Journal of Plant Nutrition, 29: 2147–2163, 2006

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904160600972811

Effect of Foliar Application of Phosphorus on Winter Wheat Grain Yield, Phosphorus Uptake, and Use Efficiency

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ABSTRACT

One would expect foliar applied phosphorus (P) to have higher use efficiencies than when applied to the soil, but limited information is available concerning this. Experiments were conducted in 2002, 2003, and 2004 to determine the effect of foliar applications of P on winter wheat grain yields, P uptake, and use efficiency. Twelve treatments containing varying foliar P rates (0, 1, 2, and 4 kg ha^{-1} in 2002 and 2003 and additional 8, 12, 16, and 20 kg ha^{-1} in 2004) with and without pre-plant rates of 30 kg ha^{-1}were evaluated. Foliar applications of P at Feekes 7 generally increased grain yields and P uptake versus no foliar P. Use efficiency was higher when P was applied at Feekes 10.54. Results from this study suggested that low rates of foliar applied P might correct mid-season P deficiency in winter wheat, and that might result in higher P use efficiencies.

Keywords: winter wheat, foliar phosphorus, phosphorus use efficiency, phosphorus uptake

INTRODUCTION

In many agricultural production systems, phosphorus (P) has been identified as the most deficient essential nutrient after nitrogen (N). Nutrient inputs into

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Received 25 July 2005; accepted 17 January 2006.

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production systems have increased as a result of the need for high yielding crops to sustain the growing population around the world. In Oklahoma, phosphate inputs in winter wheat production ranged from 37.91×10^6 kg/ 2.18×10^6 ha in 1997 to 29.88×10^6 kg /1.42×10^6 ha in 2002 (National Agricultural Statistical Service [NASS], 1998; NASS, 2003). Even though the average was 21 kg ha^{-1}, these inputs may become excessive where there were already high levels of soil P leading to many environmental concerns, especially pollution issues. The excess application of animal manure and high amounts of P fertilizer to the soil led to surface runoff. The most essential function of P is storage and transfer of energy in the form of adenosine triphosphate (ATP), adenosine diphosphate (ADP) and it is also the important structural component of nucleic acids, coenzymes, phospholipids, and nucleotides.

Phosphorus originates from the weathering of soil minerals and other stable soil geologic materials and exists in both inorganic and organic forms of which the inorganic fraction is dominant. The inorganic forms are dominated by hydrous sesquioxides, amorphous crystalline aluminum and iron phosphates in acidic soils and as calcium phosphates in alkaline soils. The amount of available soluble P depends on pH, extent of contact between the precipitated P and the soil solution, the rate of dissolution and diffusion of solid phase phosphorus, time of reaction, organic matter content, temperature, and type of clay present. When the available P is less than the crop requirement, P is applied to the soil in the form of both inorganic and organic fertilizer.

Although inorganic fertilizers are readily available, they are slowly converted to unavailable forms due to precipitation. During early growth stages, plants may utilize the readily available form, while they compete for the slowly available forms in the later stages of growth.

Phosphorus fertilizer use efficiency (PUE) averaged 8% when P was broadcast and incorporated and 16% when P was either knifed with anhydrous ammonia or applied with the seed in winter wheat (Sander, Penas, and Eghball, 1990; Sander, Penas, and Walters, 1991). Eghball and Sander (1989) reported that 13.8 to 26.4 kg P ha^{-1} was taken up in corn grain at yield levels between 4.24 and 8.83 Mg ha^{-1}, and a concentration of 0.31% P. Similarly, total P taken up in corn grain ranged from 21.4 to 47.4 kg P ha^{-1} at yield levels from 8.10 to 14.47 Mg ha^{-1}, or 0.30% P (Raun, Sander, and Olson, 1987). The diffusion coefficient of P in soil is very low, hence the root zone P is depleted and plants cannot get P when it is needed (Clarkson, 1981). Therefore, the utilization of P as a foliar application becomes increasingly important. The mechanistic processes by which foliar applied nutrients are taken up are through leaf stomata (Eichert and Burkhardt, 1999) and hydrophilic pores within the leaf cuticle (Tyree, Scherbatskoy, and Tabor, 1990).

