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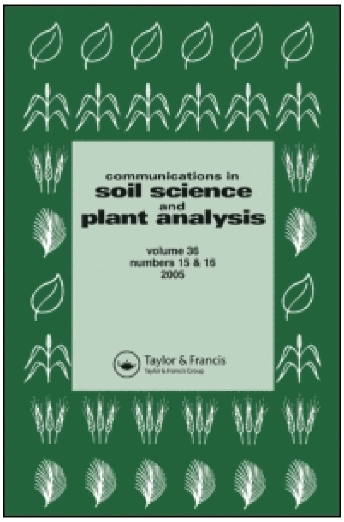

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Determination of Optimum Rate and Growth Stage for Foliar-Applied Phosphorus in Corn

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Abstract: Foliar applications of fertilizer phosphorus (P) could improve use efficiency by minimizing soil applications. Nine experiments were conducted in 2002 and 2003 to determine foliar P rates and appropriate growth stages for application. Treatments comprised of 10 factorial combinations of three foliar P application timings and four rates of foliar P. Foliar application times were V4 (collar of fourth leaf visible), V8 (collar of eighth leaf visible), and VT (last branch of the tassel completely visible but silks not yet emerged) corn growth stages. Foliar P rates were 0, 2, 4, and 8 kg ha^{-1}. Foliar P applied at the VT growth stage improved grain and forage P concentration, which was reflected in increased grain yield in some of the experiments. A foliar P rate of 8 kg ha^{-1} improved yield to some extent and forage and grain P concentration more than the smaller rates. The results suggest that foliar P could be used as an efficient P-management tool in corn when applied at the appropriate growth stage and rate.

Keywords: Bt corn, corn, corn growth stage, foliar fertilization, KH_2PO_4, phosphorus

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INTRODUCTION

Phosphorus (P) is a structural component of nucleic acids and is responsible for energy transfer, which is accomplished by phosphate ester and energy-rich phosphate (Glass, Beaton, and Bomke 1980). If the level of available P in soil is not adequate for optimum crop growth, phosphate fertilizers must be used to ensure that there are adequate amounts of this nutrient in the solution phase, which is usually variable and unpredictable (Chen and Barber 1990). The formation of insoluble compounds due to soil chemical reactions limits the plant-available P, making phosphate fertilization use efficiency by crops very low (Barber 1984). Therefore, appropriate management of phosphate fertilizers is a major concern. Also, stimulated by economic as well as environmental concerns, the efficient use of P is becoming more and more important (Kaeppler et al. 1998).

Early on, P fertilizers were surface applied or incorporated after broadcast. Later research noted that banding was a more efficient method of P placement (Sander, Penas, and Eghball 1990). The banded P usually increased early crop growth more than the broadcast placement because of increased plant uptake (Barber 1984; Mallarino and Rueber 2001; Rehm et al. 1998; Eghball, Sander, and Skop 1990). In corn (*Zea mays* L.), Zhang and Barber (1992) studied the effect of P placement on P uptake and reported similar results. It is important to improve P use of the plant by investigating alternative methods, including foliar application.

Research on foliar fertilization was possibly started in late 1940s and early 1950s (Dion, Spinks, and Mitchell 1949; Dion, Dehm, and Spinks 1949). Unlike many technologies, its pace followed an unpredictable sequence of events. In the early 1980s, studies on foliar application of fertilizers were investigated for selected crops, including cereals. However, the research was limited to micronutrients (Eddy 1999) in high-value horticultural crops (Fritz 1978) such as potato (*Solanum tuberosum* L.) (Lewis and Kettlewell 1993) and tomato (*Lycopersicon esculentum* L.) (Kaya, Kirnak, and Higgs 2001).

Some researchers concluded that in corn and other cereals, foliar P was not important (Fritz 1978; Haq and Mallarino 2000). Others advocated foliar fertilization (Faust 1996; Anonymous 1985; Eddy 2000) as a viable economical way of supplementing the plant's nutrients for more efficient fertilization. Foliar treatment of P can be applied only when the crop needs it and thus decreases cost of production (Faulkner 1999). The major reason for continued P applications to the soil is to maintain reserves in the soil because foliar P might not directly contribute to the soil P level, which is very important at the very early stage of growth. However, in cropping systems involving corn stalk chopping and incorporation, some proportion of P will be returned to the soil in an organic form, contributing to the soil P. Foliar P is very effective in high-fixing soils because having P applied to the soil would not help the plant in the long run, because of formation of insoluble aluminum and iron phosphate compounds. In P-rich soils, it may be preferable to apply foliar P on the leaves if a deficiency is expected and demands are high (Silberbush 2002). This will not only increase efficiency and decrease cost of production but also reduce runoff of soil-applied P, which is responsible for eutrophication of many of lakes and streams (Sharpley et al. 1994).

