Foliar Feeding of Cotton: Evaluating Potassium Sources, Potassium Solution Buffering, and Boron

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ABSTRACT

Foliar applications of K may be used to supplement soil applications to maximize yields of cotton (*Gossypium hirsutum* L.). Response to foliar K applications may be improved by choice of K source, buffering the spray solution, or applying K with B. Research was conducted on a Collins silt loam (coarse-silty, mixed, acid, thermic Aquic Udifluvents) and on a Memphis silt loam (fine-silty, mixed, active, thermic Typic Hapludalfs) to evaluate KNO_3, K_2SO_4, $K_2S_2O_3$, and KCl as K sources. A second study evaluated foliar KNO_3 and K_2SO_4 solutions applied unbuffered and buffered to pH 6 and 4 on cotton K nutrition and yield. Foliar K in both studies was applied at 4.1 kg K ha^{-1} per application. A third study evaluated combinations of soil-applied and foliar-applied B and K. Foliar treatments were applied in 93.5 L ha^{-1} water at early flower or 2 wk after and repeated on a 9- to 14-d interval between the four applications. Yields from the four K sources averaged 10% higher than the untreated check and yields with KNO_3 were 4% higher than the other K sources. Buffering two K source solutions to pH 4 resulted in 10% higher yields than the check or unbuffered K solutions. Adding a surfactant (ethoxylated alkyl aryl phosphate esters) to KNO_3 resulted in 5% higher yields then the check. Compared with untreated check yields, soil-applied B at 0.56 kg B ha^{-1} increased yields by 6%, four foliar applications of 0.11 kg B ha^{-1} increased yields by 8%, and four foliar applications of 0.11 kg B plus 4.1 kg K ha^{-1} increased yields by 13%. Foliar K solution buffering and/or the inclusion of foliar B are relatively inexpensive ways of improving yield response. Based on yield increases in this study, these treatments should return 8 to 10 times the product costs.

Foliar K fertilization by cotton growers, and in research tests across the U.S. Cotton Belt has resulted in inconsistent and largely unpredictable yield responses. Oosterhuis et al. (1994) evaluated foliar K applications over a wide range of soil and climatic conditions and reported that yield increases were inconsistent with location and between years.

Arkansas researchers (Maples et al., 1988–1989) speculated that the K requirement of fast-fruiting and high-yielding cultivars late in the growing season exceeds plant uptake. The plant root system activity of these high-yielding cultivars begins to decrease at flowering, which is the beginning of high K demand by the developing boll (Oosterhuis, 1993). Plant growth on a soil of limited K availability coupled with restricted root activity has a dramatic effect on K uptake.

Foliar K supplemented soil K applications for maximum cotton yields on a soil initially having a low Mehlich-1 extractable K level of 95 kg ha^{-1} (Howard et al., 1998). This research showed foliar K increased yields on soils having Mehlich-1 extractable K of 177 kg ha^{-1} or less. Yield response to foliar K continued through two years of soil-applied 112 kg K ha^{-1} plus two years of foliar-applied K (four applications per year at 4.1 kg ha^{-1} each). Oosterhuis (1993) indicated that responses to foliar K can probably be expected when Mehlich-3 soil K level is 308 kg K ha^{-1} or lower. This extractable K level is similar to the 177 level reported above, using Mehlich-1 extractant, since Mehlich 3 extracts approximately 1.5 times more K than Mehlich 1 (H.G. Savoy, personal communication, 1998). Tillage system may also contribute to the response to K fertilization. Howard et al. (1997) reported that no-tillage cotton yields were increased by applying K to a soil having 225 kg Mehlich-1 extractable K ha^{-1}, but conventional-till yields were not increased by applying K to a soil having 193 kg extractable K ha^{-1}.

The foliar-applied K source may also affect yield response to foliar fertilization. Miley and Oosterhuis (1994) summarized three years of evaluating KNO_3, K_2SO_4, $K_2S_2O_3$, KCl, and K_2CO_3 as foliar K sources and reported that KNO_3 increased lint yields, relative to the other sources, in two of the three years. Mullins and Burmester (1995) reported that lint yields were increased by foliar application of K (with no differences among the sources KNO_3, K_2SO_4, $K_2S_2O_3$, and KCl) on a Lucedale sandy clay loam (Rhodic Paleudults) having 116 kg ha^{-1} Mehlich-1 extractable K (medium test soil).

