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Screening Chinese Wheat Germplasm for Phosphorus Efficiency in Calcareous Soils

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ABSTRACT

Twenty commonly used winter wheat genotypes collected throughout China were used in field screening for phosphorus (P)-efficient germplasm in a calcareous soil with and without fertilizer P application; the same genotypes were also evaluated for high and low P inputs in a greenhouse experiment. The overall criterion for P efficiency was the capacity to produce a relatively high yield with low P availability. Significant differences in grain yield production occurred between efficient and inefficient genotypes. Four parameters were calculated to determine which was the most useful for describing P efficiency: (1) percentage of relative yield with no applied P; (2) total P uptake; (3) P-harvest index (PHI: grain P/total P uptake); and (4) P-utilization efficiency (PUE: grain yield produced per unit of P taken up). A simple but satisfactory criterion in screening P-efficient wheat genotypes, 85% of relative grain yield at low P/high P, was recommended and proved to be more effective than the other three parameters. With this criterion, 12 out of 20 genotypes were classified as P-efficient ($\leq 15\%$ yield reduction with no P applied) from both field and pot experiments. Phosphorus efficiency may have resulted from either P uptake or P-utilization efficiency. Three parameters, namely relative yield without applied P, PHI and PUE, were found to be useful, together with P uptake, in determining overall P efficiency. Successful selection for P efficiency was found to be possible at the shooting stage (but not at tillering) by comparing P uptake and P-utilization efficiency of plants at this growth stage with those of plants at maturity.

Keywords: P uptake, P harvest index, P utilization efficiency, relative yield

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INTRODUCTION

Phosphorus is one of the most limiting factors for crop production in most arable areas of China and many other parts of the world. To increase soil productivity, farmers apply substantial amounts of phosphate fertilizers to compensate for the low P-use efficiency of crops (Read et al., 1973), especially in calcareous soils that cover about 30% of the land surface worldwide (Wallace and Lunt, 1960). The P efficiency of most crops tends to be low in calcareous soils because available calcium (Ca) is abundant under high pH conditions and readily binds to P to form a number of sparingly soluble compounds, particularly calcium orthophosphate. Since these compounds are unavailable for plant uptake, regular application of P fertilizers is required to maintain crop yields. However, excessive P accumulation in the soil increases the risk of surface water pollution, leading to the eutrophication of water bodies (Sharpley et al., 1994). To alleviate crop P deficiency while maintaining high yields without high inputs of P fertilizers, plant breeders are searching for P-efficient germplasm to be used in crop breeding after widespread screening and evaluation of plant varieties as an alternative strategy to increased use of P fertilizers (Batten, 1992; Horst and Wiesler, 1986; Horst et al., 1996; Römer and Schenk, 1998; Wissuwa and Ae, 1999).

Some plant species or varieties may differentially influence soil P availability through changes in their root morphology, e.g., proteoid roots in *Lupinus* are formed by P-deficiency stress (Dinkelaker et al., 1989), and by increasing excretion of protons and organic acids under P-deficiency conditions (Dinkelaker et al., 1989; Hoffland, 1992; Li et al., 1995; Wang et al., 1998, 2000). However, the first step is to introduce a simple and satisfactory criterion for describing P efficiency. Batten (1986) suggested the P-efficiency ratio (yield per unit P uptake) as a suitable criterion and this has been put into practice for plant selection. Jones et al. (1989, 1992) recommended PHI (phosphorus harvest index, grain P/total P) as an alternative criterion for wheat P-efficiency screening. Römer and Schenk (1998) suggested that the phosphate efficiency quotient (PEQ) should be considered as a priority for P-efficiency screening in barley. In fact, the above criteria indicate only internal utilization of P absorbed by the plants to produce grains or re-translocated into the grains (Wang et al., 1999b). Alternatively, P efficiency could be expressed in terms of P uptake and P-utilization efficiency, either separately or together. Genotypes with high P uptake can take up substantially more P from soil to produce relatively higher yields under P-deficiency conditions compared with genotypes with low uptake. Genotypes with high P-utilization efficiency may not necessarily have high P uptake, but these genotypes can also utilize internal P effectively to produce higher grain yields (Wang et al., 1999b).

