Cotton Response to Phosphorus Fertigation Using Subsurface Drip Irrigation

J. Enciso-Medina, P. D. Colaizzi, W. L. Multer, C. R. Stichler

Abstract. *Subsurface drip irrigation (SDI) has expanded dramatically in cotton producing areas of the southwest United States, especially where furrow irrigation was practiced. There is ancillary evidence that cotton may experience shortages of phosphorus (P) and other nutrients more readily under SDI compared with furrow irrigation. This may be related to the smaller wetted volume of soil and hence smaller root volume under SDI. Some cotton producers using SDI in the Trans Pecos region of Texas have observed large increases in cotton lint yield by the addition of small amounts of P; however, cotton response to different P rates under SDI has not been documented in this region. This article presents results of a field experiment repeated during the 2003, 2004, and 2005 growing seasons where cotton lint yield, quality characteristics, and lint gross return were evaluated for different P application rates. The experiment was completely randomized with four treatments and three replications. Treatments were: 1) no phosphorus applications; 2) injection of 4.6 kg ha^{-1} y^{-1} P contained in Miller Solugro® (12-48-8); 3) injection of 32.9 kg ha^{-1} y^{-1} P contained in phosphoric acid; 4) injection of 65.7 kg ha^{-1} y^{-1} P contained in phosphoric acid. The cost of P treatments ranged from $21.10 to $42.20 ha^{-1} y^{-1}, but marginal gross returns for lint were $520 to $1,252 ha^{-1} y^{-1} more from phosphoric acid and $233 to $872 ha^{-1} y^{-1} more from Miller Solugro®. In 2003 and 2004, lint yields and gross returns were greatest for the 65.7-kg ha^{-1} y^{-1} P rate, which was similar to recommended rates based on a 2004 soil fertility analysis. In 2005, lint yields and gross returns were greatest for the 32.9-kg ha^{-1} y^{-1} P rate, which was slightly below recommended rates based on pre-plant 2005 soil fertility analysis. These results support injecting P at rates based on soil fertility analyses. Both phosphoric acid and Miller Solugro® were suitable for injecting P into SDI systems. The P_2O_5 application rates increased the productivity per unit of water applied during the three years of the study. Plant petiole analysis in 2004 correlated with P application rates, suggesting a qualitative method to detect P deficiencies during the growing season.*

Keywords. *Microirrigation, Subsurface drip irrigation, Cotton, Phosphorus, Fertigation.*

The adoption of subsurface drip irrigation (SDI) for cotton production has grown dramatically in the southwestern part of the United States (Ayars et al., 1999; Camp et al., 2000; Hanson et al., 2000). Henggeler (1995) estimated that approximately 1,300 ha of SDI had been installed in southern High Plains and Trans Pecos regions of Texas by the early 1990s; by 2006, SDI had expanded to 100,000 ha according to some industry estimates (H. Frerich, pers. communication, owner of Eco-drip Irrigation Company located in Garden City, and Lubbock, Tex.)

SDI generally results in greater lint yield and water use efficiencies compared with furrow irrigation (Henggeler, 1995) and mechanical-move systems [e.g., spray and low energy precision application (LEPA)] at lower irrigation rates (Bordovsky and Porter, 2003; Colaizzi et al., 2005). The adoption of SDI, however, has been constrained by its much greater initial costs and management requirements (Segarra et al., 1999; Enciso et al., 2005). The confluence of declining groundwater resources, greater energy costs for pumping, and intensifying drought now appears to justify these costs for cotton producers.

Continuous cotton production using SDI requires more frequent replacement of water and nitrogen (N) compared with furrow irrigation (Phene et al., 1990). Ancillary evidence suggested that this also applies to immobile soil nutrients such as phosphorus (P). Under extremely limited irrigation application rates typical for West Texas (Enciso et al., 2003), SDI results in a smaller volume of soil irrigated. This may result in smaller and denser root volumes and hence smaller access to nutrient reserves in the soil (Charlesworth and Muirhead, 2003). Next to water and nitrogen (N), phosphorus (P) is perhaps the third most significant constraint for cotton production in arid to semi-arid regions of the United States (Bronson et al., 2003). P is essential for early root and fruit formation and timely boll maturity (Marcus-Wyner and Rains, 1982). N is relatively mobile in soil solution and is usually applied in limited amounts before planting and during the vegetative stage (e.g., Morrow and Krieg, 1990). If soil tests indicate P deficiencies, P can be

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applied in a large, blanket amount in the form of superphosphate (P_2O_5) before planting because it is relatively immobile in the soil.

