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Response of Two Maize Inbred Lines with Contrasting Phosphorus Efficiency and Root Morphology to Mycorrhizal Colonization at Different Soil Phosphorus Supply Levels

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ABSTRACT

A pot experiment investigated the response of two maize inbred lines with contrasting root morphology and phosphorus (P) efficiency to inoculation with *Glomus mosseae* or *Glomus etunicatum* compared with non-mycorrhizal controls. Soil phosphorus was supplied at rates of 10, 50, and 100 mg P kg⁻¹ soil. Root length, specific root length, and specific phosphorus uptake of maize line 178 (P-efficient) were significantly higher than of line Hc (P-inefficient). Percentage of root length colonized showed the opposite trend regardless of soil P supply level. The two maize lines did not differ significantly in growth response to mycorrhizal colonization. Root colonization rate decreased with increasing soil phosphorus supply. The beneficial effect of the two AM fungi on plant growth and P uptake was greatest at low soil P level and the responses were negative at high P supply. Mycorrhizal responsiveness also decreased with increasing P supply and differed between the two mycorrhizal fungal isolates.

Keywords: Arbuscular mycorrhizal fungi; Soil phosphate supply; Maize; Phosphorus efficiency; Mycorrhizal responsiveness

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INTRODUCTION

Arbuscular mycorrhizal (AM) fungi are vital components of most terrestrial ecosystems, forming potentially symbiotic associations with the roots of around 80% of vascular plant species (Smith and Read, 1997). Under certain conditions AM fungi assist plants in the acquisition of mineral nutrients in exchange for carbon compounds. The key contribution of AM fungi to the plant is the supply of less mobile elements, particularly phosphate, although other beneficial functions have also been attributed to AM fungi including the supply of other elements (Marschner, 1995) and increasing plant tolerance to pathogens and to water stress (Newsham et al., 1995). The AM fungi have been shown to provide the dominant route for plant phosphorus (P) uptake (Smith et al., 2003), can supply 80% of plant P requirements (Marschner and Dell, 1994) and account for over 50% of plant P uptake even in the absence of positive plant growth responses (Li et al., 2006).

The outcome of the AM associations with respect to P uptake and plant growth is highly variable as reported in the literature. Inoculation with AM fungi can be beneficial, detrimental or of no consequence to nutrient uptake and growth of host plants (Johnson et al., 1997; Smith et al., 2003). Factors related to the fungus-host combination, in particular soil, fungal and plant traits can have a great impact on the functional diversity of the fungal symbiont. In comparison to the numerous studies conducted on soil properties and fungi parameters, relatively little information has been obtained on plant attributes and their relationships with symbiotic performance other than the general concept that any beneficial effect of AM fungi diminishes as a result of enhanced plant P uptake (Abbott and Robson, 1984; Lu et al., 1994). Differences in plant response to AM colonization have been observed among different categories at the species level, e.g., crop (Plenchette et al., 1983) and forage species (Schweiger et al., 1995), and at the cultivar level, e.g., in wheat (Azcon and Ocampo, 1981), barley (Baon et al., 1994), tomato (Bryla and Koide, 1990), and Welsh onion (Tawaraya et al., 2001). The term 'mycorrhizal dependency' is commonly used to define and quantify plant responses to AM colonization (Gerdemann, 1975; Menge et al., 1978) and the values can range from 0 to 99% (Plenchette et al., 1983). In a recent review Janos (2007) further clarified the terms 'dependency' and 'responsiveness' and suggested that plant responsiveness to mycorrhizas differs from dependence upon mycorrhizas. According to Janos, the term 'mycorrhizal dependency' used in many experiments is in fact 'responsiveness.' No matter which terms are used, experimental results have shown that plant attributes, particularly root properties such as root architecture, root hairs, root length, and root weight (Baylis, 1975; Eissenstat et al., 1993; Declerck et al., 1995; Menge et al., 1978; Tawaraya et al., 1999) are the most fundamental factors affecting plant mycorrhizal dependency (or responsiveness in regards to Janos) because these parameters are closely related to the colonization pattern of AM fungi on plant roots. For example, plants with few