Indeed, several factors including plant management and environmental factors influence the benefit of applied foliar P. Foliar application should be made when the plant is not in water stress, either too wet or too dry (Denelan 1988). Nutrients are best applied when the plant is cool and filled with water (turgid). Applications that are misapplied or too late in the season may not be effective. The most critical times to apply are when the crop is under P stress. Stress periods occur during periods of active growth activity (Anonymous 1995). This is likely when the plant is changing from a vegetative to a reproductive stage (Cantisano 2000).

The mechanism of uptake and transport of foliar applied nutrients involves a complex plant-tissue system including dermal, vascular, and ground systems (Rathore 2000; Römheld and El-Fouly 1999). Previous research showed that a foliar-applied nutrient passes through the cuticular wax, the cuticle, the cell wall, and the membrane in that order (Middleton and Sanderson 1965; Franke 1967). Sometimes the nutrient will pass through these various layers, whereas at other times it may pass through the spaces between these layers, which are typical for inorganic ions (Dybing and Currier 1961). However, it was discovered later that stomata are the major means of foliar-applied nutrient absorption into the plant (Eichert, Goldbach, and Burkhardt 1998; Eichert and Burkhardt 2001). When the stomata are open, foliar absorption is often easier (Burkhardt et al. 1999).

Advances in agriculture include treating small-scale variability to maximize input use and maintain environmental health. Current concerns call for nutrient-application methods compatible with location-specific technologies. Foliar P in corn is such a method. Therefore, the objectives of this study were to assess the suitability of foliar P for corn production and to determine appropriate application timing, rates, and efficiency of the method.

MATERIALS AND METHODS

Experimental Locations

Seven field and two greenhouse experiments were conducted at five locations in Oklahoma in 2002 and 2003. In 2002, two experiments were conducted at Perkins using Bt corn hybrid varieties with 108 and 109 days to maturity (Bt corn 108 and Bt corn 109, respectively) and one experiment at Guymon using hybrid Asgrow730RR, whereas in 2003 four experiments were conducted at Efaw, Goodwell, Lake Carl Blackwell (LCB), and Perkins using Hybrid

111, H9226BtRR, Hybrid 107, and 104, respectively at each location. The source of hybrids used at Efaw, LCB, and Perkins (both years) was Pioneer Hibred Int. Inc. (Johnston, IA), whereas the hybrids at Goodwell and Guymon were obtained from Golden Harvest Seeds Inc. (Bloomington, IL) and Monsanto (St. Louis, Mo) companies, respectively. The two greenhouse experiments were carried out at Stillwater Agronomy Research station in 2003 using Hybrid 111. The soil at Perkins is a Teller sandy loam, fine-loamy, mixed, thermic, Udic Argiustoll; at both Goodwell and Guymon Richfield clay loam, fine-loamy, mixed, superactive, mesic, Aridic Haplustepts; at Efaw, Norge loam, fine-silty, mixed, thermic Udic Paleustoll; and at LCB, Port silt loam, fine-silty, mixed, thermic, Cumulic Haplustolls. Table 1 presents initial surface soil characteristics of the experimental sites.

Treatment Structure and Experimental Design

The field experiments used a randomized complete block design with three replications. In 2002, treatments comprised of 10 factorial combinations of three application timings and four rates of foliar P. In 2003, two additional basal P treatments were included. Foliar P application times were collar of fourth leaf visible V4, V8, and VT (Ritchie and Hanway 1992). The foliar P rates were 0, 2, 4, and 8 kg ha^{-1}. The two basal P rates were 25 and 50 kg ha^{-1}applied as broadcast at all locations. For foliar treatments, potassium phosphate monobasic (KH_2PO_4) was used as the P source, whereas triple super phosphate (46% P_2O_5) was used for soil-applied treatments. Solutions for foliar treatments were prepared by dissolving 100 mL

Table 1. Initial surface (0–15 cm) soil test characteristics at Efaw, Goodwell, Guymon, Lake Carl Blackwell, and Perkins, Oklahoma

Location	pH	NH_4-N[a] (mg kg^{-1})	NO_3-N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
Efaw	5.6	14.1	3.1	15.2	100
Goodwell	7.5	—	22.5	13.0	596
Guymon	7.2	—	26.5	31.0	610
LCB	5.4	11.0	1.3	9.7	102
Perkins	4.9	12.2	2.0	13.2	105
Greenhouse I[b]	4.8	5.0	4.5	4.4	130
Greenhouse II[b]	4.9	17.0	2.8	9.4	129

[a] NH_4-N and NO_3-N were extracted with 2 M KCl solution, and P and K were extracted with Mehlich III solution. pH was determined by 1:1 soil–water ratio.

[b] Soil for greenhouse I was obtained by scratching away topsoil from upland Efaw, and soil for greenhouse II was topsoil from Perkins.

of KH_2PO_4 in 1000 mL of water. A backpack Solo sprayer (Epinions Inc., Brisbane, Calif.) with a flat fan nozzle spraying system was used for spraying the solution.