Several cotton producers in the area surrounding St. Lawrence, Texas, reported declining lint yields after using SDI for about 10 years. After injecting small amounts of P_2O_5 into the irrigation water (herein termed fertigation), they achieved large increases in lint yield, despite soil tests not always indicating P_2O_5 deficiencies (Bronson et al., 2001; Fundenburg et al., 1996). Some farmers preferred to disk the phosphorus into the soil rather than injecting it to the irrigation system due to plugging problems and due to the increase cost of knifing it into the soils. Bar-Yosef (1999) showed that P_2O_5 fertigation may increase yield by stimulating greater P uptake by the roots. Because roots develop in response to soil water distribution as applied by irrigation, fertigation may concentrate nutrients where they are most optimally absorbed by roots (i.e., regions of high root densities). Proper fertilization rates can help increase irrigation water use efficiencies in water limiting areas (Howell, 2000). Although general guidelines exist for P application rates based on P_2O_5 concentrations in soil (e.g., Bronson et al., 2003), different rates of P_2O_5 fertigation through SDI systems have not been studied explicitly as a treatment variable for cotton production in West Texas. The objectives of this study were to evaluate responses of cotton lint yield, lint quality, gross economic returns, and productivity per unit of water applied to different amounts and sources of P_2O_5 applications.

Materials and Methods

The study was conducted on a farm owned by a cooperating producer during the 2003, 2004, and 2005 cotton growing seasons near St. Lawrence, Texas. The area is semi-arid and receives less than 400 mm of rainfall per year. The soil at the field site was a Reagan silty clay loam (fine-silty, mixed, thermic Ustolic Calciorthids) with moderate permeability on a 1% slope. A genetically modified cotton variety with Bt traits (*Gossypium hirsutum* L., c.v. 458 Deltapine) was used to limit insect damage. A SDI system was installed in 1997 to supplement crop water demand unmet by rainfall, as dryland cotton production in this area is marginal. Planting dates and irrigation amounts were typical for the region (table 1), and nitrogen (N) application rates were similar to those used for maximum yield cotton production (2,000-kg ha^{-1} lint yield goal) on commercial farms and were recommended by the Texas A&M soil, water, and forage testing laboratory (table 2).

Table 1. Agronomic and irrigation data for 2003, 2004, and 2005.

Variable	2003	2004	2005
Cotton variety	DP 458 B/R[a]	DP 458 B/R	DP 458 B/R
Planting date	29 May	21 May	23 May
First in-season irrigation	9 Jun	26 May	20 Jun
Last irrigation	2 Sep	20 Sep	15 Aug
Harvest date	17 Nov	8 Dec	8 Oct
Length of growing season (days)	172	201	138
Preplant irrigation (mm)	152	179	---
In-season irrigation (mm)	269	278	175
Growing season precipitation (mm)	160	482	423
Annual precipitation (mm)	192	591	630
Cumulative growing degree days (C, 15.6°C baseline)	1488	1501	1336

[a] Delta Pine 458 Bollgard® Roundup Ready®.

Table 2. Nitrogen and phosphorus application rates for each treatment.

Treatment	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	P_2O_5 Cost ($ ha^{-1})
1. No Phosphorus	112.0	0.0	----
2. Miller Solugro® 12-48-0	113.1	4.6	21.00
3. Low Phosphoric Acid	112.0	32.9	21.10
4. High Phosphoric Acid	112.0	65.7	42.20