and short root hairs (magnolioid roots) were more dependent (or responsive) than plants with graminoid roots on mycorrhiza for P uptake (Baylis, 1975). A root hair-less barley mutant, bald root barley (brb), was more responsive to mycorrhiza than the wild type (Jakobsen et al., 2005). Musa genotypes with a proportionally high secondary and tertiary root weight had low mycorrhizal dependency (Elsen et al., 2003), and genotypes with a well-developed root system appeared not to require establishment of a mycorrhizal symbiosis. In addition to plant morphological traits, plant physiological parameters such as plant growth rate, transpiration rate (Graham and Syvertsen, 1985) and P uptake and utilization efficiency (Yao et al., 2001) have also been reported to be related to the mycorrhizal dependency of the plants.

The novelty of the present experiment was that two maize inbred lines with contrasting root morphology and differing in P efficiency were used as the experimental plants. The two maize (*Zea mays* L.) inbred lines Huang C (Hc, P-inefficient) and 178 (P-efficient) were selected from 100 inbred lines at high (60 kg ha⁻¹) and zero P supply in the field in Beijing in the year 2001 (Liu, 2003). Both inbred lines were stay-green lines and matured at almost the same time. This allowed us to test the hypothesis that root morphology and plant P efficiency might affect plant mycorrhizal responsiveness and the potential effect of AM fungi on host plant P efficiency was also evaluated at three levels of soil P status.

MATERIALS AND METHODS

The two maize inbred lines Hc and 178 were provided by the Chinese National Maize Improvement Centre at China Agricultural University. The inbred lines had contrasting root morphology with different P efficiency. Both visual observation and experimental data showed that line 178 had short and thick roots while roots of line Hc were long and thin. Line 178 was defined as P-efficient and Hc as P-inefficient based on the relative yields obtained in field experiments. In 2004 the yields of lines Hc and 178 were 1699 and 2635 kg ha⁻¹, respectively, in P fertilized soils (60 kg ha⁻¹), while the corresponding values were 528 and 1506 kg ha⁻¹ in P-deficient soils (zero P supply).

The soil was collected from the vicinity of Pangezhuang county, Daxing district, Beijing and was a sandy soil with the following physicochemical properties (dry matter basis): pH (soil:H₂O 1:2.5) 8.44, organic matter 0.95%, Kjeldahl-nitrogen (N) 0.08%, Olsen-P [0.5 mol L⁻¹ sodium bicarbonate (NaHCO₃)-extractable] 7.75 mg kg⁻¹, and exchangeable potassium K (1 mol L⁻¹ ammonium acetate) 33.6 mg kg⁻¹. The soil was sieved (<2 mm), sterilized by autoclaving at 120°C for 2 h and air-dried. The soil was amended with basal fertilizers of N, P, and K in solution. Nitrogen [as ammonium nitrate (NH₄NO₃)] and K [as potassium sulfate (K₂SO₄)] were supplied as basal fertilizers at rates of 200 mg N and 150 mg K kg⁻¹ soil. Phosphorus was supplied as

monopotassium phosphate (KH_2PO_4) at rates of 10 (P1), 50 (P2), and 100 mg P kg^{-1} soil (P3). The soil was placed in round plastic pots (1 L) containing 1.0 kg soil. First, approximately 25% of the soil was placed in the bottom of each pot, followed by 60% soil mixed thoroughly with mycorrhizal inoculum, and then the remainder of the soil on top. Mycorrhizal treatments received 100 g inoculum of *G. mosseae* (BEG167) or *G. etunicatum* (BEG 168), while the non-mycorrhizal treatment received an equivalent amount of sterilized inoculum together with a filtrate (0.45 μm pore size) of unsterilized soil to provide a similar microflora except for the absence of the mycorrhizal fungus. The mycorrhizal inocula consisted of loose soil containing spores and colonized maize root fragments. Seeds of maize (*Zea mays* L.) were surface sterilized in a 10% (v/v) solution of hydrogen peroxide for 10 min and then thoroughly washed with deionized water. Five seeds were initially sown in each pot. Seedlings were thinned to three when the third leaf appeared. There were three P supply levels, together with three mycorrhizal treatments, producing a total of nine treatments for each maize inbred line. There were four replicates of each treatment, giving a total of 72 pots.