Modifying foliar K solution chemistry has improved K uptake of cotton (Heitholt, 1994; Howard and Gwathmey, 1995; Chang and Oosterhuis, 1995). Howard and Gwathmey (1995) reported higher leaf and petiole K concentrations at 1, 3, and 7 d after foliar application of KNO_3 with a surfactant (Penetrator Plus), compared with a nonfoliar check or foliar KNO_3 applied without the adjuvant. Foliar K increased second-harvest and total lint yields of cotton produced on soils having Mehlich-1 extractable K ranging from 168 to 202 kg ha^{-1} (high test level). Increases in second-harvest lint yields indicate that K availability to the plant was marginal or deficient for boll production in the upper part of the plant. Adding Penetrator Plus–buffered foliar KNO_3 solutions to pH 5.5, compared with a pH of 9.4 for the unbuffered solution (Howard, 1993). Shafer and Reed (1986) suggested that K absorption from foliar applications could be enhanced by modifying solution pH values.

Many spray solutions of available K sources have an alkaline pH level that may result in phytotoxicity. Leaf burn was reported from foliar applications of the alkaline solutions KOH and K_2CO_3 (Miley and Oosterhuis, 1994; Chang and Oosterhuis, 1995). Chang and Ooster-

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Abbreviations: WTES, West Tennessee Experiment Station.

huis (1995) found that buffering foliar KOH and K_2CO_3 solutions to pH 4 eliminated leaf burn, increased K absorption and translocation within the plant, and increased boll numbers and lint yields compared with unbuffered foliar solutions.

Many soils that are low in K may also have limited B availability. Relatively small amounts of B are required to support the processes of growth and development of cotton fibers in the boll (Stewart, 1986). Small deformed bolls, poor fruit retention, and reduced lint yields may result from B deficiency (Murphy and Lancaster, 1971). In some regions, B application to cotton is recommended every year (Baird and Guthrie, 1992, p. 34–46). Boron is recommended in Tennessee for cotton production on soils having a pH of 6.1 or higher or when ground agricultural limestone is applied (Shelby, 1996). Combining B with K as a foliar application may enhance plant uptake and yields on soils with limited extractable K and low B levels (Woodruff et al., 1987). There is evidence that K and B play a significant role in carbohydrate metabolism and translocation in plants. The inclusion of B and K together in foliar fertilizers for cotton has not previously been researched.

Three separate studies were established to evaluate methods for improving cotton yield response from foliar nutrient applications. Our objectives for these studies were (i) to evaluate K sources for foliar application, (ii) to evaluate foliar solution chemistry modification on nutrient uptake and yield, and (iii) to evaluate foliar B and K applications compared with soil applications for improving yields.

MATERIALS AND METHODS

Field experiments were initiated in 1992 to evaluate the effects that foliar nutrient applications to conventionally tilled cotton produced on a Collins silt loam at the West Tennessee Experiment Station (WTES), Jackson, TN, and on a Memphis silt loam at Ames Plantation, Grand Junction, TN.

The cultivar D&PL 50 was planted conventionally by mid-May each year. The experimental design for the tests was a randomized complete block, with five or six replications. Individual plots were four rows wide, with cotton planted in 0.97-m rows at WTES and 1.02-m rows at Ames Plantation. Plot lengths were 12.2 m for the boron study, and 9.1 m for the other two studies. Plots were fertilized with 90 kg N ha^{-1} as NH_4NO_3, 15 kg P ha^{-1} as triple superphosphate, and 28 kg K ha^{-1} as KCl, and disked several times before planting. Recommended production practices (Shelby, 1996) were used at both locations.

Potassium Source Study

Field experiments were conducted between 1993 through 1995 at WTES on a Collins silt loam having 190 kg ha^{-1} Mehlich-1 extractable K (high soil test level) and during 1993 and 1994 at Ames Plantation on a Memphis silt loam having 222 kg ha^{-1} Mehlich-1 extractable K (high test level). Four foliar K sources (KNO_3, K_2SO_4, $K_2S_2O_3$, and KCl) were compared with a nonfoliar check. Four foliar applications of 4.1 kg K ha^{-1} were applied annually. These solutions were not altered by adjusting solution pH. A $Ca(NO_3)_2$ treatment to supply 1.6 kg N ha^{-1} per application was included to determine the magnitude of any yield increase from KNO_3 that could be attributed to the provision of foliar N in the KNO_3.

Buffered Solution Study

The study was conducted between 1992 and 1995 on a Collins silt loam initially having a Mehlich-1 extractable K level of 222 kg ha^{-1} (high level). Two K sources, KNO_3 and K_2SO_4, were selected for this evaluation. Both sources are available to growers. KNO_3 was selected because of its potential to increase yields from the N component and the fact that it was the most commonly used source in the literature for foliar K studies. K_2SO_4 was selected because of availability and the fact that it did not contain N. Foliar KNO_3 and K_2SO_4 solutions were applied as unbuffered solutions and as solutions buffered to pH 6 and 4. Additional treatments consisted of KNO_3 plus a proprietary nonionic oil concentrate–buffering adjuvant, Penetrator Plus[1] (ethoxylated alkyl aryl phosphate esters; Helena Corp., Memphis, TN), and check treatment with no solution applications were included. Solution pH levels were adjusted immediately before application using anionic buffering agents, either Buffer PS or Xtra Strength Buffer (alkyl aryl polyethoxy ethanol phosphates and organic phosphatic acids; Setre Chemical Co., Memphis, TN). All solutions were reformulated before each application. Four foliar applications of 4.1 kg K ha^{-1} were applied annually.