The experimental design was a completely randomized block with four treatments and three replications. Treatments were single factor phosphorus in the form of phosphate (P_2O_5). Application rates and specific treatments were: 1) no phosphorus applications; 2) injection of 4.6 kg ha^{-1} y^{-1} P_2O_5 contained in Miller Solugro® (12-48-8); 3) injection of 32.9-kg ha^{-1} y^{-1} P_2O_5 from phosphoric acid ("Low Phosphoric Acid"); 4) injection of 65.7-kg ha^{-1} y^{-1} P_2O_5 from phosphoric acid ("High Phosphoric Acid") (table 2). The Miller Solugro® is a liquid fertilizer containing additional trace nutrients (table 3) which is popular with cotton producers in the St. Lawrence, Texas area. The P_2O_5 treatment rates were selected from producer preferences of input costs rather than soil fertility tests. Soil tests were conducted prior to planting in 2004 and 2005. P was determined using the average Mehlich-3 extractable P. Producers in the area generally limit the input cost of Miller Solugro® to $21.00 ha^{-1} y^{-1} (treatment 2). A rate of 32.9-kg ha^{-1} y^{-1} P_2O_5 from phosphoric acid was selected for treatment (3) because the input cost was similar to the producer preference. The 65.7-kg ha^{-1} y^{-1} P_2O_5 rate (treatment 4) was approximately twice that of Treatment 3 and represented the upper limit of P_2O_5 input costs ($42.20 ha^{-1} y^{-1}) that area cotton producers would typically incur. P fertilizers where injected by having two injection points in the irrigation system. A common practice is to inject up-stream point NPhuric or sulfuric acid to lower the pH to 6.5 and to inject the P fertilizer at the downstream point before the filters in order to economize. During the experiment the NPhuric lowered the pH to 4.5 because the injection rate could not lower at lower rate. The pH was lowered to avoid the formation of phosphates with the reaction of the P fertilizer with the Ca or Mg of the irrigation water that could precipitate and clog the emitters. The water from two wells was mixed and used with the irrigation system. The water analysis is reported in table 4.

Table 3. Composition of Miller Solugro® fertilizer.

Constituent	Percentage
Total Nitrogen	12.0
Phosphorus (P_2O_5)	48.0
Potassium (K_2O)	8.0
Boron (B)	0.02
Copper (Cu)	0.05
Iron (Fe)	0.10
Manganese (Mn)	0.05
Zinc (Zn)	0.05
Molybdenum (Mo)	0.0005

Table 4. Water analysis report.

Parameter Analyzed	Well 1	Well 2	Units
Calcium (Ca)	204	172	ppm
Magnesium (Mg)	62	67	ppm
Sodium (Na)	259	206	ppm
Potassium (K)	9	10	ppm
Boron (B)	1.04	1.06	ppm
Carbonate (CO_3)	0	0	ppm
Bicarbonate (HCO_3)	195	225	ppm
Sulfate (SO_4)	714	615	ppm
Chloride (Cl^-)	177	180	ppm
Nitrate-N (NO_3-N)	17.58	9.79	ppm
Phosphorus (P)	0.67	0.45	ppm
pH	7.40	7.2	
Conductivity	2140	1867	µmhos/cm
Hardness	56	41	Grains $CaCO_3$/gal
Hardness	765	705	ppm $CaCO_3$
Alkalinity	160	184	ppm $CaCO_3$
Total Dissolved Salts (TDS)	1639	1486	ppm
SAR	4.1	3.4	

Each replicate plot was 56.1 m long and 12.2 m wide, with raised beds spaced 1.02 m apart (12 rows per plot). The SDI system consisted of permanent laterals shank-injected into the center of each planted bed and 0.35 m below the surface. Drip emitters were spaced 0.60 m along the lateral with a nominal discharge of 4 L h^{-1}, resulting in a water application rate of 6.7 mm h^{-1}. The emitters were constructed of plastic impregnated with Trifluralin to inhibit root intrusion. Each block was irrigated twice per week using electric timers with flow measured with totalizing flow meters for each plot. Each season field operations included stalk chopping, bed listing, planting, and two applications of Round Up Ultra Max® for weed control each season. Liquid N (urea ammonium nitrate 32-0-0) was injected through the SDI system in three equally spaced amounts during the vegetative to early reproductive stages of crop growth. P was injected through the SDI system in two equal amounts on 9 and 22 July 2003; 29 June and 13 July 2004; and 13 and 25 July 2005 (table 2).

Soil fertility measurements resulted from soil samples taken about one week before planting from 0- to 30-cm depths from each plot in 2004 and 2005. One sample was taken from each replication about 7.5 cm from the drip-line. N and P_2O_5 application rates were recommended based on a 2,000 kg ha^{-1} lint yield goal (table 5). Plant phosphorus content was measured weekly from petiole analysis sampled on five dates, from 19 July to 23 August 2004. Petiole analyses were used to monitor the crop and to evaluate differences between treatments. A total of 25 petioles were collected and combined from the three replications of each treatment. Rainfall and other micrometeorological data were measured by an automatic weather station (Campbell Scientific, Logan, Utah) at the site.