In general, P deficient soils require pre-plant broadcast-incorporated rates of 11 to 22 kg Pha^{-1} to correct the deficiency in either wheat or corn. At a PUE of 16%, this addition results in only 1.7 to 3.5 kg of fertilizer P taken up in the grain. Although the literature does not provide information on relative efficiencies (soil applied versus foliar applied P), intuitively, one would expect the foliar applied P to be much higher. Thus, small amounts required to correct deficiencies can be easily introduced to the plant by a foliar P application. This approach has been overlooked for decades because it was assumed that the amounts of fertilizer P required by the crop were too large to be satisfied by a single foliar application. That assumption was easily accepted when P fertilizers were first used because soil deficiencies tended to be greater than today and solution fertilizers were uncommon.

Leach and Hameleers (2001) reported that there was a significant increase in the starch content and cob index but no effect on dry matter production in maize due to foliar application of P and Zinc. Foliar applications of KH_2PO_4 were also found to delay leaf senescence and increase winter wheat grain yields during hot and dry summers (Sherchand and Paulsen, 1985; Batten, Wardlaw, and Aston, 1986). Batten (1987) later reported that net CO_2 assimilation, N concentration, and chlorophyll content decreased when wheat leaf P concentration falls below a critical level. Increased yields in barley were obtained using dilute solutions of foliar P (Qaseem, Afridi, and Samiullah, 1978). Barel and Black (1979) reported findings in corn that 66% of foliar applied P to youngest mature leaf in a pot culture experiment as ammonium triple-phosphate was absorbed within 10 days and 87% of that absorbed was translocated within that time. However, Harder et al. (1982) presented contradicting results showing that the foliar application of P applied 2 weeks after silking, significantly reduced grain yields.

Foliar fertilization with nitrogen, phosphorus, and potassium (N-P-K) can be supplemented with soil applied fertilizers but cannot replace soil fertilization in the case of maize (Ling and Silberush, 2002), because demand for P is 1/10 that of N hence, a foliar application might be beneficial. Therefore, correcting the plant's deficiency by foliar application seems plausible. Very little research has been conducted on the use of P as foliar spray at early stages of wheat and corn. However, recent work by Benbella and Paulsen (1998) showed that foliar applications after anthesis of 5 to 10 kg KH_2PO_4 ha^{-1} (1.1 to 2.2 kg P ha^{-1}) increased wheat grain yields by up to 1 Mg ha^{-1}. Wheat grain yields are hindered due to senescence of wheat during grain fill. Therefore, to effectively prolong senescence, P has to be applied during later stages of growth, which is why foliar application seems particularly promising (Benbella and Paulsen, 1998). Elliott et al. (1997) reported a critical P concentration of 0.19 to 0.23% (at 90% maximum grain yield) in wheat grain. Earlier, Bolland and Paynter (1994) reported that critical P concentration in wheat decreased from 0.91% to 0.23% (in shoot) with the growing season and 0.27% in grain.

Haloi (1980) reported that when initial P deficiency symptoms appeared 25 days after sowing in wheat, higher doses of ammonium phosphate as a foliar spray gave the greatest reduction in P deficiency and highest yields. The efficiency of basal and/or foliar application of P was found to be similar (Singh et al., 1981).

The objectives of this study were to determine whether foliar applications of P can result in increased wheat grain yields and P uptake, and improve use efficiency.

MATERIALS AND METHODS

Three experimental sites were established in the fall of 2001 at Lahoma (Grant silt loam-fine-silty, mixed thermic Udic Argiustoll), Lake Carl Blackwell (Port silt loam-fine-silty, mixed, thermic Cumulic Haplustolls), and Perkins (Teller sandy loam-fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma for evaluating the response of foliar application of P in winter wheat for three consecutive years. Initial soil test data is reported in Table 1.

A completely randomized block design with three replications was used to evaluate 12 treatments (Description of treatments is given in Table 2). Plots were 2.43 m by 3.04 m in size. At all sites, a fixed pre-plant N rate of 80 kg ha^{-1} was applied using ammonium nitrate (NH_4NO_3). As the K levels in the soil were low at Lake Carl Blackwell, 55 kg ha^{-1} K_2O was applied pre-plant. Varying foliar P rates of 0, 1, 2, and 4 kg ha^{-1}were evaluated with and without pre-plant rates of 30 kg P ha^{-1} at different growth stages at all three sites in 2002 and 2003. In 2004, the treatment structure was modified to contain additional foliar P rates of 8, 12, 16, and 20 kg ha^{-1}. Pre-plant P was broadcast and incorporated using triple superphosphate ($Ca(H_2PO_4)_2.H_2O$) for all trials. Foliar P was applied at Feekes growth stage 7 (second node of stem formed), Feekes 10.1 (heads emerging) and Feekes 10.54 (flowering completed) (Large, 1954) in 2002 and 2003, while it was applied at Feekes 9 in 2004 using KH_2PO_4 solution with a pulse modulated handheld sprayer.