Boron Study

The study was conducted between 1993 and 1995 on a Collins silt loam initially having a 190 kg ha^{-1} Mehlich-1 extractable K (high level). Foliar treatments consisted of (i) 0.11 kg B ha^{-1}; (ii) 0.11 kg B ha^{-1} plus 4.1 kg K ha^{-1}; (iii) 0.22 kg B ha^{-1}; (iv) 0.11 kg B ha^{-1} plus 1120 kg soil-applied ground agricultural limestone ha^{-1}; (v) 0.56 kg B ha^{-1}, soil applied; and (vi) an untreated check. The foliar B source was Solubor DF ($Na_2O{\cdot}5B_2O_3{\cdot}10H_2O$) [17.4% B] manufactured by U.S. Borox, Valencia, CA) and the foliar K source was KNO_3. Foliar treatments were applied four times each year.

Foliar Application Methods, Plant Material Collection, and Data Evaluation

All foliar treatments were applied in 93.5 L ha^{-1} water. In 1992, the foliar treatments were applied beginning 14 d after flowering, with subsequent applications at 14-d intervals. In 1993, foliar treatments were begun at midflowering, with subsequent applications again at 14-d intervals. In 1994, the treatments were begun at midflowering; the second application was 14 d later, with the third and fourth applications at 9-d intervals thereafter. Treatments in 1995 began at flowering, with subsequent applications at 9-d intervals. The application intervals were based on the best available information and were changed as research indicated improved effectiveness from shorter application intervals (D.M. Oosterhuis, personal communication, 1993). Foliar treatments were applied using a multiline boom mounted on a high clearance sprayer to apply treatments with one trip through the field. The spray system was pressurized with CO_2.

Petioles and leaf blades were collected from 20 fully expanded main stem leaves (generally the fourth primary leaf below the terminal) of the two center rows of each plot. Plant materials were collected from the two K studies before each

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[1] The use of trade names in this publication is for clarity and does not imply approval of the product to the exclusion of others which may be of similar suitable composition, nor does it guarantee or warrant the standard of the product.

Table 1. Mixed-model *F* statistical values from three tests to evaluate foliar K sources, buffering foliar K solutions, and B fertilization on cotton lint yields by harvest period.

Source	df	1st harvest	2nd harvest	Total harvest
Potassium source study				
Year (Yr)	2	62.21***	82.01***	372.01***
Error *a*	8			
Treatment (T)	5	4.21***	0.66	5.63***
Yr × T	10	1.71	0.95	1.46
Error *b*	65			
Buffered solution study				
Year (Yr)	3	13.64***	80.32***	55.12***
Error *a*	14			
Treatment (T)	7	6.6***	2.44*	9.69***
Yr × T	24	1.43	0.86	1.78*
Error *b*	133			
Boron study				
Year (Yr)	2	18.58***	140.29***	82.60***
Error *a*	8			
Treatment (T)	5	3.68**	NS	5.67**
Yr × T	10	1.39	0.81	1.79
Error *b*	60			

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

foliar application, to evaluate petiole K sufficiency based on Arkansas sufficiency levels (Snyder et al., 1992). Plant materials from the B test were collected at 3 d after foliar applications to evaluate uptake, since Howard and Gwathmey (1995) reported decreased K levels at 7 d following foliar application. Plant materials from the B test were collected in all three years, but the 1993 samples were not properly analyzed and the materials were discarded or lost. In 1995, the materials were collected but were incorrectly handled and contaminated. Therefore, only the 1994 samples will be reported for the B study. The petioles and leaf blades were separated, rinsed in tap water, rinsed twice in distilled water, and oven-dried at 64°C. After grinding, K was extracted from petiole and leaf tissue using 2% (v/v) acetic acid solution (Baker et al., 1994) and K concentrations were determined on a Perkin-Elmer (Norwalk, CT) Model 3100 atomic absorption spectrophotometer. Extractable leaf and petiole K was evaluated rather than total digestible based on the findings of Percell et al. (1995). Leaves were dry-ashed, dissolved in 2 *M* HCl, and B was determined using a Thermo Jarrell Ash (Franklin, MA) ICAP 61 inductively-coupled emission spectrometer.