Plants were grown for eight weeks in the glasshouse of the Department of Plant Nutrition, China Agricultural University, Beijing without supplementary illumination with a daytime temperature range of 25–32°C and a night temperature range of 20–25°C. The seedlings were irrigated with deionized water and the soil moisture was maintained at 60–70% of water holding capacity after weighing.

At harvest plants were separated into shoots and roots. Root sub-samples (0.5 g fresh weight) were cut into 1-cm-long segments to determine root length (Tennant, 1975) and the percentage of root length colonized by AM fungi (Giovannetti and Mosse, 1980). The remainder of the plant materials was dried in a forced-air oven at 70°C for 48 h and weighed. Samples were then milled with a high-speed multi-function micro-pulverizer (Whirl type, Model Y-60, Hebei, China) prior to elemental analysis. Samples of ground materials were then oven dry ashed at 500°C and dissolved in hydrochloric acid (HCl). The solution was filtered for P analysis. Plant P concentration was determined by the standard vanado-molybdate method using a Shimadzu Model UV-120-02 spectrophotometer. Responsiveness (total P uptake and plant growth) of each maize inbred line to inoculation with mycorrhizal fungi was calculated based on Janos (2007) as follows:

$$\begin{aligned} \text{Plant P uptake responsiveness} &= (\text{P content (+M)} \\ &\quad - \text{P content (-M)}) / \text{P content (+M)} \times 100; \end{aligned}$$

$$\begin{aligned} \text{Plant growth responsiveness} &= (\text{dry weight (+M)} \\ &\quad - \text{dry weight (-M)}) / \text{dry weight (+M)} \times 100 \end{aligned}$$

Where +M denotes inoculated plants and -M uninoculated plants).

Three-way analysis of variance (ANOVA) was performed using the SAS statistical software package (Version 8.0). Significant differences between means were established by calculation of LSD at the 5% level.

RESULTS

No fungal colonization was observed on the roots of the non-mycorrhizal plants (Table 1). Root infection rate of P-inefficient line Hc was significantly higher than that of P-efficient line 178. Plants inoculated with *G. mosseae* generally had higher root infection rates than those inoculated with *G. etunicatum* (except for Hc at P2). Increasing P supply in the soil greatly suppressed root infection rates of the two maize inbred lines. Root length of Hc was often significantly higher than that of 178 (Table 1). Root lengths of mycorrhizal plants at P1 were significantly higher than that of non-mycorrhizal plants across both maize

Table 1

Root length, specific root length (SRL) and root infection rate of maize inbred lines Hc and 178 inoculated with *Glomus mosseae* or *Glomus etunicatum* or uninoculated

P level	Mycorrhizal status	Root length (m)		Specific root length (m g ⁻¹)		Root infection rate (%)	
		Hc	178	Hc	178	Hc	178
P1	Uninoculated	102	71	110	92	ND	ND
10 mg kg ⁻¹	<i>G. mosseae</i>	146	131	100	70	57	33
	<i>G. etunicatum</i>	116	149	72	65	40	26
P2	Uninoculated	318	268	116	88	ND	ND
50 mg kg ⁻¹	<i>G. mosseae</i>	200	185	76	79	32	24
	<i>G. etunicatum</i>	147	120	63	62	43	12
P3	Uninoculated	289	268	99	88	ND	ND
100 mg kg ⁻¹	<i>G. mosseae</i>	248	208	85	79	19	15
	<i>G. etunicatum</i>	144	118	71	57	21	9
Significance ^a due to							
Inoculation		***		***		***	
Inbred lines		*		**		***	
P supply level		***		***		***	
Inoculation × inbred line		NS		NS		***	
Inoculation × P supply level		***		***		***	
Inbred lines × P supply level		NS		NS		*	
Inoculation × inbred line × P supply level		NS		NS		***	

^aBy analysis of variance; ***, P < 0.001; **, P < 0.01; *, P < 0.05; NS, not significant.