Wheat (*Triticum aestivum*) is a staple food crop grown over a wide area from central to northern China where calcareous soils predominate (Wang et al., 1999b). Many wheat cultivars have been produced in China, selected over a long historical period of cropping. Some of these varieties may be genetically

adapted to local conditions, as some have been observed to grow better than others under similar conditions (unpublished data). Based on this hypothesis, 20 wheat genotypes were collected and grown on calcareous soil under the same experimental conditions (in the field and in the greenhouse) in an attempt to find P-efficient germplasm that could be used in wheat-breeding programs. This paper presents the results of the nationwide screening exercise and discusses the relative merits of various parameters that can be used to compare the P efficiency of the different wheat genotypes.

MATERIALS AND METHODS

Field Experiments

Experimental Site and Design

A field experiment was carried out during 1997–1998 at the Experimental Station of the Institute of Genetics, Chinese Academy of Sciences, Changping County in the northern suburbs of Beijing (lat 40°07' N, long 116°22' E). The site has an average rainfall of 650 mm per year, a mean temperature of 10.8°C throughout the year and an accumulated day temperature of 3470.3°C (total above 10°C). These climatic conditions are quite favorable for wheat growth, with grain yields ranging from 4 to 6 t ha⁻¹ under the fertilizer regimes used in current agricultural practice. The highly calcareous soil (Haplustalf, Ustalf, Alfisol) has very low plant-available P (Olsen-P) status despite its very high total P status (Table 1).

Topsoil was sampled to a depth of 20 cm for chemical analysis. Soil organic carbon (C) was determined by oxidation with potassium dichromate, total nitrogen (N) by Kjeldahl digestion, and total P by colorimetrically following digestion with a mixture of concentrated sulfuric and perchloric acids. Soil available N was extracted with 1 M NaOH, plant-available P was determined by the Olsen method (extraction with 0.5 M NaHCO₃ at pH 8.5), and exchangeable potassium (K) was extracted with 1 M ammonium acetate at pH 7.0. All wheat genotypes tested were grown in control plots unamended with P (low P) and in treatment plots to which P fertilizer was applied (high P). The plots, each 5.2 m² in area and comprising six planted rows, were set up in quadruplicate and arranged in four fully randomized blocks.

Fertilizer Treatments

Basal fertilizer P was applied to the treatment plots as diammonium phosphate [DAP:(NH₄)₂HPO₄, 18% N and 20% P] at the rate of 90 kg P ha⁻¹. A basal dressing of urea (46% N) was also applied to bring the total N application rate up to 225 kg N ha⁻¹. The control plots received no P fertilizer, but received a

Table 1
Selected properties of the calcareous soil (20 cm depth) of the field experimental site and pot experiment (DM basis)

Experiment	pH (H ₂ O)	CaCO ₃ (g kg ⁻¹)	CEC (cmol kg ⁻¹)	Organic C (g kg ⁻¹)	Total N (g kg ⁻¹)	Total P (mg kg ⁻¹)	Extractable N (mg kg ⁻¹)	Olsen-P (mg kg ⁻¹)	Exchangeable K (mg kg ⁻¹)
Field 1997–98	8.1	82	10.8	5.57	0.58	1560	45.2	5.5	96
Greenhouse	7.9	126	11.5	4.18	0.60	1325	40.6	4.2	102

basal application of urea at the rate of 225 kg N ha^{-1} . All fertilizers were spread evenly onto the plots and immediately incorporated into the soil by rototilling before sowing the wheat cultivars.

Choice of Wheat Genotypes

Twenty winter wheat genotypes (*Triticum aestivum* L.) registered from 1970 to 1990 and widely grown in different locations were compared for P efficiency in the field based on preliminary selection among individual plants according to their response to P-deficient soil. The seeds were sown at the end of September 1997 and harvested during the middle of June 1998.

Plant Sampling and Analysis

Fifteen plants were randomly selected and removed from each plot 45 days (the tillering stage for >75% of the genotypes) and 160 days (the shooting stage for most genotypes) after germination. Tillers and dry matter (DM) yields were determined on the samples. Grain yields and total biomass were determined based on the whole plot after the final harvest (253 days after germination). All plant samples were oven-dried at 70°C for 48 h, ground, digested with a mixture of concentrated H_2SO_4 and HClO_4 and analyzed for phosphate colorimetrically using the molybdate-ascorbic acid method described by Kitson and Mellon (1944).