In the greenhouse experiments, 10 treatments consisting of basal and foliar rates and one check were arranged in completely randomized design. The basal rates were 0, 25, 50, and 150 kg P ha^{-1}. The foliar rates were the same as the rates used for the field experiments indicated. For the first greenhouse experiment (greenhouse I), soil with very low Mehlich III–extractable P levels (4 mg kg^{-1}) from Efaw was used, whereas the second greenhouse experiment (greenhouse II) had soil with moderate Mehlich III–extractable P levels (9 mg kg^{-1}) from Perkins. Nitrogen (N) and zinc (Zn) were applied to the 10 treatments at a rate of 112 and 4 kg ha^{-1}, respectively as urea (46% N) and zinc sulfate. Six pioneer hybrid 111 corn seeds were planted by hand in each pot. All foliar rates were applied to the corn at the V4 growth stage using a handheld pressurized microsprayer (designed and fabricated by Department of Biosystems and Agricultural Engineering, Oklahoma State University). Shoots were then removed 10 days after foliar spraying and were dried and ground for determination of P concentration.

Corn was planted at each location during April–May, with a John Deere MaxEmerge planter at 54,000 and 66,000 plants per hectare at Perkins and Guymon, respectively, in 2002 and at 54,000 plants per hectare in 2003 for all locations. Plots were four rows wide (76.2 cm row width) and 9.14 m long in 2002, whereas the length was reduced to 6.1 m in 2003. Nitrogen was applied at planting at the rate of 112 kg ha^{-1} using urea (46% N). The center two rows were used for harvest. All crop-management practices were carried out as per the Oklahoma State University Plant and Soil Sciences Department recommendation for respective locations.

Measurements and Laboratory Analysis

Four soil samples, each averaged from 12 soil cores, were collected prior to planting from the 0 to 15 cm depth with a bucket auger for determining available soil P. Samples for forage P-concentration determination were taken 10 days after each foliar application at Guymon in 2002 and at R1 growth stage for the rest of the experiments in 2002 and 2003. Corn plants were removed from a 1.39 m^2 area. All forage samples were dried in a forced air oven at 30°C for 10 days and weighed before grinding. In 2003, weighed forage samples were used to calculate forage yield.

At maturity, corn from the center two rows was harvested and grain yield was measured and adjusted to a 13% moisture level. Grain and forage samples were ground to pass a 140-mesh sieve (100 μm) and analyzed for available total P using a nitric acid digestion (Jones and Case 1990) followed by inductively coupled argon plasma spectrometer analyses (Fassel and

Kneseley 1974). Available soil P was extracted using the Mehlich III method (Mehlich 1984).

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

$$\mathrm{PUE} = \frac{\text{Grain P uptake in P treated plot} - \text{Grain P uptake of control}}{\text{P rate}} \qquad (1)$$

In 2003 at LCB, some plots were damaged by wild hogs. Grain yield was accordingly adjusted using plant population count and percent damage per plot.

Data Analyses

All data were subject to statistical analyses using the general linear model (GLM) and mixed procedures in SAS (SAS Institute 2001). Data for PUE was transformed using squareroot variance stabilization method as squareroot $(\mathrm{PUE} + 0.5)$. Means were then transformed back to original scale for data presentation. Treatment comparisons were made using Fisher's LSD and single-degree-of-freedom contrast analysis.

RESULTS

Combined analysis of treatments across year and locations revealed that data across years and locations were significant at $P \leq 0.05$ for grain and forage yields, grain and forage P concentration, and PUE. Thus each experiment was analyzed separately for assessing treatment effects on the measured variables mentioned.

Grain Yield

In 2002, corn did not respond to stage or foliar P-rate main effects for all trials. In 2003, yield differed among foliar P rates only at LCB ($P \leq 0.05$). Foliar P rates were significant for grain yield where 8 kg ha $^{-1}$ resulted in significantly higher (34% more) yield than the lower rates and check combined, which were not significantly different among them (Figure 1).

Test of interaction effect of stage by foliar P rate at Guymon in 2002 revealed that the grain yield obtained was different among the three growth stages with the application of 2 kg P ha^{-1} (Figure 2). Grain yield reached its peak when foliar P was applied at the V8 growth stage, with increases of 3000 kg ha^{-1}. Similar results were obtained at Goodwell in 2003 (Figure 2).

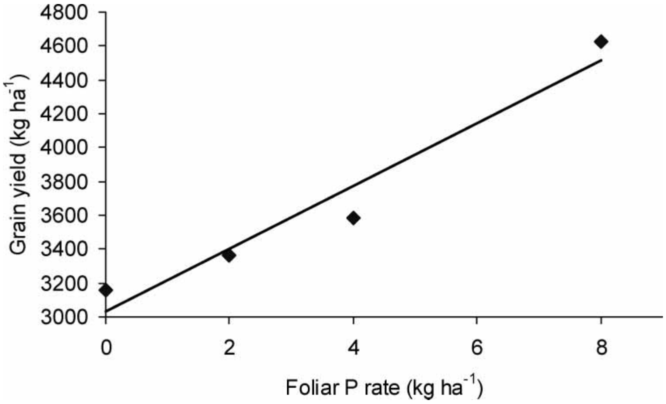

Figure 1. Corn grain yield as affected by foliar P rates at Lake Carl Blackwell in 2003. The R^2 for the linear fit was 0.95.