A recommended defoliant was applied when 60% of the bolls were open. Lint yields were determined by mechanically picking the two center rows of each plot twice each year. Cotton was first picked approximately 2 wk after leaf drop, with a second picking approximately 3 wk after the first one. This interval varied due to weather and several other factors. In most years, the date of the second picking was delayed to allow sufficient time for the top bolls to open. Percent lint was determined by combining subsamples of seed cotton from individual treatments across replications (<4.5 kg) and ginned on a 20-saw gin with dual lint cleaners. Lint yields were calculated by multiplying lint fraction by seed cotton weights.

The statistical analysis of lint yields, leaf, and petiole nutrient concentrations were performed using Mixed Model procedures of the Statistical Analysis System (SAS Inst., 1997). The Mixed Model procedure provides Type III *F*-statistic values, but does not provide mean square values for each element within the analysis or the error terms. Means separation was evaluated through a series of pairwise contrasts among all treatments (Saxton, 1998). Treatment means were contrasted (single degree of freedom) using the ESTIMATE statement in Mixed Model procedures. To more accurately compare the effects of solution buffering across foliar K sources, and between groups of treatments with different pH buffering, single degree of freedom contrasts were used. This provided greater statistical confidence than either pairwise or standard multiple comparisons of treatments. Mean differences with probabilities greater than $\alpha = 0.05$ were categorized as nonsignificant.

RESULTS AND DISCUSSION

Data from the three studies will be presented and discussed separately.

Potassium Source Study

Foliar K treatment effects on yields produced on the Collins silt loam with 190 kg ha^{-1} Mehlich-1 extractable K at WTES were consistent over the three years, since the year × treatment interaction was not significant (Table 1). Both first-harvest and total lint yields were increased by the foliar K treatments, compared with the unfertilized check (Table 2). The magnitude of response ranged from 8 to 14%. Generally, increased yields from foliar fertilization is associated with improved yields in the top of the crop and would be reflected in the second harvest (Oosterhuis, 1993; Howard and Gwathmey, 1995). First-harvest yield increases generally reflect lower than optimum K levels within the plant (Howard et al., 1998). Applying foliar KNO_3 resulted in 5% higher first-harvest lint yield and 4% higher total lint yield, compared with the other three K sources. The $Ca(NO_3)_2$ foliar treatment did not affect lint yields when statistically evaluated at $P \leq 0.05$; however, contrast data indicate that foliar $Ca(NO_3)_2$ yields were greater than the check at $P \leq 0.087$ (Table 3). Relative to the check, the magnitude of yield response to $Ca(NO_3)_2$ indicates that the higher yields from foliar-applied KNO_3 compared with the other K sources may be due to the N compo-

Table 2. Effect of foliar K sources on 3-yr average lint yields by harvest period, extractable leaf and petiole K concentrations of cotton produced on a Collins silt loam.

Treatment		Cotton yield		K in leaf blade‡				K in petioles‡			
No.†	Source	1st	total	1st	2nd	3rd	4th	1st	2nd	3rd	4th
		kg ha^{-1}		g K ha^{-1}							
1	KNO_3	1011a§	1292a	11.3a	10.0a	9.4b	8.3a	32.4a	25.3a	19.6a	19.2a
2	K_2SO_4	957b	1237b	10.7a	10.1a	10.2ab	9.7a	32.4a	27.0a	22.7a	20.9a
3	$K_2S_2O_3$	971b	1239b	11.3a	10.5a	11.5a	9.7a	32.9a	26.7a	22.3a	20.9a
4	KCl	955b	1247b	11.6a	10.3a	10.4ab	9.4a	33.6a	26.8a	20.7a	19.9a
5	$Ca(NO_3)_2$	928bc	1196bc	10.4a	9.5a	9.1b	9.1a	31.8a	26.0a	21.5a	20.3a
6	Check	886c	1143c	11.6a	11.3a	9.7b	8.1a	34.3a	29.1a	18.5a	16.2a

† Treatment numbers used in contrast analyses, Table 3.
‡ Samples collected before each foliar application.
§ Within a column, means followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 3. Contrast of 3-yr average lint yields by harvest period of cotton produced on a Collins silt loam as affected by K sources.