Pot Experiment

Experimental Design

The same 20 wheat genotypes that were used in the field experiment were compared in the greenhouse experiment using the same calcareous soil collected from the field site (Table 1). Air-dried soil (8 kg) was placed in each 30-cm-diameter and 25-cm-high cylindrical plastic pot. The pots had no drainage holes to avoid leaching out of nutrients. Pots receiving the high application rate of P fertilizer (high P) received 40 mg fertilizer P kg^{-1} soil as DAP and those receiving the low rate (low P) were given 10 mg P kg^{-1} . Sufficient urea was applied to both P treatments to give a total of 120 mg N kg^{-1} , and all pots received 40 mg K kg^{-1} as KCl. Twenty seeds were sown in each pot in mid-November. The seedlings were thinned at the three-leaf stage to give 15 plants of similar size. Thus, there were 20 cultivars, two fertilizer P regimes and four replicates, giving a total of 160 pots arranged in a fully randomized block design. The temperature was adjusted to 12°C from the sowing to the tillering stage, 18°C from shooting to heading, and 25°C from flowering to maturity.

Plant Sampling and Analysis

Five plants were randomly sampled from each pot on two occasions, 30 and 65 days after germination. These times corresponded with the tillering and shooting stages of the plants. The remaining five plants were harvested after maturity (145 days after germination). The plant samples were processed using the methods outlined above for the field experiments.

Criterion for P Efficiency, Calculation for P Uptake, P Utilization, and P-Harvest Index (PHI)

P efficiency was categorized with relative grain yield (low P/high P) as a criterion, P-efficient genotype if relative grain yield with low P/high P $\geq 85\%$, P-inefficient otherwise. Low P corresponded to about 5 mg Olsen-P kg^{-1} soil in the field experiments and 8 mg Olsen-P kg^{-1} in the pot experiment (soil dry-matter basis).

Total P uptake (grain and straw) in kg ha^{-1} or mg pot^{-1} was calculated from straw and grain DM yields multiplied by their P concentrations. P-utilization efficiency ratio (PUE: kg kg^{-1} P or g g^{-1} P) was calculated in terms of grain yield produced per unit total P taken up by the plants. Phosphorus-harvest index (PHI) is defined as the ratio between grain P uptake and total P uptake (kg or mg).

Statistical Analysis

To compare genotypes and P levels (high P and low P) the data were subjected to analysis of variance. The estimated standard errors were used to calculate Fisher's protected least significant difference (LSD) for comparisons among mean values. Phosphorus uptake and P-utilization efficiency were examined more closely using the methods of analysis and interpretation of factors described by Moll et al. (1982) to compare the correlation coefficients for significant difference tests between total DM yields and/or grain DM yields and P uptake or P-utilization efficiency.

RESULTS

Grain Yield and P Efficiency of Wheat Genotypes

Grain yields varied greatly among wheat genotypes at the same P levels; some of them were strongly P-dependable, but little difference was observed for the others in both field and pot experiments (Figure 1).

For example, the variation between the maximum and the minimum yields among all the cultivars was 46.2% at the high P and 64.7% at the low P supply

Figure 1. Absolute grain yields of wheat genotypes in both field and pot experiments. Genotypes are coded as follows: 1 = 81(85)5-3-3-3, 2 = Ji 87-4617, 3 = Yan 054, 4 = Jingdong 5227, 5 = 90-6060, 6 = Jimai 17, 7 = Taihe 5025, 8 = Lovrin No. 10, 9 = Jinghe90Jian31, 10 = Dai 108, 11 = Jing 411, 12 = 6154, 13 = Yanzhong 144, 14 = Qinmai No. 1, 15 = Jinghe90Jian17, 16 = NC37, 17 = Fengkang No. 8, 18 = Jinghe No. 1, 19 = 9269-3-1-1 and 20 = 8602.

from the field experiment. At high-P supply, there were 9 out of 20 genotypes from the field experiment and 7 out of 20 from the pot experiment over the average yields (5084 kg/ha from the field and 13.7 g pot⁻¹ from the pot experiment). However, at low P supply, 7 out of 20 from the field and 6 out of 20 from the pot experiment were over the average yields, 4298 kg ha⁻¹ and 11.1 g pot⁻¹, respectively (Figure 1).

