Chapter 11:
Foliar Potassium Fertilization of Cotton

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Introduction

Speculation has surrounded the explanation for the widespread appearance of K deficiency across the U.S. Cotton Belt in recent years. The occurrence of a complex of K-deficiency symptoms in cotton was first recognized in California during the early 1960s[3, 15]. These deficiencies have manifested themselves during the latter half of the season in a range of soils and cotton cultivars. However, the explanation for these deficiencies is unclear, and a considerable amount of research and speculation has surrounded this phenomenon. It has been shown that the occurrence of K-deficiency is related to the incidence of Verticillium wilt[90]. It has also been speculated that the deficiency symptoms may be associated with the use of higher-yielding and faster-fruiting cotton cultivars and the increased use of N fertilization in cotton management[68].

Many K deficiencies can be corrected through preplant soil applications, or partially corrected using mid-season sidedress applications of K. Foliar applications of K may offer the opportunity of correcting these deficiencies more quickly and efficiently, especially late in the season when soil application of K may not be effective. Foliar applications have the advantage of allowing producers to add the necessary K when tissue analysis indicates a pending shortage, thereby correcting the deficiency and preventing yield loss.

There is a wealth of literature about foliar fertilization which was used as long ago as 1844 to correct plant chlorosis with sprays of Fe[28]. However, the practice has only caught on in cotton production in the last two decades. In 1991 it was estimated that about 9,000 tons of K fertilizer was foliar applied to cotton in the U.S. Cotton Belt. However, there is still considerable speculation about the benefits and correct implementation of this practice. While there are many reports on research involving soil-applied K[49], there are no definitive studies available on the usefulness of foliar-applied K. A report in 1976[63] indicated that foliar applications of K significantly increased seedcotton yield. There have also been more recent reports of foliar applications of K improving both lint quality and yield[70]. With the national emphasis on lint quality[82] and the introduction of high volume instrumentation classification, the positive effect of K on lint quality may be of paramount importance.

This paper provides an overview of K nutrition of cotton, the current understanding of foliar fertilization of cotton and the benefits of this practice in cotton production. The review focuses on the importance of K in plant growth, its uptake and distribution in the plant, K deficiency symptoms and causes. The review also covers the fertilization of cotton, with some emphasis on foliar fertilization and related aspects. The review concentrates on plant nutrition rather than soil nutrition and, therefore, does not cover the various aspects of soil K availability or methods of analyzing soil K content.

Importance of Potassium for Plant Growth

Potassium is an essential nutrient for all living organisms and is required in large amounts for normal plant growth and development[54]. In higher plant cytoplasm, K is the dominant cation and is commonly found to be in concentrations ranging from 80 to 150 mM[12]. It is absorbed by roots from the soil as the monovalent cation K^+ usually by active uptake. Potassium is very mobile in the plant and can be translocated against strong electrical and chemical gradients[38].

Potassium is not a constituent of any known plant components, but it is integrally involved in metabolism and plant water relations. Its primary role is as an enzyme activator. It has been implicated in over 60 enzymatic reactions[26] which are involved in many processes in the plant such as photosynthesis, respiration, carbohydrate metabolism, translocation, and protein synthesis. Potassium balances charges of anions and influences their uptake and transport. Another important function is the maintenance of osmotic potential and water uptake[25]. These two functions of K are manifest in its role in stomatal opening[45] when stomatal conductance and turgor are coupled. Another major role of K is in photosynthesis[44] by directly increasing leaf growth, leaf area index, and, therefore, CO_2 assimilation[95]. Potassium increases the outward translocation of photosynthate from the leaf[2].

There have been a number of reviews of the K nutrition of cotton (e.g. Hearn, 1981[36]; Kerby and Adams, 1985[49]). Potassium plays a particularly important role in cotton fiber development, and a shortage will result in poorer fiber quality and lowered yields[18]. Potassium is a major solute in the fiber (single cells) involved in providing the turgor pressure necessary for fiber elongation[23]. If K is in limited supply during active fiber growth, there will be a reduction in the turgor pressure of the fiber resulting in less cell elongation and shorter fibers at maturity. As K is associated with the transport of sugars, it is likely implicated with secondary wall deposition in fibers and, therefore, related to fiber strength and micronaire. Xi et al.[96] reported poor cuticle development in cotton plants grown without sufficient K, which may have resulted in increased water loss by non-stomatal transpiration. Potassium has been reported to reduce the incidence of Verticillium wilt[30] although the physiological reasons for this are not clear.