inbred lines, but at P2 and P3 the opposite trend occurred. Root length of non-mycorrhizal and mycorrhizal Hc was significantly lower at P1 than at P2 or P3, and the last two did not differ significantly. Similar trends were observed for line 178 except for plants inoculated with *G. etunicatum* whose root length was reduced when P was added. Specific root length (SRL) of Hc was generally significantly higher than that of 178 (Table 1). Inoculation with AM fungi reduced SRL of both maize inbred lines, and the SRL of plants inoculated with *G. mosseae* was higher than that of plants inoculated with *G. etunicatum*. P supply level did not significantly affect the SRL of non-mycorrhizal plants or of plants inoculated *G. etunicatum*, but the SRL of Hc plants inoculated with *G. mosseae* decreased significantly at P2 compared to P1 and P3 and that of line 178 plants inoculated with *G. mosseae* was higher at P2 and P3 than at P1.

There was no significant difference between Hc and 178 in shoot or root dry weight (Table 2). Shoot and root dry weights of both inbred lines were significantly affected by P supply level and by inoculation with AM fungi. The dry weights of shoots and roots of mycorrhizal plants were substantially higher than of the controls at P1, but at P2 and P3 growth of mycorrhizal plants was not promoted (except for shoot dry weight of plants inoculated with *G. mosseae* at

Table 2
Dry weight (DW) of shoots and roots of maize inbred lines Hc and 178 inoculated with *Glomus mosseae* or *Glomus etunicatum* or uninoculated

Treatment	Inoculum	Shoot DW (g)		Root DW (g)	
		Hc	178	Hc	178
P1 10 mg kg ⁻¹	-M	1.72	1.76	0.81	0.94
	<i>G. mosseae</i>	3.27	2.66	1.87	1.67
	<i>G. etunicatum</i>	3.06	3.81	1.47	2.14
P2 50 mg kg ⁻¹	-M	4.28	4.42	2.77	3.07
	<i>G. mosseae</i>	4.58	4.64	2.64	2.86
	<i>G. etunicatum</i>	3.70	3.49	2.29	1.92
P3 100 mg kg ⁻¹	-M	5.83	5.78	2.94	3.03
	<i>G. mosseae</i>	4.93	4.47	2.94	2.77
	<i>G. etunicatum</i>	4.04	4.10	2.21	2.04
Significance ^a due to:					
Inoculation		**		*	
Inbred lines		NS		NS	
P supply levels		***		***	
Inoculation × inbred lines		NS		NS	
Inoculation × P supply levels		***		***	
Inbred lines × P supply levels		NS		NS	
Inoculation × inbred lines × P supply levels		NS		NS	

^aBy analysis of variance; ***, P < 0.001; **, P < 0.01; *, P < 0.05; NS, not significant.

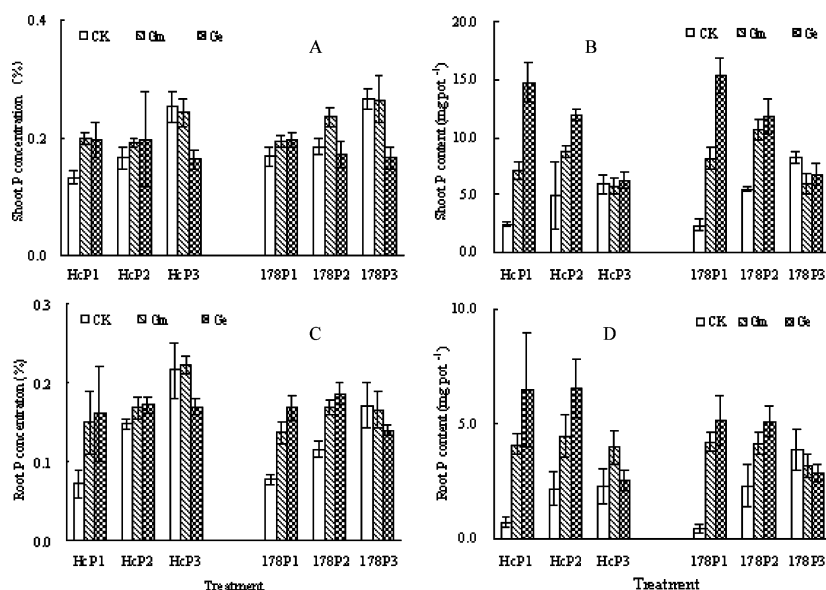


Figure 1. P concentration and content of shoots (A and B) and roots (C and D) of maize inbred lines Hc and 178 associated with *Glomus mosseae* or *Glomus etunicatum* or uninoculated at three P supply levels. Error bars: ± 1 SE.