Treatment contrasts	Contrasted treatments†	Yield diff.	Pr > *t*
		— kg ha^{-1} —	
1st harvest			
Foliar K vs. check	1,2,3,4 vs. 6	87	0.0003
Other K sources vs. KNO_3	2,3,4 vs. 1	50	0.036
$Ca(NO_3)_2$ vs. check	5 vs 6	42	0.152
Total harvest			
Foliar K vs. check	1,2,3,4 vs. 6	110	0.0001
Other K sources vs. KNO_3	2,3,4 vs. 1	51	0.042
$Ca(NO_3)_2$ vs. check	5 vs. 6	52	0.087

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Numbers correspond to K source treatments shown in Table 2.

nent. The mean total lint yield difference of 53 kg ha^{-1} (not significant at $P \leq 0.05$) between the foliar $Ca(NO_3)_2$ and the nonfertilized check is similar to the mean yield difference between the three non-N foliar K sources and KNO_3 (51 kg ha^{-1}). In other studies, lint yields were increased with foliar N applications to cotton produced on two soils having high levels of Mehlich-1 extractable K (Howard et al., 1997).

These findings agree with research conducted by Miley and Oosterhuis (1994), but differ from those of Mullins and Burmester (1995); however, Miley and Oosterhuis (1994) reported higher total lint yields and higher second-harvest lint yields from foliar-applied KNO_3, whereas second-harvest yields were not affected by treatment in this study. The study by Miley and Oosterhuis (1994) was conducted over a three-year period, evaluating five K sources on a Loring–Calloway soil complex (Typic and Glossaquic Fragiudalfs) having 200 kg ha^{-1} Mehlich-3 extractable K. Mullins and Burmester (1995) reported no yield differences from foliar application of KNO_3 and K_2SO_4 to cotton produced on a Lucedale sandy clay loam (Rhodic Paleudults) having 116 kg ha^{-1} Mehlich-1 extractable K.

Foliar K source treatments did not affect lint yields of cotton grown on the Memphis silt loam (data not shown). Two-year average lint yields from the Memphis silt loam ranged from 743 to 803 kg ha^{-1}, which were 35 to 40% lower than lint yields from the Collins silt loam. Although the soil had 222 kg ha^{-1} of Mehlich-1 extractable K, plant uptake of soil K was sufficient for the yield level. Oosterhuis (1993) pointed out that the peak demand for K is at boll fill, with greater boll load and potential yield associated with a greater need by the plant for K. These requirements were apparently lower on the Memphis soil in this study.

Leaf and petiole K concentrations from cotton produced on the Collins silt loam were not affected by treatment except for the third leaf blade sample (Table 2). The decrease in petiole K for the KNO_3 and check treatments during 1994 were compared with the Arkansas sufficiency K level (Fig. 1). The petiole K concentrations of both treatments dropped below the sufficiency level 14 d after flowering. This suggests that K from foliar treatments was directly translocated to K sinks elsewhere in the plant, such as bolls. Bednarz and Oosterhuis (1996) reported that petiole K levels of deficient plants ranged from 18 g kg^{-1} in the top of the plant to 8 g kg^{-1} several nodes below the top. They also concluded that acropetal translocation of K is reduced first in the boll development process. Therefore, petiole K in the top of the plant may be sufficient at flowering, only to decrease to a deficient level with boll formation and development.

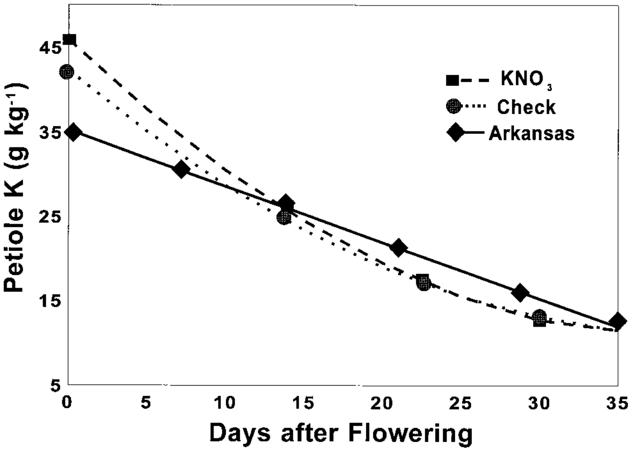

Fig. 1. Effect of foliar KNO_3 and unfertilized check treatments on 1994 petiole K concentrations from the K source experiments compared with the Arkansas petiole K sufficiency levels.

Buffered Solution Study

The analyses of variance indicate that lint yields from the first and second harvests and total lint yields were affected by treatment (Table 1). The foliar treatment effects on total lint yields were inconsistent over the four years, as indicated by the year × treatment interaction.