Potassium Uptake and Distribution in the Cotton Plant

Potassium is required in large quantities by cotton: from 3 to 5 kg K/ha/day[32,94]. The total quantity of K taken up by the plant is related to the level of available soil and fertilizer K[10,49]. An average mature cotton crop is estimated to contain between 110 and 250 kg/ha of K, of which about 54 percent is in the vegetative organs and 46 percent is in the reproductive organs[77]. However, only about 20 kg of K are needed to produce one bale (218 kg) of cotton fiber, with about 2.5 to 6 kg being removed mainly by the seeds[39,77].

Plant uptake of K follows a pattern similar to dry weight accumulation (**Figure 1**), except that dry matter continued to increase until maturity, whereas maximum K accumulation was reached in about 110 days after which there was a decrease[34]. Potassium was absorbed more rapidly than dry matter was produced, as evidenced by the higher concentration of K in young plants[7]. The rate of K uptake was slow during the seedling stage, about 10 percent of the total, but increased rapidly at flowering and reached a maximum of 4.6 kg/ha/day between 72 and 84 days[32]. Mullins and Burmester[61] reported maximum daily uptake rates of 2.24-3.47 kg/ha/day 63 to 98 days after planting. Basset et al.[7] reported corresponding values of 2.1 to 3.4 kg/ha/day between 90 and 127 days after planting for older later-maturing varieties.

The need for K increases dramatically when bolls are set on the plant because bolls are a major sink for K[50]. These authors showed that the total K in an individual boll increased from 0.19 mg/boll 10 days after flowering to 1.19 mg/boll at boll maturity 56 days after flowering. This appears low compared to the 126 mg K/boll reported by White[94]. If an average cotton crop contains about 150 kg K/ha[39] with about 50 percent of the K in the reproductive unit[77], then for a hypothetical average 100 bolls/m^2, there would be 75 mg K/boll. This is closer to the higher value of White[94] although his data were from Acala cotton, which with a larger boll size should have a higher total K (T.A. Kerby, personal communication).

During boll development the K concentration increased from 19 to 55 g/kg dry weight between 10 and 55 days, and K concentration in the fiber decreased from 22 to 6 g/kg at boll maturity[50]. The decline in fiber K concentration was due to redistribution of the K within the boll to the seed and capsule wall during the seventh and eighth week of boll development. The high concentration of K in the boll is related to the role of K in the maintenance of osmotic potential to generate the turgor pressure necessary for fiber elongation[23]. Potassium is the most abundant cation in cotton fiber[50]. The capsule wall of the boll contains approximately 4 percent K and accounts for between 32 to 60 percent of all the K accumulated by the boll[7,49].