Among all the genotypes in both experiments, genotypes 1–8 from the field experiment showed P less dependable, as the yields with and without P supply were very closed (Figure 1). The corresponding genotypes were 81(85)5-3-3-3, Ji 87-4617, Yan 054, Jingdong 5227, 90-6060, Jimai 17, Taihe 5025, and Lovrin No. 10, respectively. However, from the pot experiment, genotypes 1–4, and

7, 10, and 12 showed very close yield response with high and low P supply (Figure 1). They were 81(85)5-3-3-3, Ji 87-4617, Yan 054, Jingdong 5227, Taihe 5025, Dai 108 and Dai 6154.

When we took 85% of relative yield at low P vs. high P as a criterion, the first 12 genotypes from the field experiment and the first 13 from the pot experiment were classified as P-efficient (Figure 2). Some genotypes, e.g., code numbers 20 (genotype 8602) and 19 (genotype 9269-3-1-1), had about 40% of grain yields lost without sufficient P supply, which was the most strongly P-dependable. Code no. 1 [81(85)5-3-3-3] in either the field or the pot experiment was the least P-dependable; the relative yields of low P/high P

Figure 2. Relative grain yields at low-P/high-P in both field and pot experiments. Genotypes are coded as follows 1=81(85)5-3-3-3, 2=Ji 87-4617, 3=Yan 054, 4=Jingdong 5227, 5=90-6060, 6=Jimai 17, 7=Taihe 5025, 8=Lovrin No. 10, 9=Jinghe90Jian31, 10=Dai 108, 11=Jing 411, 12=6154, 13=Yanzhong 144, 14=Qinmai No. 1, 15=Jinghe90Jian17, 16=NC37, 17=Fengkang No. 8, 18=Jinghe No. 1, 19=9269-3-1-1 and 20=8602.

were about or over 90%. The results indicate that P-efficient genotypes could produce almost as much grain yield under low-P as in high-P conditions.

From the statistics, a high correlation coefficient between the field and the pot experiments in grain yield at high P ($r = 0.63^{**}$, $n = 20$), low P ($r = 0.65^{**}$, $n = 20$), and the ratio of low P/high P ($r = 0.71^{**}$, $n = 20$) was found. This result demonstrates that most of the genotypes had a good stability in different experimental conditions.

In either the field or the pot experiment, no significant correlation was found between grain yield and yield components, e.g., number of ears per plant, number of seeds per ear, or 1000-seed weight (data not shown). However, the total biomass was significantly correlated with the grain yield from the field ($r = 0.46^{**}$ at high-P and $r = 0.38^{*}$ at low-P levels, $n = 40$).

Phosphorus Uptake, P-Utilization Efficiency (PUE), and P-Harvest Index (PHI)

Phosphorus uptake may or may not result in a high P efficiency. For instance, in both the pot and the field experiments, cultivar Yanzhong 144 showed the highest P uptake in both high-P and low-P conditions (Table 2), but did not exhibit the highest relative yield (Table 2). As a matter of fact, the relative yields of low P/high P were 86% in the pot experiment and 84% in the field (Figure 1) because of moderate or low utilization despite high P uptake. However, under low-P conditions, the P-efficient genotypes Ji 87-4617, Jing 411, and Yan 054 showed high P uptakes, but the inefficient genotypes 9269-3-1-1, 8602, Fengkang No. 8, and Jinghe No. 1 had a relatively low uptake of P (Table 2).

The PUE values of the genotypes corresponded well with the P-efficient or inefficient criterion of 85% of relative yield. For example, most of the P-efficient genotypes, such as 81 (85) 5-3-3-3, Jingdong 5227, 6154, and Jing 411, showed the highest PUE values, while the P-inefficient genotypes, e.g., NC 37 and Qinmai No. 1, showed the lowest PUE values (Table 2).