Foliar solutions of K_2SO_4 buffered to pH 4 and KNO_3 with the adjuvant Penetrator Plus increased the 1992 lint yields compared with the check, unbuffered K_2SO_4, and K_2SO_4 buffered to pH 6 (Table 4). The contrast analyses show that, as a group, the foliar K treatments did not increase the 1992 lint yields (Table 5), mainly due to the effect of the K_2SO_4 treatment buffered to pH 6. Buffering both K sources to pH 4 increased lint yields compared with applying solutions buffered to pH 6. Foliar application of pH-6-buffered K_2SO_4 resulted in a lower yield than the check or other treatments: thus, the interaction. Buffering the two foliar K sources to pH 4 also increased the 1993 lint yields compared with the untreated check and unbuffered KNO_3 solutions (Table 4). The 1993 contrast analyses indicate that foliar K solutions increased yields relative to the nonfoliar treated check (Table 5). Buffering the two K source solutions to pH 4 resulted in higher yields than with pH 6 buffering. In 1994, buffering K_2SO_4 to pH 4 significantly increased yields compared with the other treatments (Table 4). Applying the unbuffered K_2SO_4 and pH-6-buffered K_2SO_4 solutions resulted in the lowest yields in 1994. Buffering the K sources to pH 4 produced higher yields than buffering to pH 6 in 1992, 1993, and 1994 (Table 5). Foliar treatments did not affect the 1995 lint yields.

Across years, foliar applications of KNO_3 with the

Table 4. Effect of buffering two foliar K sources on annual total lint yields and on 4-yr average lint yields.

Treatment		Solution	Total lint yield				4-yr yields by harvest		
No.†	Source	pH	1992	1993	1994	1995	1st	2nd	Total
			kg lint ha^{-1}						
1	KNO_3	9.3	1148abc‡	944b	1395bc	1292a	814de	382bc	1195de
2	KNO_3	6.0	1154ab	1027ab	1386bc	1319a	861bcd	362bc	1222cd
3	KNO_3	4.0	1171ab	1163a	1490b	1337a	877bc	414a	1291ab
4	KNO_3§	5.5	1195a	1038ab	1482b	1303a	895ab	361bc	1255bc
5	K_2SO_4	9.5	1091c	1038ab	1354c	1278a	843bcde	348c	1190de
6	K_2SO_4	6.0	991d	1048ab	1340c	1289a	788e	380bc	1169e
7	K_2SO_4	4.0	1209a	1163a	1642a	1347a	953a	388ab	1340a
8	Check		1129bc	949b	1383bc	1276a	822de	364ab	1185de

† Treatment numbers are used in the contrast analyses, Table 5.

‡ Within columns, means followed by the same letter are not significantly different at $\alpha = 0.05$.

§ Adjuvant (Penetrator Plus surfactant) added at 1.25% (v/v).

adjuvant Penetrator Plus or the two K sources buffered to pH 4 resulted in higher first-harvest and total yields compared with the unfertilized check (Table 4). The magnitude of increase ranged from 6 to 16%. Contrast analyses further indicate that buffering the foliar solutions to pH 4 increased four-year average yields, compared with applying K solutions that were either unbuffered or buffered to pH 6. Increased first-harvest lint yields indicate that the treatments were improving early boll development that may have been restricted by reduced K availability to the plant (Howard et al., 1998).

Foliar application of KNO_3 solutions buffered to pH 4 increased four-year average second-harvest lint yields compared with other treatments, except for the pH 4 K_2SO_4 and the check (Table 4). Contrast analysis indicates that both K sources buffered to pH 4 resulted in higher yields than did pH-6-buffered solutions (Table 5). Increased second-harvest lint yields indicate that the treatments were contributing to late boll development. A foliar K response at second harvest would be expected when K deficiencies, whether hidden or visible, occur in the upper portion of the plant and when conditions allow late-set bolls to mature (Howard and Gwathmey, 1995).

Table 5. Contrast of yearly total lint cotton yields and 4-yr average 1st and 2nd harvested yields and 4-yr average total lint yields as affected by solution buffering.

Treatment contrasts†	Contrasted treatments‡	Yield diff.	Pr > *t*
		kg ha^{-1}	
1992 total yield			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	8	0.763
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	61	0.005
Adjuv. vs. check	4 vs. 8	66	0.049
Unbuff. K vs. pH 6	1,5 vs. 2,6	47	0.062
pH 4 vs. pH 6	3,7 vs. 2,6	117	0.0001
1993 total yield			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	111	0.035
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	38	0.334
Adjuv. vs. check	4 vs. 8	89	0.195
Unbuff. K vs. pH 6	1,5 vs. 2,6	47	0.327
pH 4 vs. pH 6	3,7 vs. 2,6	125	0.0121
1994 total yield			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	58	0.213
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	22	0.537
Adjuv. vs. check	4 vs. 8	99	0.111
Unbuff. K vs. pH 6	1,5 vs. 2,6	12	0.788
pH 4 vs. pH 6	3,7 vs. 2,6	203	0.0001
4-yr 1st harvest			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	40	0.079
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	11	0.530
Adjuv. vs. check	4 vs. 8	73	0.016
Unbuff. K vs. pH 6	1,5 vs. 2,6	4	0.848
pH 4 vs. pH 6	3,7 vs. 2,6	91	0.0001
4-yr 2nd harvest			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	13	0.370
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	14	0.197
Adjuv. vs. check	4 vs. 8	3	0.887
Unbuff. K vs. pH 6	1,5 vs. 2,6	6	0.651
pH 4 vs. pH 6	3,7 vs. 2,6	30	0.025
4-yr total harvest			
Foliar K vs. non-K	1,2,3,4,5,6,7 vs. 8	53	0.012
KNO_3 vs. K_2SO_4	1,2,3 vs. 5,6,7	3	0.837
Adjuv. vs. check	4 vs. 8	70	0.011
Unbuff. K vs. pH 6	1,5 vs. 2,6	2	0.918
pH 4 vs. pH 6	3,7 vs. 2,6	121	0.0001