The winter wheat varieties used were 'Jagger' at Lahoma in all years and at Perkins in 2003 and 2004, 'Custer' at Lake Carl Blackwell (2003) and Perkins

Table 1

Initial surface (0–15 cm) soil test characteristics at Lahoma, Lake Carl Blackwell (LCB), and Perkins, OK

Site	pH	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
Lahoma	6.2	8.0	1	5.9	155
LCB	5.5	8.2	0	10.3	107
Perkins	5.8	12.7	0	9.2	279

NH_4-N and NO_3-N-2 M KCl extraction.

P and K–Mehlich−III extraction.

pH–1:1 Soil: Water.

Table 2
Treatment structure for foliar P study experimental sites at Lahoma, Lake Carl Blackwell and Perkins, OK in 2002 and 2003

	P rate (kg ha^{-1})			
Treatment No.	Pre-plant	Feekes 7	Feekes 10.1	Feekes 10.54
1	0	-	0	0
2	0	1	0	0
3	0	2	0	0
4	0	4	0	0
5	30	-	0	0
6	30	1	0	0
7	30	2	0	0
8	30	4	0	0
9	0	0	2	0
10	30	0	2	0
11	0	0	0	2
12	30	0	0	2

(2002), and '2174' at Lake Carl Blackwell in 2002 and 2004. Wheat was planted in October in all years. Wheat was harvested with a Massey Ferguson 8XP experimental combine in June, removing an area of 2.0 m × 3.04 m from the center of each plot. It was then weighed and sub sampled for P analysis. Grain samples were dried in a forced-air oven at 66^{o}C, ground to pass a 140 mesh sieve (100 μm), and analyzed for total P. The concentration of P in the wheat grain was determined with a wet acid digestion procedure (Jones and Case, 1990), and analyzed using a high-resolution inductively coupled plasma spectrophotometer (Thermo-Jarrell Ash IRIS ICP). Soft winter wheat flour standard reference material (SRM) (National Institute of Standards and Technology) was used to evaluate the wet acid digestion procedure of the grain tissue and resulted in 94% recovery of P in the grain.

Phosphorus use efficiency (PUE) in the wheat grain was calculated based on the following relationship:

$$PUE = \frac{Grain P uptake in P treated plot - Grain P uptake of control}{P rate} \tag{1}$$

All data were subjected to statistical analysis using SAS/STAT analytical tools (SAS Institute, 200). Single degree of freedom contrasts were performed for evaluating the differences in grain yield, grain P concentration, and grain P uptake. The description and number of significant trials for each contrast are given in Table 3. The PUE data was transformed before analysis using arc sin

Table 3

Number of significant site-year combination contrasts for grain yield, grain P content and grain P uptake in 2002 and 2003 crop years

No.	Description of contrast	Grain yield	Grain P concentration	Grain P uptake
1	Pre-plant vs. foliar[a]	2	1	3
2	Pre-plant + foliar vs. only pre-plant	2	3	2
3	Foliar linear at Feekes 7	-	1	-
4	Foliar quadratic at Feekes 7	2	2	2
5	Foliar at Feekes 7 + pre-plant linear	2	2	1
6	Foliar at Feekes 7 + pre-plant quadratic	-	2	1
7	Foliar at Feekes 7 vs. 10.1	-	1	-
8	Foliar at Feekes 7 vs. 10.54	3	1	3
9	Foliar at Feekes 10.1 vs. 10.54	3	-	1
10	Foliar at Feekes 7 vs. 10.1 + 10.54	1	1	2

[a] Rates are as presented in Table 2. All contrasts involving foliar application stages were made only at the same rate of P (i.e., 2 kg P ha^{-1}).

variance stabilization method (Chambers et al., 1983) as follows:

$$\mathrm{PUE}_{\mathrm{trans}} = 2^{*}(\arcsin\sqrt{}\mathrm{PUE}) \qquad (2)$$

Where PUE_{trans} referred to the transformed PUE data. Means were detransformed to the original scale for reporting.