Forage Yield

Forage yield was analyzed only for 2003 data. At Efaw, it was not significant across growth stage and P rates. However, single-degree-of-freedom contrasts showed that it increased by 601 kg ha $^{-1}$ when either soil or foliar P were applied. At Goodwell on the other hand, stage, P rates, and interaction of stage and P rates resulted in difference in forage yield. Foliar P applied at the VT growth stage outyielded the rates applied at the V4 growth stage by

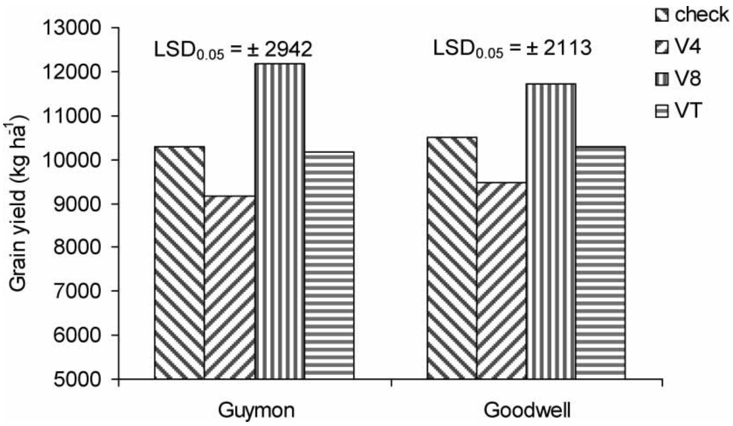

Figure 2. Corn gain yield as influenced by foliar P rate of 2 kg ha^{-1} applied at three growth stages of corn at Guymon in 2002 and Goodwell in 2003. Check refers to plots that did not receive foliar or basal P at Goodwell and received only 20 kg ha^{-1} basal P at Guymon.

15%. Foliar P applied at the VT growth stage with the rates of 4 and 8 kg ha^{-1} resulted in highest forage yield (Figure 3). At LCB, three single-degree-of-freedom contrasts were found significant. Accordingly, soil-applied P resulted in greater dry-matter accumulation than foliar applied P (900 kg ha^{-1} more). Application of basal and foliar P improved forage production when compared with no P (425 kg ha^{-1}). Comparison made between foliar and no P also showed that foliar application of P resulted in additional forage yield of 600 kg ha^{-1}.

Grain P Concentration

Stage main effect was significant at Goodwell, LCB, and Perkins ($P \leq 0.05$) in 2003 only. At Goodwell, foliar P applied at the VT growth stage resulted in superior grain P concentration than that applied at V4 (Table 2). At LCB across growth stages, grain P concentration was significantly higher when foliar P was applied at the VT stage than the V4 stage (9% more P when applied at the VT stage; Table 2). However, at Perkins the foliar P applied at the VT growth stage had superior P concentration compared with only the check.

Foliar P rates were significant at Guymon ($P \leq 0.05$) and Perkins for Bt corn 109 ($P \leq 0.01$) in 2002 and at Goodwell ($P \leq 0.05$) in 2003. At both locations in 2002, the largest foliar P rate (8 kg ha^{-1}) resulted in superior grain P concentration (Figure 4). At Goodwell, both 4 and 8 kg ha^{-1} foliar P rates showed 300 mg kg^{-1} more P in the grain than the 2 kg ha^{-1} foliar P rate.

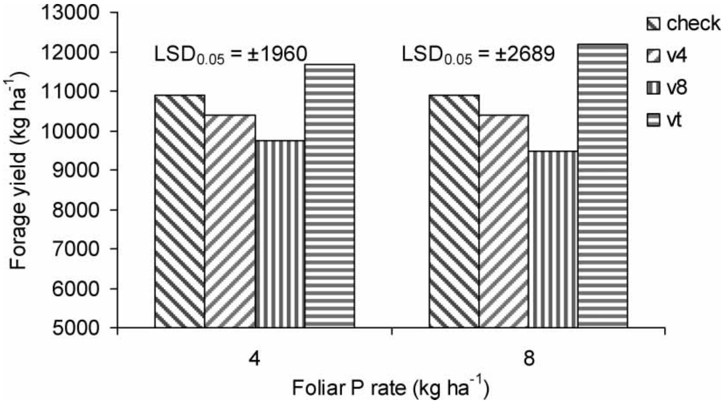

Figure 3. Response of forage yield to foliar rates of 4 and 8 kg P ha^{-1} at three growth stages of corn at Goodwell in 2003. The check refers to plots that did not receive foliar or basal P. The initial soil P level is given in Table 1.