† Adjuv., adjuvant (Penetrator Plus surfactant); Unbuff., unbuffered.

‡ Numbers correspond to K + buffering treatments shown in Table 4.

Total lint yields, averaged across four years, were increased by 10% with foliar applications of the pH-4-buffered K sources and by 5% with foliar KNO_3 containing the adjuvant Penetrator Plus, compared with yields from the unfertilized check and unbuffered foliar K solution treatment (Table 4). The four-year average contrast analyses indicate that total yields of pH-4-buffered K sources were 10% higher than pH-6-buffered K source yields (Table 5). Foliar solutions buffered to pH 6 did not affect four-year lint yields, compared with the unfertilized check.

These findings differ from those of Mullins and Burmester (1995), who found that buffering foliar KNO_3 and K_2SO_4 solutions to pH 4 did not increase lint yields on a soil having 116 kg ha^{-1} Mehlich-1 extractable K. Chang and Oosterhuis (1995) reported that foliar application of pH-4-buffered solutions of KNO_3 and K_2SO_4 increased lint yields on a soil having 258 kg ha^{-1} Mehlich-3 extractable K by 146 and 130 kg ha^{-1} (14 and 13%), respectively, compared with the untreated check. In our studies on a soil having 222 kg ha^{-1} Mehlich-1 extractable K, buffering KNO_3 and K_2SO_4 to pH 4 increased four-year average total lint yields by 106 and 155 kg ha^{-1} (9 and 13%), respectively, compared with the untreated check. Yield increases from buffering the K sources to pH 4 in Tennessee and Arkansas are similar.

Petiole K concentration of the pH-4-buffered K_2SO_4 and check treatments for the 1994 sample periods were compared with the Arkansas sufficiency levels (Snyder et al., 1992) (Fig. 2). The pH-4-buffered K_2SO_4 represents a high-yielding foliar treatment, while the check was a nonfoliar low-yielding treatment. The decrease in petiole K concentrations with time is similar with previous findings (Baker et al., 1994). The petiole K

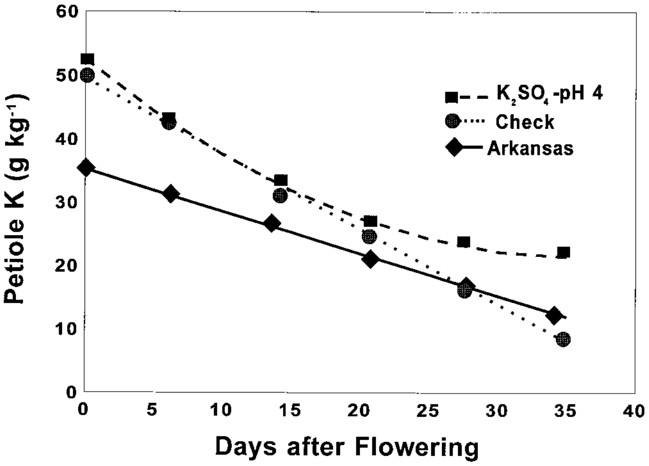

Fig. 2. Effect of pH-4-buffered K_2SO_4 and unfertilized check treatments on 1994 petiole K concentrations from the foliar K buffering experiments compared with the Arkansas petiole K sufficiency levels.

concentration of the unfertilized check was above the Arkansas sufficiency level at 23 d after flowering, but had dropped below the sufficiency level by 31 d after flowering. Buffering K_2SO_4 to pH 4 resulted in petiole K concentrations that remained above the Arkansas sufficiency level throughout the sample period. Higher yields were also associated with the higher petiole K concentrations, which suggests that buffering to less than pH 6 may improve the likelihood of a yield response.