RESULTS

Grain Yield

Grain yield significantly varied among treatments at Lahoma for all trials and at Perkins in 2002. Some single degree of freedom contrasts were also significant for all trials except at Lake Carl Blackwell in 2002 (number of total significant contrasts across six trials were given in Table 3). Neither overall treatment effects nor single degree of freedom contrasts were found to be significant at Lake Carl Blackwell in 2002. Even though this site had high grain yields and the initial soil test results showed a low extractable P level, no actual P deficiencies were noted for this specific trial (mean grain yields across 12 treatments are presented in Table 4). Grain yield from plots fertilized with only pre-plant P significantly exceeded those plots that received only foliar P (Treatment 5 versus 2, 3, 4, 9, and 11) in both years at the Perkins site (556 and 746 kg ha^{-1} increases in yield in 2002 and 2003, respectively). A comparison

Table 4
Mean wheat grain yields (kg ha^{-1}) for treatments at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2002 and 2003 crop years

	Lahoma		Lake Carl Blackwell		Perkins	
Treatment[a] no.	2002	2003	2002	2003	2002	2003
1	1998	3440	4191	4375	1700	2891
2	2126	3535	4211	4291	1906	2672
3	2485	3442	4246	4103	1872	3088
4	2119	3607	4598	4458	1841	2995
5	1740	4067	4095	4479	2412	2915
6	2416	4484	4238	4579	2337	2754
7	2158	3856	4005	4345	2407	2872
8	2529	4591	4138	4412	2429	2771
9	2354	3105	4236	3928	1766	2848
10	2421	4109	4065	4501	2271	2766
11	1841	4277	4603	4263	1816	2520
12	2317	4724	4214	4157	2048	3173
SED	362.9	971.9	281.5	291.1	352.0	383.3

[a] Refer to Table 2 for treatment description.

made between a combination of pre-plant + foliar P fertilization versus only 30 kg ha^{-1} pre-plant rate showed a 630 kg ha^{-1}increase at Lahoma in 2002 (treatments 6, 7, 8, 10, and 12 versus 5).

Mean grain yields were higher at Lahoma (2002) by 644 kg ha^{-1}and Perkins (2003) by 567 kg ha^{-1}(2003) when 2 kg ha^{-1} P was foliar applied at Feekes 7 compared to Feekes 10.54 (treatment 3 versus 11). At Lahoma in 2003, the opposite was observed, where 2 kg ha^{-1} foliar P applied at Feekes 7 resulted in lower yields than the same rates applied at Feekes 10.54 (a decrease of 834 kg ha^{-1}).

At Lake Carl Blackwell with no pre-plant P, 2 kg P ha^{-1} applied at Feekes 10.54 significantly increased yields when compared to the check and other 0 pre-plant P treatments that received P at Feekes 7 in 2003. This increase was not noted at all sites. At Lake Carl Blackwell and Lahoma in 2003, it was apparently advantageous to delay applying foliar P until Feekes 10.54 when compared to Feekes 7. At Lahoma in 2002, foliar P applied at Feekes 10.1 increased mean grain yield by 513 kg ha^{-1} compared with that at Feekes 10.54 (treatment 9 versus 11), while at Lahoma and Lake Carl Blackwell in 2003, mean grain yield was superior by 1172 and 335 kg ha^{-1}, respectively at Feekes 10.54 compared with Feekes 10.1. At Lahoma in 2002, 2 kg ha^{-1}foliar applied P at Feekes 7 versus that applied at Feekes 10.1 and 10.54 (Treatment 3 versus 9 and 11) resulted in a grain yield increase of 387 kg ha^{-1}.

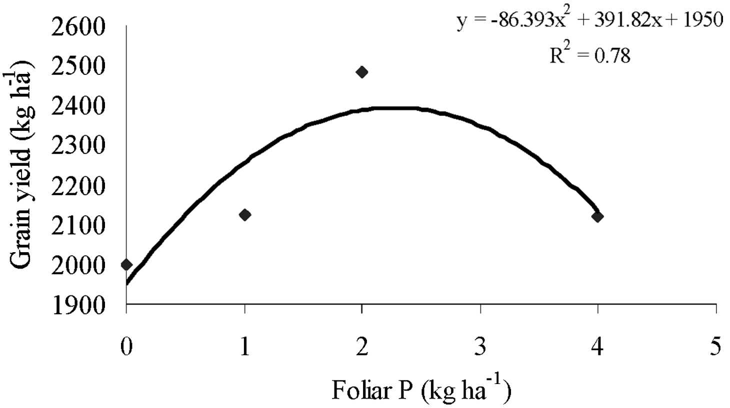

Figure 1. Relationship between grain yield and foliar P rates applied at Feekes 7 without pre-plant P at Lahoma, 2002.