Table 2. Effect of foliar P applied at three growth stages of corn and check (plots with no P applied) at selected locations in 2003

	Grain P concentration ($mg\ kg^{-1}$)			Forage P concentration ($mg\ kg^{-1}$)	
Stage	Goodwell	LCB[a]	Perkins	Efaw	Goodwell
Check	2894	2723	2576	2215	1432
V4	2689	2847	2699	2229	1441
V8	3096	3064	2741	2246	1756
VT	3226	3278	2832	2678	1846
$LSD_{0.05}$	531	408	239	310	288

[a] Lake Carl Blackwell.

Interaction of stage by foliar P rate was significant at Guymon ($P < 0.1$) and at Perkins for Bt corn 109 ($P \leq 0.05$) in 2002 and at LCB ($P \leq 0.05$) and Perkins ($P < 0.1$) in 2003. At Guymon and Perkins for Bt Corn 109, foliar P rates were significantly different for rates applied at the V4 and VT growth stages. For both stages at Guymon and at the VT stage at Perkins for Bt corn 109, 8 kg ha^{-1} P resulted in 600, 300, and 250 mg kg^{-1} respectively more grain P concentration than any of the other rates. At Goodwell, investigation into the interaction means revealed that grain P concentration was significantly higher at the VT than either the V4 or the V8 growth stages with the application of 8 kg P ha^{-1} (Figure 5). Foliar P rates applied at the VT growth stage were also different, unlike foliar P applied at the other stages. At Perkins, a result similar to LCB was obtained with a foliar rate of 8 kg ha^{-1} where a

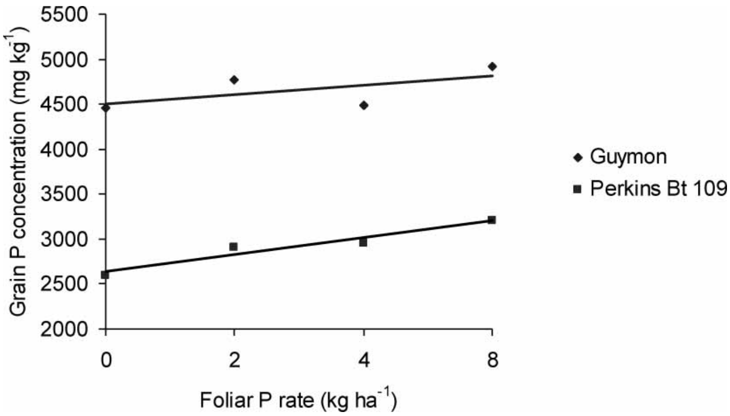

Figure 4. Grain P concentration as affected by foliar P rates at Guymon and Perkins (Bt corn 109) in 2002. At both locations, a significant linear relationship was observed ($R^2 = 0.41$ and 0.94 at Guymon and Perkins, respectively).

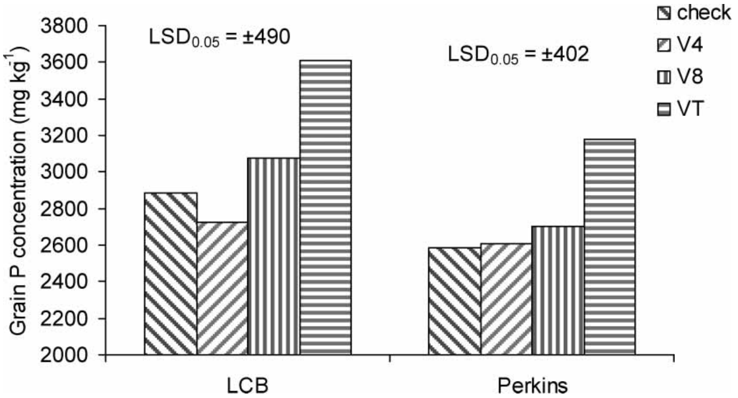

Figure 5. Grain P concentration as influenced by 8 kg ha^{-1} foliar P rate applied at Lake Carl Blackwell (LCB) and Perkins in 2003. The check refers to plots that received no foliar P at both locations. The initial soil P level at the two locations is given in Table 1.

higher grain P concentration was recorded at the VT stage compared with the other stages.

Contrast between the check and foliar rates showed that grain P concentration was increased by foliar P treatment (5% more at Guymon and 14% more at Perkins for hybrid Bt corn 109 than the check) in 2002. Similarly, single-degree-of-freedom comparisons for grain P concentration at LCB in 2003 showed basal-applied P resulted in 870 mg kg^{-1} more grain P content than foliar-applied P. At this location, application of either basal or foliar P resulted in superior grain P concentration than the untreated check (850 and 698 mg kg^{-1} for basal and foliar, respectively). Likewise, at Perkins in 2003, basal- and foliar-applied P increased grain P concentration by 201 and 198 mg kg^{-1}, respectively, compared with untreated check. Linear (at Efaw and Perkins) and quadratic (at Goodwell) trends for foliar P rates were also discovered (Figure 6).