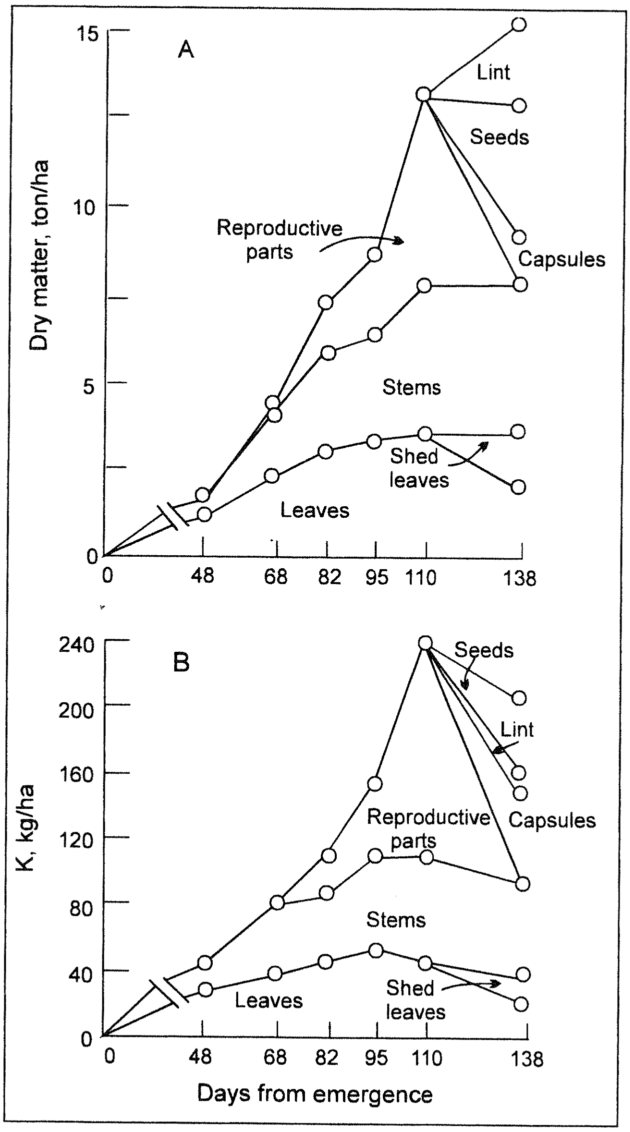

Figure 1. **Accumulation and distribution of dry matter (A) and uptake and distribution of K (B) in the aerial components of the cotton plant during the season (from Halevy et al., 1987).**

The mineral nutrients and assimilates for the growth of young leaves, the early "sinks", are translocated from the root and stem as well as from mature leaves. As fruiting begins, the developing boll load forms a new and stronger sink which becomes dominant for available assimilate[50]. During boll development, K is withdrawn from the older leaves and petioles and is retranslocated via the phloem to the bolls. This strong source-sink relationship is critical for high yields and any factor that adversely affects the relationship can result in K deficiencies and lower yields and fiber quality.

Potassium can be taken up in luxury amounts[47], and this could possibly confuse tissue diagnostic recommendations. However, there is evidence that luxury consumption of K is actually beneficial and a relatively cheap insurance policy against environmental stress[47]. Potassium is the most abundant cation in the phloem sap[35] amounting to about 80 percent of the total cation sum. It is usually stored in the vacuoles in large quantities. Recent reports by Bednarz and Oosterhuis[8] suggested that the luxury storage of K by the cotton plant may explain the apparent inability of researchers to accurately predict the onset of K deficiency from tissue analysis.

Sensitivity of Cotton to Potassium Availability

Cotton appears to be more sensitive to low K availability than most other major field crops and often shows signs of K deficiency on soils not considered K deficient[17]. Cope[21] reported that in a 21-year field comparison of five field crops (cotton, vetch, corn, wheat, and soybeans), cotton was the most sensitive to K deficiency and was the most responsive to K fertilization. Potassium is relatively immobile in the soil and moves slowly, mainly by diffusion[6]. The rate of plant uptake of K depends on root length density and total root surface area[14]. However, the cotton root system is notable for its low density relative to other major row crops[27]. Thus, the relative sensitivity of cotton to the soil K supply may reflect in part the low density root system of the cotton plant. The high requirement for K in cotton coupled with an inherent low root length density and the immobile nature of the element means that K uptake is particularly sensitive to poor root growth, and deficiencies may appear even in soils with a relatively high K content. Furthermore, anything which restricts root growth, such as disease or insect damage, nematodes, root pruning, poor drainage, soil acidity, compaction etc, will reduce nutrient uptake and may, therefore, exacerbate K deficiency.

Symptoms of Potassium Deficiency

Potassium deficiency occurs more frequently and with greater intensity on cotton than for most other agronomic crops[49]. Typical K deficiency symptoms consist of yellowish-white mottling of the leaves that changes to numerous brown specks at the leaf tips, around margins, and between veins[85]. The leaf tip and margin curl downwards as the tissue breakdown continues. Finally, the whole leaf becomes rust colored, brittle, and drops prematurely, stopping boll development. This results in dwarfed and immature fruit, some of which may not open. Small bolls are a typical symptom of severe K deficiency in cotton. Many of these symptoms are related to the disturbance of tissue water balance resulting in tip drying, leaf edge curling, and early senescence. Potassium deficiency symptoms in cotton are quite distinctive and, due to the characteristic bronzing that occurs, were once termed *cotton rust* before the true cause was known[49]. The symptoms of K deficiency have been mistaken for Verticillium wilt symptoms as they seem to occur under similar environmental conditions[92]. Furthermore, the growth and yield of cotton varieties less susceptible to Verticillium wilt are often less affected by late-season K deficiency[3, 56].