Trend analysis of mean grain yields for foliar P applied at Feekes 7 with no pre-plant P revealed a significant quadratic relationship between foliar P rates and grain yield at Lahoma in 2002 (Figure 1). On the other hand, at a pre-plant rate of 30 kg P ha^{-1}, foliar P at Feekes 7 showed a linear trend at Lahoma in 2002 (Figure 2). In 2004 at this site a quadratic response was observed for foliar rates up to 8 kg ha^{-1} where maximum yields were achieved at 4 kg ha^{-1} (Figure 3).

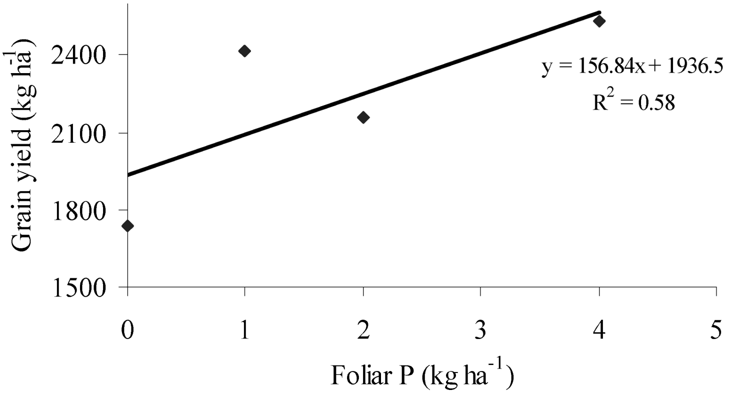

Figure 2. Relationship between grain yield and foliar P rates applied at Feekes 7 with pre-plant rate of 30 kg ha^{-1} at Perkins, 2002.

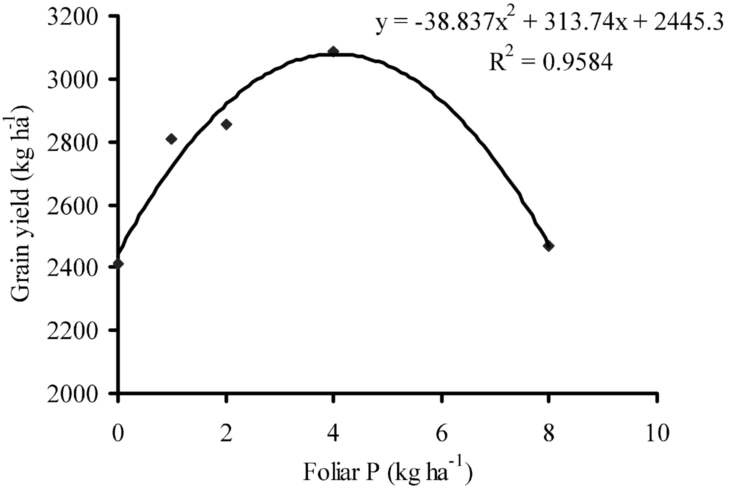

Figure 3. Relationship between grain yield and foliar P rates applied at Feekes 9 without pre-plant rate at Lahoma in 2004.

Grain P Concentration

Much like grain yield, grain P was high (>3.10 g kg^{-1}) at Lake Carl Blackwell in both years and low (1.80 g kg^{-1}) at Perkins in 2003, while it ranged between 2.00 and 2.60 g kg^{-1} for the remaining trials (Table 5). Some contrasts were also significant for this variable (Table 3). At Lahoma in 2002, grain P was higher by 0.17 g kg^{-1} for P applied pre-plant compared to that applied as foliar (Treatments 5, 6, 7, and 8 versus 2, 3, 4, 9, and 11). On the other hand, the pre-plant + foliar treated plots showed a 0.22 and 0.39 g kg^{-1} lower grain P at Lahoma in 2002 and 2003, respectively, compared with only pre-plant treated plots. Similarly, at Lake Carl Blackwell in 2003, 0.39 g kg^{-1} more P was measured in pre-plant + foliar treated plots. At Lake Carl Blackwell in 2002, foliar P applied at Feekes 7 showed lower grain P concentration than rates applied at both Feekes 10.1 (Treatment 3 versus 9) and at Feekes 10.1 and 10.54 (Treatment 3 versus 9 and 11) by 0.33 g kg^{-1}, and at Feekes 10.54 (Treatment 3 versus 11) by 0.31 g kg^{-1}.