P2), and was actually reduced, particularly in the case of plants inoculated with *G. etunicatum*. Shoot dry weight was significantly higher at P2 and P3 than at P1 (except line 178 inoculated with *G. etunicatum* at P2), while root dry weight at P1 was generally lower than at P2 or P3.

No significant differences were observed between lines Hc and 178 in shoot P concentrations but root P concentrations of Hc were usually higher than of 178 (Figure 1; Table 3). Shoot P concentrations of both maize inbred lines were significantly increased by inoculation with *G. mosseae* at P1 and P2, while at P3 there was no significant difference between mycorrhizal and non-mycorrhizal plants. Compared to the non-mycorrhizal plants, shoot P concentrations of plants inoculated with *G. etunicatum* were increased at P1 but at P2 were not significantly affected, and at P3 shoot P concentrations were markedly reduced. Similar trends were observed in root P concentrations of both inbred lines except that root P concentrations of plants inoculated with *G. etunicatum* were significantly higher than those of non-mycorrhizal controls at P2. For both maize inbred lines, shoot and root P concentrations of non-mycorrhizal controls and of plants inoculated with *G. mosseae* increased with increasing P supply level in the soil but no significant differences in shoot or root P concentrations of plants inoculated with *G. etunicatum* were observed among the three P supply levels, except that root P concentrations of line 178 were greatly depressed at

Table 3
Analysis of variance for Figures 1 and 2

	Shoot P conc. (%)	Root P conc. (%)	Shoot P cont. (mg pot ⁻¹)	Root P cont. (mg pot ⁻¹)	Specific P uptake (mg m ⁻¹)
Significance ^a due to					
Inoculation	***	***	***	**	***
Inbred lines	NS	**	NS	NS	**
P supply levels	***	***	***	***	***
Inoculation × inbred lines	NS	NS	NS	NS	NS
Inoculation × P supply levels	***	***	***	***	***
Inbred lines × P supply levels	NS	**	NS	*	NS
Inoculation × inbred lines × P supply levels	NS	NS	***	NS	NS

^aBy analysis of variance; ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$; NS, not significant.

P3. Inoculation with AM fungi and P supply significantly affected shoot and root P contents of both maize inbred lines and the effects of the two parameters on P nutrition of the plants followed similar trends as on plant P concentrations, except that the reduction in P contents of shoots and roots of plants inoculated with *G. etunicatum* was more pronounced at P3 (Figure 1; Table 3). Specific P uptake of 178 was significantly higher than that of Hc. Mycorrhizal inoculation resulted in increased specific P uptake of both inbred lines at P1 and P2, but not at P3 (Figure 2; Table 3). Specific P uptake of non-mycorrhizal plants and of Hc and 178 plants inoculated with *G. mosseae* tended to increase with increasing P supply level but no such trend was observed in plants inoculated with *G. etunicatum*.

The responsiveness of the two inbred lines to mycorrhizal fungi fell within the range of 44–55% (dry matter basis) or 47.9–69.4% (total P uptake) at P1 and decreased substantially with increasing P supply level. While plant responsiveness to inoculation with *G. mosseae* was positive at P2, that of plants to *G. etunicatum* was negative. The mycorrhizal responsiveness of the two lines was strongly negative at P3. Plants had higher responsiveness to inoculation with *G. mosseae* than with *G. etunicatum* except for line 178 at P1 (Table 4).