Potassium deficiency symptoms fall into two categories, namely those that occur at the bottom of the plant on the lower, older or mature leaves, and the more recent symptoms[53, 86, 92] that show up on young cotton leaves at the top of the plant, late in the season. The characteristic rusting and premature senescence is the same for both lower and upper canopy K deficiencies. However, unlike the lower, older leaf symptoms, researchers have not been fully able to explain the real cause of these new upper-canopy deficiency symptoms which have aroused much speculation. Current thinking is that modern varieties develop bigger yields over a shorter fruiting period, and K moving upward from the roots is intercepted by the developing boll load at the expense of the upper leaves.

The sensitivity of various cotton organs to K deficiency (in terms of decrease in K accumulation) was reported by Rosolem and Mikkelsen[80] as: leaves < bolls < roots < stems. These results indicate that by the time K deficiency symptoms are manifested in the leaves, the growth of all other plant parts (including the economically important boll) are already detrimentally affected. However, a recent report by Bednarz and Oosterhuis[9] showed a contradictory order of organ sensitivity to K deficiency in cotton as: bolls < stems and petioles < leaves < roots, such that bolls were the last organ to be affected.

Reasons for the Widespread Occurrence of Potassium Deficiencies in Cotton

Much speculation has surrounded the widespread occurrence of apparent "K deficiency" symptoms that have appeared in recent times in the U.S. Cotton Belt. Many theories have been proposed to account for these deficiencies, but the explanation is still not clear. It has been proposed that the deficiencies are related to soils with K availability problems[18], the relative inefficiency of cotton at absorbing K from the soil compared to most other crop species[17], or the incidence of Verticillium wilt[90]. It has also been postulated that the widespread K deficiency that has occurred in recent years is related to earlier-maturing, higher-yielding, faster-fruiting cotton varieties creating a greater demand than the plant root system is capable of supplying[71].

The decrease in root activity after the start of flowering[16] may further exacerbate the K deficiency syndrome. This is because the decrease in root growth occurs during peak K demand as the developing boll load increases and exerts the major demand for available assimilate, including K. When K is limiting in the soil, this decline in root activity can be expected to have a dramatic effect on K uptake by the roots and therefore, on the growth, management, yield and lint quality of the cotton crop. The high demand for K by the developing boll load will be further hindered if root development is poor due to nematodes, compaction, high water tables, or cool soils as are often experienced early-season in the Mississippi Delta. Irrigated and dryland cotton crops have different rooting patterns[11]. Dryland crops have a more extensive root system with significant genotypic differences. This could also influence the availability of K.

Recent evidence indicates that modern cotton cultivars have less K in storage prior to boll development[9] which could account for the unpredictable appearance of K deficiency in certain environments. This would be further exacerbated by the higher yields and bigger boll loads, and concomitant increase in K requirement, of modern cotton crops. In addition, in recent years more cotton has been planted on poorer soils low in available K[49].

The modern K deficiency syndrome appears to be a complex anomaly related to: (i) the greater demand for K by higher-yielding modern cultivars, (ii) the inability of the root system to supply this demand due to the decrease in root activity late in the season or due to poor or restricted root growth, (iii) soil K fixation, (iv) the relative inefficiency of cotton at absorbing K from the soil compared to most other crop species, (v) possible relationships with diseases such as Verticillium wilt, and possibly, (vi) less storage of K by modern cultivars prior to boll development. Obviously all these factors are related to environmental conditions, and influenced by production management practices.

Fertilization with Potassium

The goal of fertilizer programs for cotton should be to achieve maximum economic return for the fertilizer investment[49]. This may not necessarily coincide with maximum yield, and it may change with time and with location. Fertilizer applications are made to meet the annual crop nutrient requirements and return to the soil those nutrients removed by the crop. Adequate fertilization is important to every cotton farmer because the amounts used, and therefore the cost, are slight compared to the dollars lost from yield limitations[31].

An effective fertilizer management program must include consideration of the optimum times when the different nutrients are needed as well as the fate of the nutrients when applied to the soil. The uptake pattern for K by cotton is well documented[7, 32], with the need for K rising dramatically when the boll load begins to develop[32] because the bolls are the major sinks for this nutrient. However, most fertilizer programs utilize a single preplant application of K. This may not always be sufficient because the peak demand by the plant occurs much later during boll development, and because of the many factors that can affect K uptake by the cotton plant (the decline in root growth during boll development, nematodes, soil K fixation, etc).