Cotton yield and quality data were obtained for each plot from samples harvested by hand along two 3.04-m-long planted rows. Seed cotton samples from each plot were weighed, and 600-g sub-samples were ginned at the Texas A&M Agricultural Research and Extension Center in Lubbock, Texas. Lint was analyzed for fiber quality at the International Textile Center of Texas Tech University in Lubbock. Gross returns were computed as the product of lint yield and loan value (base price adjusted for fiber quality). The return ratio for added P_2O_5 was computed as the additional gross return over the "No Phosphorus" treatment divided by the cost of P_2O_5. Lint yield, micronaire, fiber length, fiber uniformity, fiber strength, loan value, lint gross return, and return ratio for P_2O_5 were tested for differences between each P_2O_5 treatment, using the SAS Mixed Model (PROC MIXED, Littell et al., 2006) with least square means ($\alpha \leq 0.05$). Individual years (i.e., by 2003, 2004, and 2005) and combined years were examined with the model.

Results and Discussion

Rainfall and Irrigation Patterns

Rainfall patterns and amounts were different during each year of the study, resulting in different irrigation needs for

Table 5. Fertilizer recommendations for 2,000 kg ha^{-1} lint yield goal based on soil analyses for each treatment and replication, 2004 and 2005.

		2004		2005	
Treatment	Replication	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})
1. No phosphorus	1	84	73	56	56
2. Miller Solugro® 12-48-0	1	56	73	62	50
3. Low phosphoric acid	1	34	67	84	73
4. High phosphoric acid	1	50	73	73	56
1. No phosphorus	2	73	73	67	39
2. Miller Solugro® 12-48-0	2	45	56	56	22
3. Low phosphoric acid	2	62	73	56	34
4. High phosphoric acid	2	0	78	45	28
1. No phosphorus	3	17	56	17	34
2. Miller Solugro® 12-48-0	3	56	78	45	39
3. Low phosphoric acid	3	0	67	67	34
4. High phosphoric acid	3	0	78	39	28
Average for all replications					
1. No phosphorus		58	67	47	43
2. Miller Solugro® 12-48-0		52	69	54	37
3. Low phosphoric acid		32	69	69	47
4. High phosphoric acid		17	77	52	37

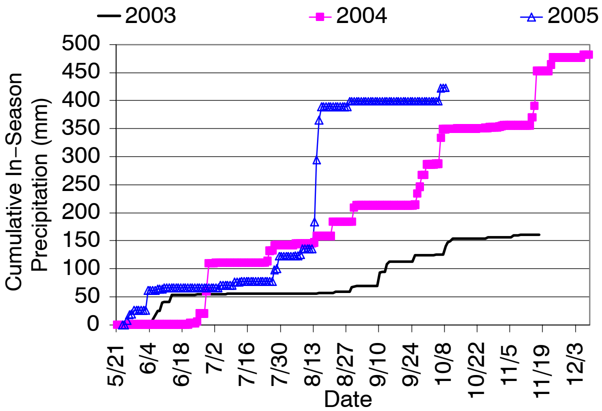

Figure 1. Cumulative in-season precipitation during 2003, 2004, and 2005.

each season (fig. 1, table 1). Rainfall in 2003 was the least, with 160 mm occurring during the growing season, and generally followed a bimodal pattern with most falling during either early June or September. The annual total during the study was 192 mm, well below the long term average of 380 mm. Irrigation totals in 2003 were 152 mm preplant and 269 mm during the season (421 mm total). In-season rainfall in 2004 (482 mm) was the greatest among the study years, and evenly distributed. Rainfall in November delayed harvest until 8 December. Preplant and early season rainfall in 2004 was sparse, forcing pre-plant (179 mm) and growing season (278 mm) irrigation for a total of 457 mm. In 2005, in-season rainfall totaled 423 mm, but 250 mm occurred during 13 to 16 August. Annual rainfall totals for 2004 and 2005 were 591 and 630 mm, respectively, well above the 380-mm long-term average. No preplant irrigation was applied in 2005 because 125 mm of precipitation occurred from late January until planting on 23 May (data not shown). Irrigation applied during the 2005 growing season was limited to 175 mm due to the 250 mm of rainfall occurring when cotton plants were at peak reproductive stages during August. Drier conditions afterward allowed an earlier harvest on 8 October. Cumulative growing degree days (15.6°C base temperature; Peng et al., 1989) totaled 1,488, 1,501, and 1,336 for 2003, 2004, and 2005, respectively. The differences mainly affected the total length of the growing season.