Grain P concentration had a linear relationship with foliar P rates at Lahoma in 2002, and a quadratic relationship at Lake Carl Blackwell and Perkins in 2003 at 0 kg ha^{-1} pre-plant rate (Figure 4). At 30 kg P ha^{-1}pre-plant rate, two linear trends, one at Lake Carl Blackwell in 2002 and another at Perkins in 2003 (Figure 5) were significant while at Lahoma and Perkins (Figure 6) in 2002, a quadratic trend was revealed.

Table 5
Mean wheat P concentration (g kg^{-1}) at Lahoma, Lake Carl Blackwell and Perkins, OK during 2002 and 2003 crop years

	Lahoma		Lake Carl Blackwell		Perkins	
Treatment[a] no.	2002	2003	2002	2003	2002	2003
1	2.41	2.51	3.24	3.53	2.00	1.65
2	2.34	2.54	2.91	3.24	1.80	1.81
3	2.54	2.61	2.93	3.35	2.02	1.83
4	2.56	2.53	2.86	3.58	2.10	1.67
5	2.73	2.82	3.21	3.15	1.97	1.88
6	2.32	2.40	3.43	3.37	2.05	1.70
7	2.56	2.56	3.15	3.49	2.58	2.02
8	2.70	2.36	2.95	3.47	2.16	2.11
9	2.40	2.82	3.27	3.47	2.23	1.73
10	2.62	2.53	3.34	3.82	2.11	1.87
11	2.54	2.73	3.24	3.33	2.01	1.84
12	2.39	2.23	3.30	3.57	2.21	1.87
SED	0.13	0.23	0.15	0.18	0.16	0.11

[a] Refer to Table 2 for treatment description.

Grain P Uptake

Grain P uptake was significant in three of six trials for 2002 and 2003. The highest was at Lake Carl Blackwell (>13.50 kg ha^{-1}) and the lowest (<4.32 kg ha^{-1}) was at Perkins in 2002, while it ranged between 5.29 and 9.80 kg ha^{-1}

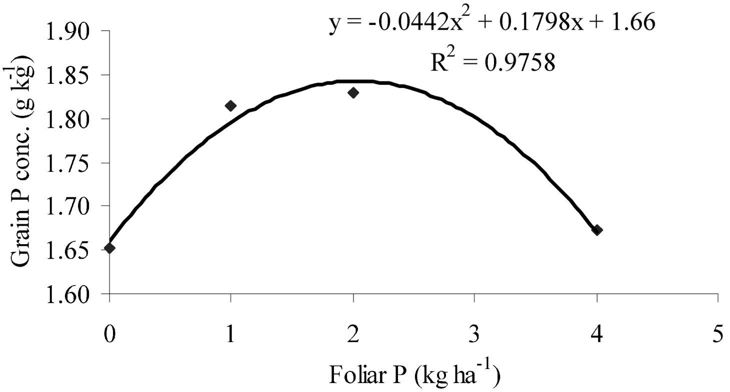

Figure 4. Relationship between grain P concentration (g kg^{-1}) and foliar P rates applied at Feekes 7 without pre-plant rate at Perkins, 2003.

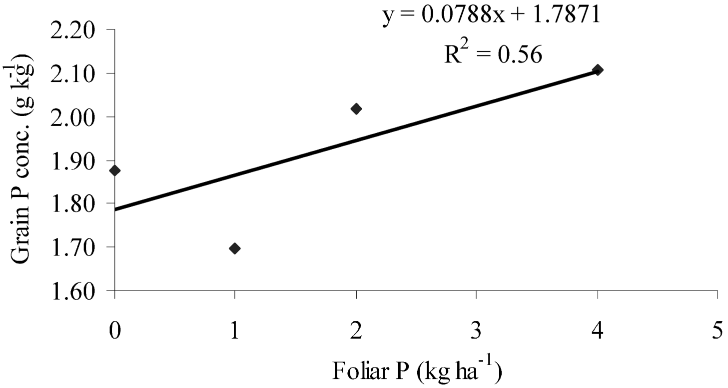

Figure 5. Relationship between grain P concentration (g kg^{-1}) and foliar P rates applied at Feekes 7 with pre-plant P rate of 30 kg ha^{-1} at Perkins, 2003.