Forage P Concentration

There was not a significant stage effect for forage P concentration in 2002; however, in 2003, foliar P application stages differed significantly at Efaw ($P \leq 0.05$) and Goodwell ($P \leq 0.01$). At both locations, foliar P applied at the VT growth stage resulted in superior P concentration (Table 2). Forage P concentration was significant across foliar P rates at Guymon ($P < 0.1$) and Perkins for Bt corn 108 ($P \leq 0.05$) in 2002. At Guymon, a quadratic response and at Perkins, a linear response was observed (Figure 7). Similarly, in 2003, significant difference was obtained at Goodwell ($P \leq 0.05$), whereas a marginally significant effect was obtained at Perkins

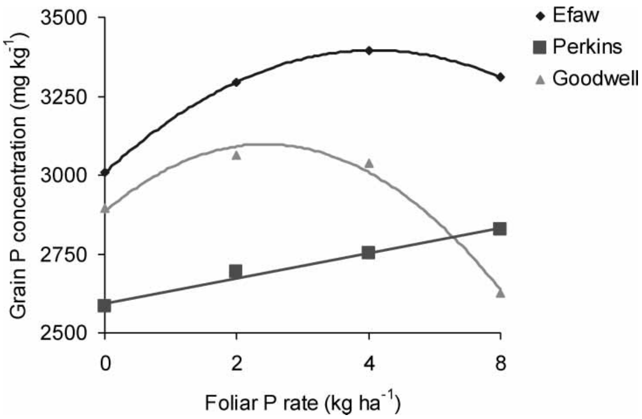

Figure 6. Response of corn grain P concentration to foliar P rates at three locations in 2003. At Efaw and Goodwell, response was quadratic ($R^2 = 0.99$ and 0.98, respectively), whereas it was linear at Perkins ($R^2 = 0.98$).

($P < 0.1$). In both cases, the foliar P rate of 8 kg ha^{-1} resulted in higher forage P concentration than the lower rates considered in the study (Figure 7).

Interaction of stage and foliar P rates were significant at Efaw, Goodwell, and LCB at $P < 0.1$. At Efaw and LCB, 600 mg kg^{-1} more forage P concentration was obtained when 8 kg ha^{-1} foliar P was applied at the VT stage than the V8 and V4, respectively. Likewise, at Goodwell, 400 mg kg^{-1} more forage P was obtained with 2 kg P ha^{-1}at the VT than at the V4 growth stage. At Goodwell, contrasts made between no fertilizer versus fertilizer P

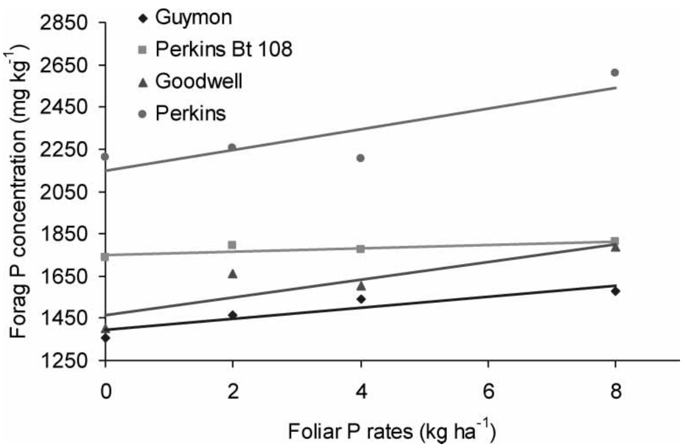

Figure 7. Linear response of forage P concentration to foliar P rates at Guymon ($R^2 =$ 0.85) and Perkins (Bt corn 108, $R^2 = 0.66$) in 2002 and Goodwell (0.78) and Perkins (0.75) in 2003.

(foliar or basal) and no P versus foliar P showed significant difference where forage P concentration was increased by 19.3 and 17.3%, respectively.

The results of the greenhouse I experiment showed that P concentration in corn dry matter was substantially increased by the high basal rate (150 kg P ha^{-1}) in the presence of adequate N supply. However, low basal rates and all foliar rates did not improve the P concentration in corn dry matter. An interesting outcome of this experiment was that as the amount of basal P increased from the 0 and 25 kg ha^{-1} to 50 kg ha^{-1}, a remarkable response in foliar P rates was observed (Figure 8). However, this only occurred before the P rate was elevated beyond 50 kg ha^{-1}. In the greenhouse II experiment, a similar result was observed where the highest P rate resulted in superior P concentration in forage. No foliar rate response was obtained, however.

Phosphorus-Use Efficiency

In 2002 at Guymon, stage was significant ($P \leq 0.01$), but in 2003 there was not a significant stage effect. Stage main effect at Guymon was higher (148% more) for P applied at the V8 growth stage than that applied either at the V4 or VT growth stages.

Foliar P rates at Guymon were significant ($P < 0.01$) in 2002 and at Goodwell ($P < 0.05$) in 2003. The lowest P rate (2 kg ha^{-1}) was superior in PUE compared to the other two higher rates at both locations (Figure 9). Application of 2 kg ha^{-1} at the V8 growth stage exhibited 510% PUE at Goodwell.