Examination of the PHI values reveals that, in general, the most P-efficient genotypes, e.g., Dai 108, Jing 411, Taihe 5025, Lovrin No. 10, and Ji 87-4617 had higher ratios of P re-translocated from the shoots to the grains compared with inefficient cultivars, e.g., Jinghe No. 1, NC 37, and Qinmai No. 1 under conditions of both high and low P supply. However, there were some exceptions. For example, the inefficient genotype 8602 had a relatively higher PHI, but the P uptake was fairly low; the efficient genotype Jingdong 5227 had a relatively lower PHI, but the PUE was relatively higher, especially at the low-P condition (Table 2).

The data for P uptake, P-utilization efficiency, and P-harvest index from the field experiment (data not shown) showed a good correlation with those from the pot experiment, especially at the low-P condition (Table 3). The contribution of variation in efficiency components to cultivar sum of squares for P efficiency was calculated to further compare the dominant effect of either P

Table 2
Phosphorus uptake, P-utilization efficiency, and P-harvest index of wheat genotypes receiving 40 (high P) and 10 (low P) mg fertilizer P kg⁻¹ in the pot experiment

Genotypes	P-uptake ^a		PUE ^b		PHI ^c	
	High P	Low P	High P	Low P	High P	Low P
81(85)5-3-3-3	72.9	48.3	209	282	0.65	0.62
Ji 87-4617	90.7	59.8	180	236	0.76	0.74
Yan 054	78.8	54.0	170	213	0.72	0.70
Jingdong 5227	51.1	35.6	213	275	0.60	0.56
90-6060	81.9	50.5	160	226	0.74	0.71
Jimai 17	53.6	41.5	220	244	0.69	0.73
Taihe 5025	65.9	42.1	170	233	0.81	0.75
Lovrin No. 10	69.9	46.0	179	235	0.74	0.75
Jinghe90Jian31	52.9	34.4	185	241	0.71	0.74
Dai 108	69.0	44.8	182	250	0.77	0.78
Jing 411	91.3	54.9	182	262	0.76	0.75
6154	94.0	51.4	174	304	0.67	0.61
Yanzhong 144	109.2	67.5	167	231	0.69	0.71
Qinmai No. 1	62.8	45.9	152	197	0.55	0.63
Jinghe90Jian17	88.7	50.8	175	240	0.67	0.67
NC37	82.8	50.8	144	184	0.58	0.68
Fengkang No. 8	75.8	35.2	186	250	0.77	0.78
Jinghe No. 1	76.4	33.5	161	239	0.57	0.70
9269-3-1-1	25.9	22.5	220	351	0.66	0.71
8602	68.3	24.9	217	346	0.71	0.74
LSD (P < 0.05)	23.8	16.2	98	112	0.37	0.29

^aGrain P uptake + straw P uptake, mg pot⁻¹.
^bGrain DM yield/(grain P uptake + straw P uptake), g DM g⁻¹ P.
^cRatio of grain P uptake/(grain P uptake + straw P uptake).

Table 3
Correlation coefficients (*r*) on P-uptake, PUE, and PHI between the field and pot experiments

P rates	P-uptake ^a	PUE ^b	PHI ^c
High P	0.53*	0.67**	0.48
Low P	0.62**	0.72**	0.76**

^aGrain P uptake + straw P uptake, mg pot⁻¹.
^bGrain DM yield/(grain P uptake + straw P uptake), g DM g⁻¹ P.
^cRatio of grain P uptake/(grain P uptake + straw P uptake).
*Significant at P < 0.05; **Significant at P < 0.01 (n = 20).

Table 4

Contribution of variation in efficiency components to genotype sums of squares for efficiency of P uptake and utilization (pot experiment)

Trait (Yi or Xi)	P treatment	Fraction of cultivar SS ($\sum X_i Y / \sum Y^2$)	r_{yxi}	S_{xi}/S_y
Dry weight (D_w) at shooting stage-Y1				
P uptake (P_U) at shooting-X1	High P	0.38	0.59*	0.64
	Low P	0.05	0.23	0.20
P-utilization efficiency (D_w/P_U) at shooting stage-X2	High P	0.52	0.46	1.13
	Low P	0.83	0.77**	1.08
Grain yield (G_w) at maturity Y2				
Total P uptake (P_U)-X3	High P	0.21	0.50	0.41
	Low P	0.08	0.24	0.33
P-utilization efficiency (G_w/P_U)-X4	High P	0.38	0.54	0.72
	Low P	0.77	0.83**	0.93

r_{yxi} = correlation coefficient between Yi and Xi.