Cotton Yield and Quality Response to P Applications

Phosphorus treatments had significant effects on cotton lint yield, lint quality, gross returns, and return ratios in all three years (table 6). In 2003, the Miller Solugro® and phosphoric acid treatments had significantly greater lint yield, fiber length, and gross returns than the control treatment (no phosphorus added). The high phosphoric acid treatment had significantly greater lint yield, fiber length, fiber strength, and gross return than all other treatments. The largest return ratio (increase in gross return per P_2O_5 investment) resulted from the Miller Solugro® treatment (41.5), followed by the low phosphoric acid treatment (40.4). The high phosphoric acid treatment had a lower return ratio (29.7), although it was not significantly different according to the PROC MIXED procedure. Marginal gross return (increase in gross return over the control treatment) were \$872, \$854, and \$1,272 ha^{-1} y^{-1} for the Miller, low phosphorus, and high phosphorus ttreatments, respectively. The Miller Solugro® and low phosphoric acid treatments had no significant differences in lint yield, fiber quality, gross return, and return ratio, despite the large difference in

Table 6. Cotton lint yield, fiber quality, and returns for phosphorus fertility study, 2003, 2004, and 2005.

Treatment	Lint Yield[a] (kg ha^{-1})	Fiber Micronaire	Fiber Length (mm)	Fiber Uniformity (%)	Fiber Strength (g tex^{-1})	Loan Value (\$ kg^{-1})	Gross Return (\$ ha^{-1})	Productivity per Unit of Water Applied (kg ha^{-1} mm^{-1})	P_2O_5 Cost (\$ ha^{-1})	Return Ratio for P_2O_5 Invest.[b]
2003										
1. No phosphorus	1201 c	4.4 a	26.5 c	81.6 c	27.3 b	1.141 b	1,371 c	2.85	----	----
2. Miller Solugro® 12-48-0	1856 b	4.3 a	28.0 b	82.0 bc	27.9 b	1.208 a	2,242 b	4.41	21.00	41.5 a
3. Low phosphoric acid	1832 b	4.4 a	28.2 b	82.3 ab	28.1 b	1.215 a	2,225 b	4.35	21.10	40.5 a
4. High phosphoric acid	2156 a	4.4 a	28.9 a	82.7 a	29.2 a	1.217 a	2,623 a	5.12	42.20	29.7 a
2004										
1. No phosphorus	1232 c	3.6 a	27.5 b	81.0 b	28.1 b	1.154 b	1,422 c	2.70	----	----
2. Miller Solugro® 12-48-0	1598 b	3.6 a	28.3 a	81.1 b	27.9 b	1.182 ab	1,889 b	3.50	21.00	22.2 ab
3. Low phosphoric acid	1658 ab	3.7 a	28.7 a	82.1 a	28.7 ab	1.191 ab	1,975 ab	3.63	21.10	26.2 a
4. High phosphoric acid	1742 a	3.5 a	28.8 a	82.2 a	29.3 a	1.201 a	2,095 a	3.81	42.20	15.9 b
2005										
1. No phosphorus	1287 c	4.1 a	26.7 b	79.4 b	26.0 b	1.162 c	1,497 c	7.35	----	----
2. Miller Solugro® 12-48-0	1461 b	4.0 a	26.9 b	80.3 ab	26.9 ab	1.185 bc	1,731 b	8.35	21.00	11.1 b
3. Low phosphoric acid	1635 a	3.8 a	28.0 a	80.5 a	27.5 a	1.234 a	2,017 a	9.34	21.10	24.6 a
4. High phosphoric acid	1610 a	3.8 a	28.0 a	80.5 a	27.3 a	1.230 ab	1,980 a	9.20	42.20	11.5 b
All years										
1. No phosphorus	1240 c	4.0 a	26.9 c	80.6 b	27.1 c	1.152 c	1,430 c	4.30	----	----
2. Miller Solugro® 12-48-0	1638 b	4.0 a	27.7 b	81.1 ab	27.5 bc	1.192 b	1,954 b	5.42	21.00	24.9 ab
3. Low phosphoric acid	1708 ab	4.0 a	28.3 a	81.6 a	28.1 ab	1.213 ab	2,072 ab	5.77	21.10	30.4 a
4. High phosphoric acid	1836 a	3.9 a	28.6 a	81.8 a	28.6 a	1.216 a	2,233 a	6.04	42.20	19.0 b

[a] Means with the same letter are not significantly different within each column of data and also within each year.
[b] Return ratio defined as increase in gross return per P_2O_5 investment.