Boron Study

Boron treatment effects on lint yields were consistent over the three years, since there was not a year × treatment interaction (Table 1). Both first-harvest and total lint yields were improved by all but one treatment compared with the untreated check (Table 6). First-harvest lint yields were increased by 9% with soil-applied B, by 8% with applied limestone and foliar B, and by 13% with foliar-applied B plus K applications. Total lint yields were increased compared with the check by all the foliar B treatments except the 0.22 kg B ha^{-1} level. Relative to the untreated check, foliar applications of B plus K increased yield 13%, foliar B applications increased yields 11%, and applying B to the soil increased yields 6% (Table 6). The high foliar B treatment reduced both first-harvest and total lint yields by 9 and 8%, respectively, compared with the lower foliar B applications. Apparently, giving four foliar applications of 0.22 kg B ha^{-1} was approaching an excess for cotton produced in this experiment. Leaf B concentration was significantly higher after the first sample period for this foliar B rate compared with foliar application of 0.11 kg B ha^{-1}, and was approximately twice that of the check after the fourth application. Four foliar applications, each at 0.11 kg B ha^{-1}, resulted in lint yields comparable to soil application of B at 0.56 kg ha^{-1}. Foliar-applied B plus K solution further increased total lint yields by 5% relative to applying foliar B alone (0.11 kg B ha^{-1} per application), but did not have an effect on first-harvest lint yields. This observation suggests that K uptake from this soil may have limited the response to applied B, but this is only speculation, since a foliar K treatment was not included. Four foliar applications of 0.22 kg B ha^{-1} reduced both first harvest (by 7%) and total lint yields (by 6%) relative to the 0.11 kg B ha^{-1} rate. Applying limestone did not reduce B availability sufficiently to make the yield response to applying foliar B greater than that produced by the foliar 0.11 kg B ha^{-1} application rate.

Neither foliar B nor foliar B plus K treatments had any effect on the 1994 leaf blade or petiole K concentrations (data not shown). Results from this study differ from those of Heitholt (1994), who found no yield response to soil or foliar B application to cotton on a Beulah fine sandy loam (Typic Dystrochrepts). Heitholt (1994) demonstrated that leaf B concentrations increased from about 50 to 150 mg kg^{-1} at 3 d after foliar B applications of 1.78 kg B ha^{-1}. The lack of yield response was attributed to leaf B concentrations above a critical concentration of 25 mg kg^{-1}. Our study suggests that yield responses to foliar B are possible at concentrations above this critical level. However, yield responses may depend in part on foliar application of B throughout the reproductive phase (0.11 kg B ha^{-1} per application) and optimizing K nutrition at the same time. This indicates that an integrated strategy of foliar feeding of B and K may be developed.

CONCLUSIONS

Obtaining a yield response in cotton to foliar K may be improved by choice of K source, buffering the K solution and by applying in combination with B. The treatments that produced the largest response in these

Table 6. Evaluation of soil and foliar boron and K on 3-yr average 1st harvest and total lint yields and 1994 leaf B concentrations of cotton.

Treatment	Soil		Foliar		Yield, by harvest		Foliar B, by leaf sample‡			
no.†	B	Lime	B	K	1st	total	1st	2nd	3rd	4th
	kg ha^{-1}						mg B kg^{-1}			
1	–	–	0.11	–	889ab§	1176ab	46.7a	48.6bc	56.9bc	65.3bc
2	–	–	0.11	4.1	932a	1237a	47.6a	56.5ab	62.7b	74.1b
3	–	–	0.22	–	828b	1110cd	52.5a	61.1a	77.0a	93.3a
4	–	1120	0.11	–	892a	1185ab	41.0a	51.6bc	57.8b	69.7b
5	0.56	–	–	–	899a	1164bc	41.4a	45.9c	50.3cd	54.2c
6	Check	–	–	–	828b	1093d	42.4a	45.3c	46.9d	52.3c

† Treatment numbers used in contrast analyses, Table 6.
‡ Sample collected before each foliar application.
§ Within columns, means followed by the same letter are not significantly different at $\alpha = 0.05$.

studies consisted of four applications of 4.1 kg K ha^{-1} as K_2SO_4 buffered to pH 4. This treatment significantly increased lint yields in three years out of four, and increased four-year average yields 13% relative to the check. This treatment also maintained petiole K concentrations above critical levels throughout the flowering and boll-filling stages. For unbuffered solutions, applying KNO_3 produced 4% higher yields than K_2SO_4 in one study, and equivalent yields in another. Yield response to KNO_3 was improved by 5% with the adjuvant Penetrator Plus (pH 5.5), and by 8% with buffering to pH 4. Response to foliar K appears to depend, however, on adequate B nutrition. Foliar K solution buffering and/or the inclusion of foliar B are relatively inexpensive ways of improving yield response. Based on the yield increases observed in this study, these treatments should return 8 to 10 times the product costs. Additional research is needed to optimize rates and pH of combined foliar B and K treatments.

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