li H, Shen J, Zhang F, Marschner P, Cawthray G, Rengel Z (2010b) Phosphorus uptake and rhizosphere properties of intercropped and monocropped maize, faba-bean, and white lupin in acidic soil. Biol Fert Soil 46:79–91

Li H, Shen J, Zhang F, Tang C, Lambers H (2008) Is there a critical level of shoot phosphorus concentration for cluster-root formation in Lupinus albus? Funct Plant Biol 35:328–336

Li L, Li S, Sun J, Zhou L, Bao X, Zhang H, Zhang F (2007) Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. Proc Natl Acad Sci 104:11192–11196

Li L, Sun J, Zhang F, Guo T, Bao X, Smith FA, Smith SE (2006) Root distribution and interactions between intercropped species. Oecologia 147:280–290

Li L, Sun JH, Zhang FS, Li XL, Yang SC, Rengel Z (2001) Wheat/maize or wheat/faba-bean strip intercropping I: yield advantage and interspecific interaction on nutrients. Field Crops Res 71:123–137

Li L, Zhang FS, Li XL, Christie P, Sun JH, Yang SC, Tang C (2003) Interspecific facilitation of nutrient uptake by intercropped maize and faba-bean. Nutr Cycl Agroecosyst 68:61–71

Liao H, Rubio G, Yan X, Cao A, Brown K, Lynch JP (2001) Effect of phosphorus availability on basal root shallowness in common bean. Plant Soil 232:69–79

Liao H, Yan X, Rubio G, Beebe S, Blair MW, Lynch JP (2004) Genetic mapping of basal root gravitropism and phospho-

rus acquisition efficiency in common bean. Funct Plant Biol 31:959–970

Lindsay WL (1979) Chemical equilibria in soils. Wiley, New York, USA, 449

Liu Y, Mi G, Chen F, Zhang J, Zhang F (2004) Rhizosphere effect and root growth of two maize (Zea mays L.) genotypes with contrasting P efficiency at low P availability. Plant Sci 167:217–223

Lv D, Xu F, Zhang J, Li Y (1989) The research of NPK fertilizer application for maize in Wuding river basin (in Chinese). Agri Sci J Shanxi 6:22–23

Lv Y, Shen J (2010) Coordination of root morphological and physiological adaptation to phosphorus deficiency for five plant species in acid and calcareous soils. In: Zhang F (ed) Book of abstracts for 4th ISPDSC. Beijing, China

Lynch JP (2011) Root Phenes for Enhanced Soil Exploration and Phosphorus Acquisition: Tools for Future Crops. Plant Physiol 156:1041–1049

Ma L, Ma WQ, Velthof GL, Wang FH, Qin W, Zhang FS, Oenema O (2010) Modeling Nutrient Flows in the Food Chain of China. J Environ Qual 39:1279–1289

Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. Academic, London, p 47

Mitsukawa N, Okumura S, Shirano Y, Sato S, Kato T, Harashima S, Shibata D (1997) Overexpression of an Arabidopsis thaliana high-affinity phosphate transporter gene in tobacco cultured cells enhances cell growth under phosphate-limited conditions. Proc Natl Acad Sci 94:7098–7102

Olsen S, Cole C, Watanabe F, Dean L (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular Nr 939, US Gov. Print, Washington, D.C

Raghothama KG (1999) Phosphate acquisition. Annu Rev Plant Physiol Plant Mol Biol 50:665–693

Raghothama KG, Karthikeyan AS (2005) Phosphate acquisition. Plant Soil 274:37–49

Rae AL, Jarmey JM, Mudge SR, Smith FW (2004) Overexpression of a high-affinity phosphate transporter in transgenic barley plants does not enhance phosphate uptake rates. Funct Plant Biol 31:141–148

Rubio G, Liao H, Yan X, Lynch JP (2003) Topsoil foraging and its role in plant competitiveness for phosphorus in common bean. Crop Sci 4:598–607

Seo HM, Jung Y, Song S, Kim Y, Kwon T, Kim DH, Jeung SJ, Yi YB, Yi G, Nam MH, Nam J (2008) Increased expression of OsPT1, a high-affinity phosphate transporter, enhances phosphate acquisition in rice. Biotechnol Lett 30:1833–1838

Smith FW, Mudge SR, Rae AL, Glassop D (2003) Phosphate transport in plants. Plant Soil 248:71–83

Tang X, Ma Y, Hao X, Li X, Li J, Huang S, Yang X (2009) Determining critical values of soil Olsen-P for maize and winter wheat from long-term experiments in China. Plant Soil 323:143–151

The Yearbook of China Statistics 2007

Vance CP, Uhde-Stone C, Allan DL (2003) Phosphorus acquisition and use: critical adaptations by plants for securing a non renewable resource. New Phytol 157:423–447

Vitousek PM, Naylor R, Crews T, David MB, Drinkwater LE, Holland E, Johnes PJ, Katzenberger J, Martinelli LA, Matson PA, Nziguheba G, Ojima D, Palm CA, Robertson GP, Sanchez

PA, Townsend AR, Zhang FS (2009) Nutrient Imbalances in Agricultural Development. Science 324:1519–1520

Wang F, Dou Z, Ma L, Ma W, Sims JT, Zhang F (2010) Nitrogen Mass Flow in China's Animal Production System and Environmental Implications. J Environ Qual 39:1537–1544

Wang X, Cao Y, Zhang F, Chen X (1995) Application of Building-up and Maintenance approach in agriculture. Plant Nutr Fert Sci 1:59–63

Wang X, Wang Y, Tian J, Lim BL, Yan X, Liao H (2009) Overexpressing AtPAP15 enhances phosphorus efficiency in soybean. Plant Physiol 151:233–240

Wu J, Tan J, Li C (1990) The high yield fitting ratio model of nitrogen-phosphorous of summer corn in different ecotype regions of Henan province (in Chinese). J Henan Agri Uni 2:137–142

Xiao K, Katagi H, Harrison M, Wang Z (2006) Improved phosphorus acquisition and biomass production in Arabidopsis by transgenic expression of a purple acid phosphatase gene from M. truncatula. Plant Sci 170:191–202

Yang Q, Wang Z (1985) The research of the amount and the best ration of NPK fertilizer application in rice (in Chinese). Sal Us 2:21–30

Yip W, Wang L, Cheng C, Wu W, Lung S, Lim BL (2003) The introduction of a phytase gene from Bacillus subtilis improved the growth performance of transgenic tobacco. Biochem Biophys Res Commun 310:1148–1154

Zhang F, Chen X, Chen Q (2010) Fertilization guide of major crop species in China. China Agricultural University Press.

Zhang W, Ma W, Ji Y, Fan M, Oenema O, Zhang F (2008) Efficiency, economics, and environmental implications of phosphorus resource use and the fertilizer industry in China. Nutr Cycl Agroecosyst 80:131–144

Zhong X, Zhao X, Bao H, Li H, Lin Q (2004) The evaluation of phosphorus leaching risk of 23 Chinese soils. I. Leaching criterion (in Chinese). Acta Ecol Sin 24:2275–2280

Zhu M (1984) The analysis of economic benefit on NP fertilizer application for wheat in north Henan (in Chinese). J Baizhuan Agric Coll 12:1–8