P_2O_5 applications (4.6 and 32.9 kg ha^{-1} y^{-1} , respectively). The reason could be that the Miller solution contained elements such as zinc, manganese, iron, and copper which could have interacted with P fertilizer (Cakmak and Marschner, 1986). They also demonstrated that increasing the P supply can result in zinc deficiency symptoms as well as P toxicity symptoms which could eventually impact yield.

In 2004, lint yield, fiber length, fiber uniformity, fiber strength, loan value, and gross return also increased from P_2O_5 applications, but differences in treatment responses were somewhat less compared with those observed in 2003 (table 6). The low phosphoric acid treatment yielded the greatest return ratio (26.2), which was significantly greater than the high phosphoric acid treatment (15.9). Marginal gross returns were \$467, \$553, and \$673 ha^{-1} y^{-1} for the Miller, low phosphorus, and high phosphorus treatments, respectively. Although the present study did not address the P and Zn relationship, we speculate that the high P treatments could have induced some Zn deficiencies, resulting in lint yields that did not increase in proportion with the amount of phosphorus injected (Cakmak and Marschner, 1986). Similar to 2003, the 2004 crop responded to quality variables (except for fiber uniformity) which were not significantly different between the Miller Solugro® and low phosphoric acid treatments. Unlike 2003, all response variables (except for return ratio) also were not significantly different between the low and high phosphoric acid treatments.

Phosphorus (P) concentrations in plant petioles were measured on five dates in 2004 during mid-bloom to boll opening (fig. 2). Relative petiole P content generally followed the P_2O_5 treatment application rates and final lint yield, loan value, and gross return. However, petioles from the Miller Solugro® treatment (4.6 kg ha^{-1} y^{-1} P_2O_5) had nearly the same P concentrations as the low phosphoric acid treatment (32.9 kg ha^{-1} y^{-1} P_2O_5) by 2 August and greater P concentrations by the last petiole sample date on 23 August. Potash (K_2O) and other micronutrients present in the Miller Solugro® (table 3) may have influenced P plant uptake, and in turn influenced final yield and fiber quality. A review of previous studies on cotton nutrition supported this hypothesis. Aneela-Sardar et al. (2003) found that P concentrations in cotton leaves were correlated with K_2O application. Tupper and Ebelhar (1993) reported that lint yield was more correlated to the soil test K/P ratio than either K or P alone. In experiments with cotton plants grown in hydroponic solutions, Yang-Qiong et al. (1995) indicated that P uptake was maximized within an optimal range of B concentration. Zhu-Jian et al. (2001) reported that B deficiency sometimes inhibited B, P, K, and Mg uptake depending on the cotton cultivar. Conversely, Ohki (1975) reported that P concentrations were less in cotton leaves with increased Mn concentration. Cakmak and Marschner (1986) reported that P uptake was actually enhanced by Zn deficiencies in the Deltapine 15/21 cotton variety.

In 2005, lint yield, fiber quality, loan value, and gross return followed the same general trends for the first three treatments as in 2004; however, most response parameters for the high phosphoric acid treatment were slightly less than those for the low phosphoric acid treatment (table 6). Marginal gross returns were \$233, \$520, and \$483 ha^{-1} y^{-1} for the Miller, low phosphorus, and high phosphorus treatments, respectively. The declining yield response to the high phosphoric acid treatment in 2005 (relative to 2004) may

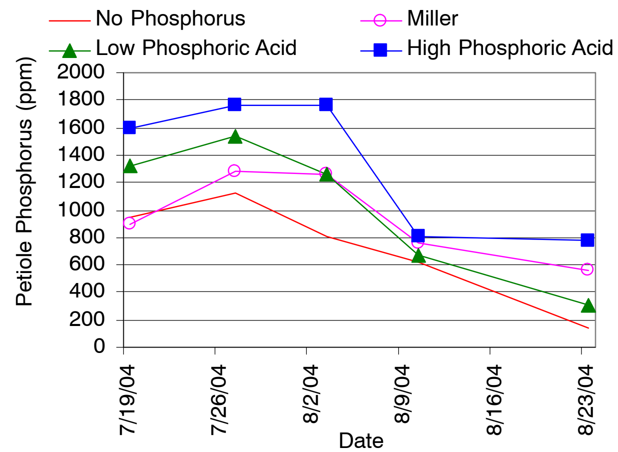

Figure 2. Phosphorus content of petiole samples during the 2004 season.