S_y = standard deviations for Xi and Yi, respectively.

The proportion of the sum of squares for Y attributable to Xi is $\sum X_i Y / \sum Y^2 = (r_{yxi}) S_{xi}/S_y$.

*Significant at $P < 0.05$; **Significant at $P < 0.01$.

P-utilization efficiency at shooting stage represents DM produced by per g of P taken up.

uptake or P-utilization efficiency on DM production at shooting stage and grain yield after harvest under high-P and low-P conditions (Table 4). The correlation coefficients between both DM and grain yield and P utilization (r_{yxi}) were significant at $P < 0.01$ under low-P conditions, while those between DM production and P-uptake efficiency were significant ($P < 0.05$) only at the shooting stage of plant development (Table 4).

To find out some useful parameters at the early stage to predict P efficiency for wheat genotypes, a good correlation in P uptake and P utilization was observed at the shooting but not at the tillering stage (Table 5). To further compare

Table 5

Correlation coefficients (r) between plants at maturity and at tillering and shooting stages in P concentration, P-uptake, and utilization (pot experiment)

Growth stage	P concn. (mg g^{-1})	P-uptake (mg plant^{-1})	PUE ($\text{g DM g}^{-1} \text{ P}$)
Tillering	0.01	0.21	0.18
Shooting	-0.12	0.32*	0.43**

*Significant at $P < 0.05$; **Significant at $P < 0.01$ ($n = 60$).

which parameter plays the more important role in leading to P efficiency for individual genotypes, the P concentration, P uptake, and P-utilization efficiency were compared for ten P-efficient genotypes from the pot experiment at shooting stage (Table 6). The results show that the last six of the 10 P-efficient genotypes based on grain yield (Table 6) had high uptake efficiencies under low-P conditions (ratio of low-P/high-P P concentrations $>85\%$), but the percent relative utilization efficiencies (rate of DM production per unit of P taken up) in low P/high P was below the average (118). In the case of the other four P-efficient genotypes, the percent low P/high P, in terms of P uptake, was lower, especially for cultivar 81(85)5-3-3-3 (only 60%), but the percent relative utilization efficiency (low P/high P) rose to 120–168 (Table 6).

DISCUSSION

There were significant differences in yield production and P-efficiency among the 20 Chinese wheat genotypes studied under both high-P and low-P conditions. This result implies that it is possible to increase wheat yield through breeding for high P efficiency because variability exists among those genotypes or cultivars in grain yield under P stress. This variability in crops has been observed by a number of other researchers (Batten, 1986; Jones et al., 1989; Nielsen and Schjorring, 1983). The criterion of $\geq 85\%$ relative grain yield was found to be a satisfactory basis for describing P efficiency, since both P uptake and P-utilization efficiency were taken into account, despite the fact that PHI and PUE have been preferred in the past as criteria for wheat screening (Batten, 1986; Jones et al., 1989, 1992).

Since P efficiency is composed of both uptake and utilization efficiency (as mentioned above), either one of these aspects of efficiency could play an important role in determining overall P efficiency. A similar result was obtained in topless faba beans by Stelling et al. (1996) and in spring barley by Römer and Schenk (1998), who concluded that a combination of high uptake efficiency and high utilization efficiency in a cultivar might be possible.

These results imply that some of the P-efficient genotypes, e.g., Yanzhong 144 (Wang et al., 2000), Ji 87-4617 (Wallace and Lunt, 1960), Jing 411 (Li et al., 1995), and Yan 054 (Sharpley et al., 1994), could increase P uptake from P-deficient soil, and that P uptake was a major process leading to P efficiency for these genotypes. Other genotypes might efficiently utilize P absorbed from the soil to maximize yield, but the rate of P uptake by these genotypes might not be high, and P-utilization efficiency was the dominant process determining P efficiency.