Interaction of stage by foliar P rates was also significant at Guymon and Perkins (for both varieties) in 2002 ($P < 0.01$). At Guymon, detection of significant interaction effects guided by test of effect slices at the 5% level of

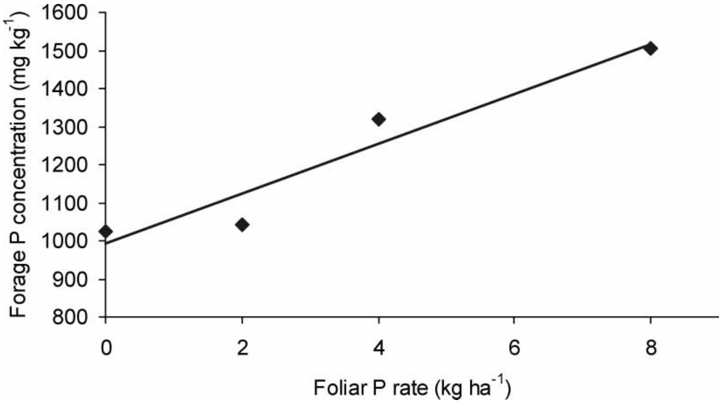

Figure 8. Linear (R^2= 0.92) response of corn forage P concentration at V4 growth stage to foliar P rates with application of 50 kg ha^{-1} basal P in greenhouse experiment I.

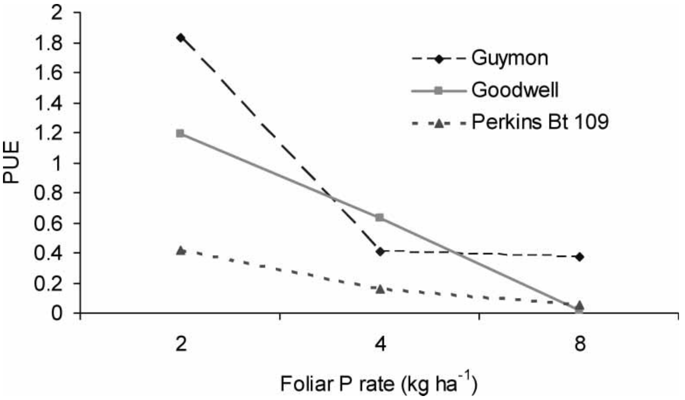

Figure 9. Phosphorus-use efficiency of corn as affected by foliar P rates at Guymon and Perkins (Bt corn 109) in 2002 and Goodwell 2003.

significance showed that at the V8 growth stage, the lowest P rate resulted in highest PUE (more than 10-fold). Conversely, the application of 2 kg ha^{-1} at V8 resulted in higher PUE than the other stages (data not shown). At Perkins, the interaction of foliar rate and growth stage showed that application of 2 kg P ha^{-1} (at both the V8 and VT stages) improved PUE by at least 60% versus that applied at the V4 growth stage. The PUE at V4 was not better than the check. For Bt corn 108 at Perkins, two treatment combinations, 4 kg P ha^{-1} at the V4 (62%) and VT (65%) stages, resulted in highest PUE.

For the Guymon location, single-degree-of-freedom polynomial contrast revealed that a quadratic relationship occurred among the foliar rates. On the other hand for Bt corn 109, a linear relationship was observed for foliar P rates considered in 2002. In 2003, basal- versus foliar-applied P contrast at LCB was significant. At this location, the foliar rate of 2 kg P ha^{-1} resulted in 35% more PUE than the basal P.

DISCUSSION

Grain and Forage Yields

Across years and locations, the stages in which the rates were applied or the foliar rates did not impact yield very much except at Guymon in 2002 and LCB in 2003. There are several possible explanations for this. First, it is suspected that the foliar rates might not be sufficient to deliver additional statistically detectable yield difference among treatments. In winter wheat, Mosali (2004) found a lack of response in grain yield to foliar rates of 2 and 4 kg ha^{-1} in Oklahoma, which were attributed to the low rates considered. Second, the soil P level explains the lack of response to foliar rates considered in this study. Most of the locations considered in the study have reasonable initial soil-test P levels (Zhang 2001). The fact that the corn plant–root system can extend and explore the soil by increasing the surface of root contact to P coupled with good growing conditions might explain the improved sufficiency once plant roots are well developed. Third, the lack of good growing conditions might interfere with the plants' capacity to make use of supplied P at some locations. For example, Perkins is located in a relatively high evapotranspiration area of Oklahoma, and high yield is not expected. At this location, we suspected that high heat and low moisture status for optimum corn growth might have affected treatment effects. On the other hand, at this location, the soil-test P index was 40, which is a sufficiency level of 95%, slightly less than the amount required by corn crop (Zhang 2001; Bundy 1998; Heckman et al. 2001). Consequently, absence of significant foliar-applied P was not surprising. At Guymon in 2002, mean grain yield was higher because the corn at this location was supplied with irrigation. The preplant soil-test P index was nearly 140, which was in excess of the corn requirement. Despite the large amount of available P reported in the soil for this location, analysis of interaction effects revealed that the grain yield obtained was higher at V8 with the application of 2 kg ha^{-1} foliar P. This was largely due to the stimulating effect of the supplemental foliar P of the irrigated corn root system, allowing more exploration of P and other nutrients that are required for improved yield. The results obtained are also supported by the work of Ling and Silberbush (2002), who concluded that foliar fertilization may partially compensate for insufficient uptake of essential nutrients by the roots of corn, which are required for grain filling.