A knowledge of the soil being used is important because the mineralogy, organic matter, and level of K depletion for a specific soil can significantly affect the fate and availability of applied fertilizer K[78]. Accurate soil analysis coupled with mid-season plant tissue analysis is needed to formulate a suitable K fertilizer program. Soil sampling and analytical methods of assessing soil available K are reviewed by Sabbe and Zelinski[81].

Most fertilizer applications of K are surface applied or shallowly incorporated into the topsoil. Previous research in California by Gulick et al.[29] showed that cotton root systems fail to exploit available K in the topsoil adequately. These authors suggested that K uptake by cotton could be improved if a large proportion of the root system was exposed to adequate available K. Mullins et al.[62] suggested that cotton may, therefore, respond to deep placement of K in the subsoil. They demonstrated that deep placement of about 16 kg K/ha produced higher yields than surface broadcast applications, although at higher rates the surface broadcast application consistently produced higher yields than deep placement. Research in the Mississippi Delta has shown increased yields on some soils as a result of deep placement of K fertilizer at a depth of 15 to 30 cm[88]. Deep placement of fertilizer K has not consistently resulted in yield increases (T. Keisling, personal communication) and additional research is needed. Soils exhibiting the greatest response to deep placement of K generally have subsoils with low to very low soil K.

Foliar Fertilization with Potassium

Potassium deficiencies can be corrected through preplant soil applications or partially corrected using mid-season sidedress applications of K. Foliar applications of K may offer the opportunity of correcting these deficiencies more quickly and efficiently, especially late in the season, when soil application of K may not be effective or possible. Foliar applications have the advantage of allowing producers to add the necessary K when tissue analysis indicates a pending shortage, thereby correcting the deficiency and preventing yield loss. It is of interest that foliar feeding of a nutrient may actually promote root absorption of the same nutrient[87].

While there are many reports on research involving soil applied K , there are very few on the usefulness of foliar-applied K. Oosterhuis[63] working in southern Africa reported significant increases in cotton yield from foliar fertilization with K (as KNO_3) without any apparent K deficiency. Halevy and Markovitz[33] in Israel reported increased lint yield and average boll weight from foliar sprays containing N, P, K and S in locations where the soil fertility was low.

More recent research in Arkansas[70, 71, 72] indicated that foliar-applications of KNO_3 can increase yields and improve lint quality (**Table 1**). Five treatments were used: (1) a control with no added soil or foliar K, (2) low (33.6 kg K/ha) soil-applied KCl preplant (3) high (67.2 kg K/ha) soil-applied KCl preplant (i.e. at twice soil recommendations) (4) low preplant soil-applied KCl and foliar-applied KNO_3, and (5) high preplant soil-applied KCl and foliar-applied KNO_3. The foliar treatment was applied at a rate of 11.2 kg KNO_3/ha at 2, 4, 6, and 8 weeks after first flower in 94 liters water/ha using a CO_2 backpack sprayer. In addition, 1.54 kg N/ha was added as foliar urea to treatments 2 and 3 each time the foliar-KNO_3 was applied to the foliar treatments 4 and 5 to negate the possible effect of the N in KNO_3. The effect of foliar-applied K averaged over five locations in Arkansas between 1989 to 1992 is presented in **Table 1**. The average yield increase was 73 and 17 kg lint/ha compared to the low and high soil-applied K treatments, respectively. The average lint yield was increased from 1,107 kg/ha in the untreated control to 1,136 kg/ha in the low soil-applied K treatment (using recommended levels of K), and increased to 1,207 kg/ha in the combined low soil-K plus foliar-K treatment. However, in some years the high-soil K treatment was really a "normal" recommended level[84] and the high-soil K treatment was, therefore, similar to the low-soil K plus foliar-K yield. Under those circumstances it would be difficult to justify foliar K, unless deficiencies appeared and/or petiole analysis revealed a need for additional K.

In some cases it appeared possible to achieve the same affect as the foliar K by doubling the initial soil K. This may not, however, be practical due to possible salt buildup and K fixation in some soils. Furthermore, excessive K application to the soil, on soils testing low in Mg, can induce Mg deficiency and reduce yield if fertilizer recommendations are not followed closely[22]. It is interesting that foliar K without any soil-applied K increased lint yield an average of 81 kg/ha compared to the untreated control, and 25.8 kg/ha compared to the standard soil K treatment (**Table 1**). The small response to K in certain years was probably due to the extended growing season which allowed the younger upper-canopy bolls, which would not usually have had the K or the time to fully develop, to grow into mature harvestable bolls.