DISCUSSION

Soil phosphorus availability has a profound influence on plant response to AM fungi (Grant et al., 2005; Sieverding and Howeler, 1985). At low P concentrations AM fungi often enhance plant P uptake and plant growth (Smith and Read,

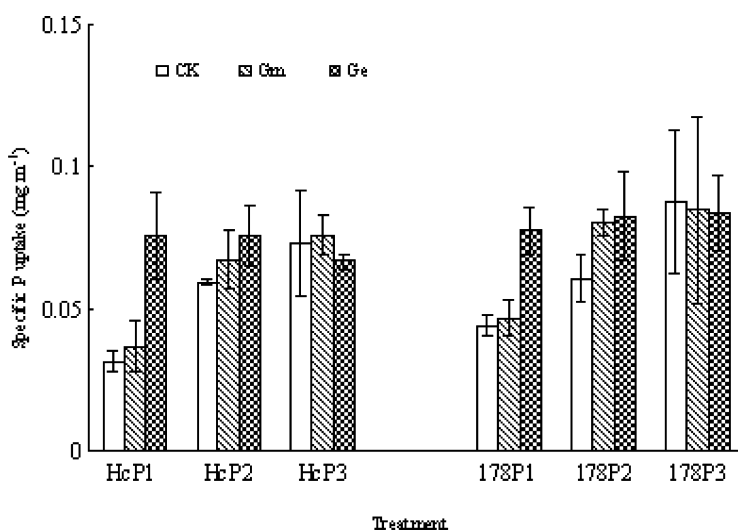


Figure 2. Specific P uptake of maize inbred lines Hc and 178 associated with *Glomus mosseae* or *Glomus etunicatum* or uninoculated at three P supply levels. Error bars: \pm 1 SE.

1997) but this effect declines at high soil P supply levels (Hirata et al., 1988; Takacs et al., 2006). Our results agree with these findings. Root colonization rate of both maize inbred lines was markedly suppressed at intermediate and high P levels (Table 1). Inoculation with AM fungi resulted in enhanced P nutrition and greater shoot growth at 10 mg kg⁻¹ P supply, and at the intermediate P supply level the beneficial effect of the AM fungi was strongly reduced and the responses were negative at high P supply (Tables 1 and 4; Figure 1). High

Table 4

Responsiveness (dry weight and total P uptake) of maize inbred lines Hc and 178 to inoculation with *Glomus mosseae* or *Glomus etunicatum*

Treatment	Inoculum	Dry weight responsiveness (%)		Total P uptake responsiveness (%)	
		Hc	178	Hc	178
P1	<i>G. mosseae</i>	50.8	37.7	69.4	47.9
10 mg kg ⁻¹	<i>G. etunicatum</i>	44.2	54.8	65.1	67.3
P2	<i>G. mosseae</i>	2.39	0.00	15.6	20.4
50 mg kg ⁻¹	<i>G. etunicatum</i>	-17.6	-38.6	-0.8	-35.3
P3	<i>G. mosseae</i>	-11.4	-21.8	-14.8	-20.9
100 mg kg ⁻¹	<i>G. etunicatum</i>	-40.2	-43.4	-105.1	-111.9

P availability in the soil can inhibit AM colonization of plants roots, decrease the frequency of entry points and vesicles (Abbott and Robson, 1984; Amijee et al., 1989), and reduce the length of external hyphae associated with the AM fungi (Abbott and Robson, 1984; Liu et al., 2000). In addition, AM fungi may compete with plants for carbon so that plant growth may be reduced (Bago et al., 2000). The AM fungi act as a carbon drain and the carbon consumption of AM fungi may exceed the nutritional or yield benefit produced (Graham et al., 1997). A recent study showed that carbon (C) flow to fungi actually increased during the initial period of infection under high P conditions (Olsson et al., 2006). In the present study, intermediate and high P supply tended to suppress the beneficial effects of the AM fungi. We did not find any significant differences in hyphal length density of the two maize inbred lines among the three P supply levels (data not shown). Therefore, we assume that in addition to the low root colonization rate caused by the high P supply, the carbon consumption of the two fungal isolates may also partly account for the diminished effects of the AM fungi on plant P uptake and growth. The AM fungi have been shown to induce an extra C flow amounting to 3% of daily gross photosynthesis (Grimoldi et al., 2006).