The results from LCB showed that when soil P level was low, responses to basal or foliar rates were considerable. The significant stage effect also warrants that the application of foliar P at later growth stages would likely help obtain a higher yield that could have been lost as a result of P deficiency when the nutrient was needed most.

Several research findings were reported on both the presence and lack of yield response to foliar P rates. Harder, Carlson, and Shaw (1982) found that foliar fertilizer applied after silking did not translate into increased grain yield. On the other hand, Barel and Black (1979b) reported an increased grain yield due to foliar P compared with control (untreated check).

Grain and Forage P Concentration

Grain and forage P concentration differed as results of stage and foliar P rates in several of the experiments. The foliar P rates applied at the V8 and VT growth stages generally resulted in higher concentration, indicating the effectiveness of foliar fertilization. With regard to foliar P rates, the results showed that 8 kg ha^{-1} increased P concentration. When higher foliar rates were applied at later growth stages, at least in the current context of VT stage, a high level of grain or foliar P concentration is possible to achieve. One consistent result of the study was that all foliar-applied P treatments achieved higher concentrations than the check. In their study, Harder, Carlson, and Shaw (1982) found that percent P in grain was increased by 230 mg kg^{-1} (4.7% increases) by foliar fertilization compared with the control. However, their analysis did not detect significant differences within foliar P rates. High P concentration in forage might be remobilized if it is needed during grain filling, whereas high concentration in grain might improve yield or be kept in the seed as P, which is very important for germination and initial development until roots extend to contact soil (Pellerin, Mollier, and Plénet 2000). In corn, the concentration of P in plant ranges between 0.3 and 0.5% (3000–5000 mg kg^{-1}) of plant dry matter during vegetative growth (Barry and Miller 1989).

Phosphorus-Use Efficiency

Phosphorus-use efficiency was generally higher for foliar-applied than basal-applied P. The results obtained here also revealed that foliar P rate applied at the V8 growth stage resulted in higher PUE than the earlier or later applied foliar P rates. The lowest foliar P rate was found to be more efficient than the higher rates. Interaction effects at Goodwell and Perkins experiments in 2002 revealed that applying 2 kg P ha^{-1} at the V8 growth stage highly improved PUE. The decrease in efficiency with higher rates of foliar P could be due to several reasons that influence the actual amount of applied P that comes in contact with the plant, retained on the corn leaf or stalk, absorbed by leaves and translocated.

The formulation used as foliar fertilizer coupled with hot summer conditions at the experimental locations might interfere with the retention and uptake of the fertilizer. Barel and Black (1979a) found that ammonium salts of orthophosphate dried rapidly and left dry crystals on the surface of the leaf, which depending on moisture availability and conditions such as temperature and humidity might be taken up later or washed away. In moist conditions, potassium phosphate is rapidly absorbed by leaf. Because most of the foliar ionic nutrients are absorbed through stomata, their opening and closure greatly affect the uptake of foliar P. Although, according to Linskens, Heinen, and Stoffer (1965), leaf hairs have thinner cell walls near their base, which enhances entrance of ionic foliar nutrients at any time.

CONCLUSIONS

The responses in grain and forage yields and grain and forage P concentrations obtained from foliar P indicate that this work should be pursued further. Foliar P applied at the VT growth stage improved grain and forage P concentration, and PUE was high only when low foliar P rates were applied.

Foliar P rate at 8 kg ha^{-1} improved yields to some extent and largely forage and grain P concentration of corn compared to the lower rates, although again this was not translated to high use efficiency. The benefit of foliar P might be indirect through the initiation of chain of processes in the cell that in turn enhances photosynthesis, which in turn increases water uptake, which obviously leads to nutrient absorption through the root. The result is healthy growth and increased grain yield. In conclusion, the benefit of foliar P entirely depends on the type of soil and weather conditions prevailing in the corn growing environment plus the effective formulation. Further investigation is required before consistent conclusions are drawn for foliar fertilization of P on corn in Oklahoma. It is also important to note that foliar fertilization is not meant to substitute soil application. This is because at early growth stages, leaf area is too small to intercept foliar P rates required as starter fertilizer and the economically achievable number of foliar applications are limited. The results suggest that foliar P applied at V8 growth stages and later could be used as an efficient P-management tool in corn.

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