Some researchers have also found that P or other nutrient efficiency can be achieved by uptake or utilization efficiency (Clark, 1983; Gabelman and Gerloff, 1983; Föhse et al., 1988; Sattelmacher et al., 1994). Other researchers have observed that at high P supply, P efficiency was more favored by a high P uptake,

Table 6
Phosphorus uptake and utilization efficiency of wheat genotypes at the shooting stage in the pot experiment

Genotypes	P concentration			P uptake			P-utilization efficiency		
	mg g ⁻¹		%	mg plant ⁻¹		%	g DM g ⁻¹ P		%
	High P	Low P		High P	Low P		High P	Low P	
81(85)-5-3-3-3	1.8	1.0	60	4.3	1.7	40	570	955	168
906060	2.1	1.6	75	4.3	1.9	45	479	638	133
Taihe 5025	2.5	1.9	79	3.3	2.0	61	406	514	127
Lovrin No. 10	2.2	1.9	83	3.2	1.7	53	450	541	120
Jing 411	2.1	1.8	86	3.6	2.0	55	476	556	117
Jingdong 5227	1.2	1.0	87	2.5	1.3	51	838	965	115
Dai108	2.0	1.7	87	2.6	1.4	53	498	573	115
Yan 054	2.0	1.8	89	2.6	2.4	89	490	549	112
Ji87-4617	1.6	1.6	102	2.8	2.1	75	627	617	99
Jimai 17	1.3	1.4	109	2.3	2.0	87	766	703	92
Mean	1.9	1.6	85	3.2	1.8	58	560	661	118
LSD (P<0.05)	0.5			0.8			68		

whereas in P-deficiency conditions it was likely explained by a high internal P-utilization efficiency (Stelling et al., 1996).

Although young cereal crops require sufficient P to develop tillers and spikelets (Römer and Schenk, 1998), a poor correlation was found between young (tillering stage) and mature plants in DM vs. grain yield, P concentration, P uptake, and P-utilization efficiency in our experiments (Table 5). It does seem to be possible to find an effective approach for screening P-efficient genotypes. Similar results were obtained by Leon et al. (1989) for maize, by Thung (1990) for *Phaseolus* beans, and by Römer and Schenk (1998) for barley. However, P uptake and P-utilization efficiency at shooting stage may offer the possibility of evaluating wheat genotypes for P efficiency, because a positive correlation for those parameters between plants at this development stage and maturity was found (Table 5).

The level of plant-available P in the soil is an important factor in screening for P-efficient wheat genotypes. No response will occur if available P is either too high or too low because an adequate P supply may mask the potential of an efficient genotype, and in contrast when P availability is too low, even efficient genotypes will not be able to express their genetic characteristics (Wang et al., 1999a). However, according to our experience, a soil Olsen-P level of about 5–8 mg kg⁻¹ is optimal for screening of P-efficient wheat genotypes in our highly calcareous soils, although some researchers have worked with much higher levels (P = 100 mg kg⁻¹) in a P-stressed environment (Römer and Schenk, 1998; Stelling et al., 1996). The calcareous soil in this study contained a relatively high amount of total P, but the bio-availability (e.g., the amount of extractable P) was relatively low (Table 1).

DM or grain-yield production results from both P uptake and utilization efficiency, but the latter seems more important, especially under P-deficiency conditions. This accords well with our previous report that P-efficient wheat genotypes required a lower application rate of P fertilizer to obtain maximum yield and had lower critical P concentrations in shoots compared with the inefficient cultivars (Wang et al., 1999a). This suggests that there is potential for introducing genotypes with high P-efficiency in agriculture to produce optimum yields with low inputs of P fertilizers. This could allow maintenance of adequate yields with economic savings and protection of the environment by minimizing the risk of non-point source pollution and eutrophication of rivers and lakes.

CONCLUSIONS

Significant yield differences among wheat genotypes were found with and without P fertilizer application. These effects could be exploited for the screening and identification of P-efficient germplasm that could help to provide superior genetic material in breeding programs. Some Chinese wheat cultivars with high

yield and high P-efficiency (e.g., Jingdong 5227) were identified. These may be useful for extensive agricultural systems or as parental lines in plant breeding. Low-yield cultivars with high P efficiency (e.g., Jinghe90Jian31) can be grown in infertile soil to produce a relatively high yield. However, with those germplasms, some transgenic plants with high yield and high P efficiency associated with some other traits, such as resistance to disease, pathogens, etc., could be produced through molecular bio-techniques. There are two broad types of P efficiency: uptake capacity from the soil and efficiency in the internal utilization of absorbed P in the plant. The latter seems to play a more important role in P efficiency in wheat.

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