One of our hypotheses was that P-efficient line 178 may be more responsive than Hc to mycorrhizal colonization, based on their root parameters. However, we did not observe higher mycorrhizal responsiveness in line 178 except when inoculated with *G. etunicatum* at P1 in terms of plant dry weight. The mycorrhizal response (dry weight and total P uptake) and root colonization rate of 178 were actually lower than those of Hc. These results contradict those of other studies which indicated that root parameters are key factors influencing plant responses to inoculation with AM fungi (Baylis, 1975; Declerck et al., 1995; Tawaraya et al., 2001). Other plant attributes can also have some influence on the mycorrhization of the plants, and plant responses to mycorrhizal colonization may not necessarily be related to root traits. For example, Collier et al. (2003) reported that root diameter was not related to colonization levels in the field and they presumed that the mycorrhizal response might be related to root longevity. It can be inferred from our study that the two maize inbred lines may have inherently similar mycorrhization properties during their breeding programs. This is further indicated by the response of the two inbred lines to mycorrhization. Inoculation with both mycorrhizal fungi had similar effects on the root length and specific root length of the two maize lines (Table 1). To further compare the inherent mycorrhizal dependency properties of the two maize inbred lines, plant growth and P uptake should be tested over a larger number of soil P supply levels as suggested by Janos (2007). In addition, genetic analysis of the two inbred lines may provide more information on this aspect.

Although the two inbred lines have been classified as P-efficient (178) and P-inefficient (Hc) according to their relative yields in field experiments, no significant differences in P uptake or plant growth were observed between the two lines (Figure 1; Table 2), indicating that their P efficiency may not

appear at the seedling stage. High P efficiency of the plants can be the consequence of improved phosphorus uptake efficiency and/or phosphorus utilization (Marschner, 1995). The higher specific P uptake of 178 may partly explain the high P efficiency of this line. In addition, other plant traits attributable to plant P acquisition and uptake may have effects on the genotypic differences in P efficiency as reviewed by Gahoonia and Nielsen (2004) and Bucher (2007).

The two mycorrhizal fungal isolates used in the present study are dominant AM fungal species on the North China Plain. Root colonization rate was higher in plants inoculated with *G. mosseae* than in those inoculated with *G. etunicatum* (Table 1). The growth and P uptake of Hc plants was greatly enhanced by inoculation with *G. mosseae* and, in contrast, of 178 by inoculation with *G. etunicatum* (Table 2; Figure 1). Fungal species and isolates differ in their affinities to host plants, in their uptake and transfer of P to the host plants (Jakobsen et al., 1992a; b; Smith et al., 2000), and in the infection pattern and growth of their hyphae (Avio et al., 2006), and likely therefore as a result, in plant growth and P uptake (Smith et al., 2003, 2004). In the present experiment the two fungi also differed in their tolerance to external P supply levels. While the mycorrhizal dependency of *G. mosseae* was positive at 50 mg kg⁻¹, that of *G. etunicatum* was negative, indicating that *G. mosseae* may have greater adaptation than *G. etunicatum* to higher P concentrations. Differences in the tolerance of AM fungi has also been observed by other workers (Pearson et al., 1994; Treseder and Allen, 2002).

Our results indicate that the two maize lines did not differ in P uptake or plant growth during the early seedling stage. There was no significant difference between the two maize inbred lines in response to the inoculation of AM fungi despite the fact that the maize lines had contrasting root morphology. Enhanced P uptake and plant growth were greatest at the low P supply level. Increasing plant P efficiency for high productivity is one of the purposes of the breeding programs. Our results indicate that the two maize inbred lines may at least have maintained their capacity to benefit from mycorrhizal associations during the screening programs and they have inherently similar characteristics with respect to mycorrhizal colonization. Current practices of heavy usage of P fertilizers to promote maize yields may diminish any beneficial effects of mycorrhizal colonization. However, under low soil P conditions, maize plants may have some potential to benefit from AM fungi and selection of appropriate mycorrhizal fungal isolates may be an environmentally friendly approach to optimizing the growth and P uptake of maize inbred lines.

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