for other sites (Table 6). For all trials, one or more contrasts were significant (Table 3). A trend for increased grain P uptake was observed when foliar P was applied with pre-plant P (Treatments 5–8) but this was not consistent over sites. At Lahoma in 2002, 1.17 and 1.68 kg ha^{-1} more P was taken up when foliar P was applied at Feekes 7 compared with that applied at Feekes 10.1 and 10.54, respectively. On the other hand, at Lake Carl Blackwell in 2002, grain P uptake was lower by 2.01 and 2.59 kg ha^{-1} at Feekes 7 than Feekes 10.1 and 10.54, respectively. At Lahoma in 2003, grain P uptake was increased by 2.84 and 3.06 kg ha^{-1} when P was applied at Feekes 10.54 than at Feekes 7 and 10.1, respectively.

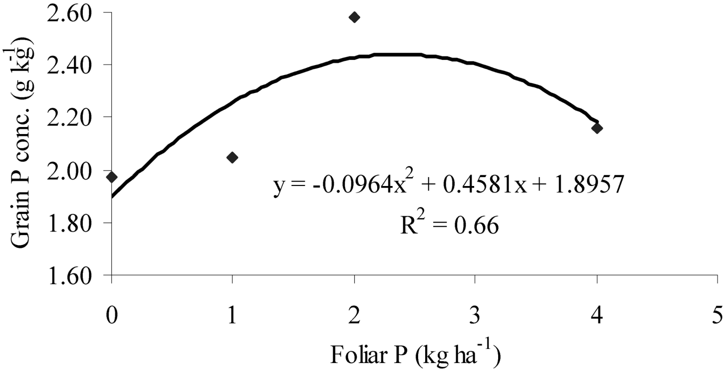

Figure 6. Relationship between grain P concentration (g kg^{-1}) and foliar P rates applied at Feekes 7 with pre-plant P rate of 30 kg ha^{-1} at Perkins, 2002.

Table 6
Mean grain P uptake (kg ha^{-1}) for treatments at Lahoma, Lake Carl Blackwell, and Perkins, OK during 2002 and 2003 crop years

	Lahoma		Lake Carl Blackwell		Perkins	
Treatment[a] no.	2002	2003	2002	2003	2002	2003
1	4.8	8.7	13.6	15.5	3.6	4.8
2	4.9	9.0	12.3	13.9	3.4	4.6
3	6.3	9.0	12.4	13.8	3.8	5.7
4	5.4	9.0	13.1	15.9	3.9	5.0
5	4.8	11.4	13.1	14.1	4.8	6.5
6	5.6	10.8	14.5	15.5	4.8	4.7
7	5.5	9.6	12.6	15.2	6.5	5.8
8	6.9	10.8	12.3	15.2	5.2	5.9
9	5.7	8.8	13.9	13.7	3.9	4.9
10	6.3	10.1	13.6	17.2	4.8	5.2
11	4.7	11.8	15.0	14.2	3.7	4.7
12	5.6	10.5	13.8	14.8	4.2	5.9
SED	0.72	1.28	0.98	1.01	0.49	0.74

[a] Refer to Table 2 for treatment description.

Phosphorus Use Efficiency

Over all sites and years, PUE was higher when P was foliar applied at 2 kg P ha^{-1} (Table 7). PUE was as high as 86, 16, and 159% at Lake Carl Blackwell (2002), Lahoma (2002), and Lahoma (2003), respectively when 2 kg P ha^{-1} was foliar applied at Feekes 10.54 (Table 7). On average, PUE was higher when P was applied at Feekes 7 (39%) and Feekes 10.54 (47%).

DISCUSSION

Grain yield and P concentration were not highly correlated. The poor correlation between P concentration and grain yield is not surprising since the role of foliar P on growth of wheat is more on delaying maturity. Phosphorus concentrations in plants can be affected by limited P uptake due to variations in soil moisture status (McLachlan, 1984), root temperature (Mackay and Barber, 1984), and various other environmental factors (Bates, 1971).

Regardless of the method of P application, response to P fertilization should have been observed across all trials. This is because initial soil test P levels were all below 100% sufficiency. Despite this, only 50% of the trials showed significant response to applied P. The significant grain yield response to P at

Table 7
Detransformed mean PUE (%) for treatments at Lahoma, Lake Carl Blackwell (LCB), and Perkins, OK during 2002 and 2003 crop years

	Lahoma		Lake Carl Blackwell		Perkins		
Treatment[a] no.	2002	2003	2002	2003	2002	2003	Average
2	22	37	0	22	10	11	17
3	77	67	0	23	14	55	39
4	15	28	4	31	8	13	16
5	0	11	0	1	4	6	4
6	4	8	2	4	4	0	4
7	4	4	0	0	6	3	3
8	6	6	0	1	5	3	4
9	64	23	22	0	18	19	24
10	5	5	0	6	4	2	4
11	16	159	86	0	9	10	47
12	4	6	0	1	3	4	3
SED	19	33	20	16	8	19	

[a] Refer to Table 2 for treatment description.