have been related to differences in preplant P_2O_5 levels in the soil for each year. Soil samples from each plot were analyzed for fertility just before planting in 2004 and 2005, and recommendations were made for N and P_2O_5 application rates (table 5). In 2004, recommended P_2O_5 rates were 67 to 77 kg ha^{-1} y^{-1} (average of each treatment replication), which were slightly greater than the high phosphoric acid rate (65.7 kg ha^{-1} y^{-1}). In 2005, however, recommended P_2O_5 rates were only 37 to 47 kg ha^{-1} y^{-1} (average of each treatment replication), which were above the low phosphoric acid rate (32.9 kg ha^{-1} y^{-1}) but less than the high phosphoric acid rate. In previous studies similar results had been obtained by Bronson et al. (2001) and Fundenburg et al. (1996) who concluded that cotton response to P fertilizers is often difficult to predict, even with soil tests. In 2005, the return ratio for the low phosphoric acid treatment (24.6) was significantly greater than both the Miller Solugro® treatment (11.1) and the high phosphoric acid treatment (11.5).

When all three years were combined, most response parameters were positively correlated with P_2O_5 application rates (table 6). Lint yield, loan value, and gross return for all phosphorus treatments were significantly greater than the control (no phosphorus) treatment. The return ratio was largest for the low phosphoric acid treatment, and this was significantly greater than the high phosphoric acid treatment and numerically greater than the Miller Solugro® treatment.

The phosphorus application rates had a large impact on the productivity per unit of water applied during the three years of the study. In 2003, the productivity per unit of water applied was 54.5%, 52.5%, and 79.5% greater for the Miller Solugro®, low, and high phosphoric treatments, respectively, than the control (no P) treatment. In 2004, the productivity decreased slightly, but was also greater for the injection treatments. Productivity per unit of water applied was 29.7%, 34.6%, and 41.4% greater for the Miller Solugro®, low, and high phosphoric treatments, respectively, than the control treatment. In 2005, productivities increased dramatically to 7.35, 8.35, 9.34 and 9.2 kg ha^{-1} mm^{-1}. However, the productivities per unit of water applied increased only 13.5%, 27.0%, and 25.1% for the Miller Solugro®, low, and high phosphoric treatments, respectively. Greater productivities per unit of water were obtained in 2005 because less irrigation was needed (175 mm), and more opportune rainfall was received during the growing season. Rainfall was received before planting and during peak vegetative stages.

Conclusion

During a three-year study at a cooperating producer's farm near St. Lawrence, Texas, cotton lint yield, loan value (as reflected by fiber quality), and gross returns for lint increased dramatically after injecting soluble phosphate into irrigation water in a subsurface drip irrigation system (SDI). The P_2O_5 application rates were 4.6 kg ha^{-1} y^{-1} (in the form of Miller Solugro®, cost of \$21.00 ha^{-1} y^{-1}), 32.9 kg ha^{-1} y^{-1} (low phosphoric acid rate, cost of \$21.10 ha^{-1} y^{-1}), and 65.7 kg ha^{-1} y^{-1} (high phosphoric acid rate, cost of \$42.20 ha^{-1} y^{-1}). Response was significant even for the small (4.6 kg ha^{-1} y^{-1}) P_2O_5 application rate. Extra gross returns for lint were \$520 to \$1,252 ha^{-1} y^{-1} more using phosphoric acid, and \$233 to \$872 ha^{-1} y^{-1} more using Miller Solugro®. This corresponded to three-year average return ratios (increase in gross return per P_2O_5 investment) of 24.9, 30.4, and 19.0 for the 4.6, 32.9, and 65.7 kg ha^{-1} y^{-1} P_2O_5 application rates. The P_2O_5 application rates increased the productivity per unit of water applied during the three years of the study. These results support the use of P_2O_5 in SDI systems for continuous cotton production at this location. However, the specific form of P_2O_5 and its application rate should be selected based on site-specific soil tests, chemistry of irrigation water (e.g., to maintain pH that would prevent precipitates from clogging drip emitters), operating constraints of the SDI system, and general advise and guidelines from extension agents, crop consultants, and reputable SDI dealers. It is also recommended to explore other lines of fertigation in future studies such as the addition of small amounts of potassium with the application of phosphorus.

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