Lahoma can be explained by the fact that the soil has a relatively low level of initial soil P compared to the other two sites. At Lahoma, the number of significant single degree of freedom comparisons obtained was more than the other two sites (with the exception of Perkins 2003) owing to the low initial soil P level.

Pre-plant P application consistently increased grain yield compared with top-dress P. Application of P pre-plant with supplemental foliar P also resulted in a better grain yield than pre-plant application in most instances where significance was observed. This suggests that wheat grain yield can be improved by supplementing P in foliar form when the plant is in need. Luxurious vegetative growth due to excess supply of N might induce hidden P hunger and the foliar correction of this hunger would likely improve yield. Similar explanation was given in high yielding environments with low soil P supply where foliar application of P helped to correct deficiencies and maintain higher yield (Dixon, 2003). Green and Racz (1999) reported a 300 kg ha^{-1} grain yield increment of wheat due to foliar P applied to a P deficient wheat crop.

In plots treated with only foliar rates at Feekes 7 and flowering, there was an apparent response which indicates that foliar P in wheat is still a potential option to manage P deficiency in wheat. Chambers and Devos (2001) reported that depending on soil P status, foliar feeding of small amounts of P after heading increased yields over no P up to 672 kg ha^{-1} and added up to 538 kg ha^{-1} to the pre-plant P plots. However, the results were from trials conducted on a soil testing low in P and one would not expect to see these large yield increases on higher P fertility soils by foliar fertilization. Benbella and Paulsen (1998) also showed that foliar applications after anthesis of 5 to 10 kg KH_2PO_4 ha^{-1} (1.1 to 2.2 kg P ha^{-1}) increased wheat grain yields by up to 1 Mg ha^{-1}.

The foliar rates considered in this study also showed apparent grain yield, and PUE increases. The 2004 grain yield data revealed that an addition of foliar P in excess of 8 kg ha^{-1} did not improve grain yield. The results from single degree of freedom comparisons generally lacked consistency.

Foliar application of P at Feekes 7 was generally better than applied at Feekes 10.1 or 10.54 in terms of grain yield and P uptake. The PUE data suggests that 10% more can be achieved if foliar fertilization is delayed until Feekes 10.54. However, it is preferable to apply at Feekes 7 since at this stage producers can simultaneously apply both N and P using the same equipment. In a preliminary foliar rate study made in Virginia, yield obtained from foliar rates applied at vegetative wheat stages surpassed that of the foliar rate applied at reproductive stages (Chambers and Devos, 2001; Stanley, Hula, and Philips, 2003). Haloi (1980) suggested that the delayed P applications resulted in a “stay green” effect whereby photosynthesis continued to take place during grain fill and that without the foliar P, more rapid senescence would be present. In order to realize any “stay green” benefit, environmental conditions must have been ideal (no moisture stress) from post flowering to maturity. Whenever plants are under moisture stress P uptake is reduced (McLachlan, 1984; Bolland, 1992).

When looking at Tables 4 and 7, data suggests that increases in grain yield from foliar P generally took place when yield levels were lower, likely due to increased moisture stress. This would make sense since P uptake due to contact exchange would be less under moisture stress, thus enhancing the benefits of foliar P in these years.

CONCLUSIONS

Results presented here confirm the beneficial use of foliar P fertilization in wheat, although the conditions in which this method would be used should be sought carefully. The Feekes 7 growth stage identified as the optimum growth stage for foliar P application is also the stage in which N is applied to avoid yield loss. Consequently, this allows reduction of cost associated with a separate application.

Research on improving uptake of P by wheat leaves needs to be further studied. This might include study of formulations that might improve retention and penetration into the wheat leaves. Also, research has to be directed to see if foliar P applications during early stages of plant produce significant results. However, increased P use efficiency from low rates of foliar application was encouraging and will be pursued further.

ACKNOWLEDGMENT

Contribution from the Oklahoma Agricultural Experiment Station, Stillwater, OK.

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