Boll weight (seedcotton) was increased from 3.52 g/boll in the soil-applied KCl control plots to 3.87 g/boll in the soil plus foliar K plots[70]. As with yield, the greatest influence on boll weight was obtained from the combined soil-K plus foliar-K treatment. Potassium deficiency symptoms occurred in all treatments at most sites but least of all in the soil-plus-foliar K treatment. Petiole analysis of upper-canopy leaves indicated that the combined application of soil and foliar K significantly enhanced plant K content compared to controls during both vegetative and reproductive development. The soil test K level averaged about 345 kg K/ha...172 parts per million (ppm)...(**Table 1**). From a regression analysis of the data, yield increase can probably be expected when using foliar-applied K on soils with a relatively low soil K status of less than 125 ppm K (Oosterhuis, unpublished data), although in some cases responses to foliar fertilizer on cotton growing in soils with a higher K status have been recorded.

Fiber quality was also significantly improved by foliar applied KNO_3, with the increases occurring primarily in fiber length uniformity and strength (**Table 2**). Micronaire was also increased in certain years. Application of KNO_3 either as foliar treatments alone, or in combination with supplemental soil KCl, effectively improved uniformity and strength. Surprisingly, however, soil application of KCl alone did not enhance any of the fiber quality components. Fiber quality in 1991 was unaffected due to above average quality of the cotton crop in general. Foliar plus soil K increased fiber dry weight compared to the preplant soil applica-

Table 1. **The influence of soil- and foliar-applied K on cotton lint yields at four sites in Arkansas, 1989 to 1992. (From Oosterhuis et al., 1992 and 1993).**

	1989	1990			1991		
Treatment	MES[1]	CBS	MES	NEREC	MSCO	CBS	SEBES
	---------- kg lint/ha ----------						
Control	606 0	1579 c	834 c	982 a	1043 b	1157 a	1499 a
Low soil K	619 bc	1725 b	844 bc	1000 a	1102 bc	1148 a	1515 a
High soil K	—[3]	—	—	967 a	1133 ac	1210 a	1490 a
Foliar KNO_3	631 ab	1725 b	907 ab	—	—	—	—
Low soil + foliar K	649 a	1839 a	913 a	1020 a	1257 a	1224 a	1580 a
High soil + foliar K	—	—	—	1015 a	1222 a	1182 a	1394 a
Preplant soil K[4]	400	176	314	546	274	272	217

[1] MES = Main Experiment Station, Fayetteville; CBS = Cotton Branch Station, Marianna; NEREC = North East Research and Extension Center; MSCO = R.D. Jackson Farm, Mississippi County; SEBES = Southeast Branch Experiment Station.

[2] Values within a column followed by the same letter are not significantly different (P = 0.05).

[3] Treatment not included.

[4] Preplant 0 to 15 cm soil test K status in kg K/ha.

tion of K. The K concentration and the K content of the fibers were also increased by the foliar plus soil K application[71]. The capsule wall contained the highest amount of K of the three components and may have acted in a storage capacity.

Table 2. The influence of soil- and foliar-applied K on cotton fiber quality, as measured by high volume instrumentation (from Oosterhuis et al., 1990).

Treatment	Length uniformity index, %	Strength, g/tex
Control	84.5 b[1]	24.4 b
Soil-applied KCl	85.8 b	24.2 b
Foliar-applied KCl	87.1 a	26.6 a
Soil- + foliar-applied KNO_3	86.0 ab	25.1 ab

[1] Values within a column followed by the same letter are not significantly different (P=0.05).

A three-year Beltwide study from 1991 to 1993 evaluated the effect of foliar-applied KNO_3 compared to soil-applied KCl on cotton yield and fiber quality[73]. The study was a cooperative effort conducted under different environmental conditions at 12 sites from North Carolina to California. The preliminary results have been variable with significant yield increases from foliar K recorded about 40 percent of the time[67].

Research findings to date suggest that where a potential K deficiency exists, KNO_3 applied as a foliar spray to supplement preplant soil-applied K can have a significant effect on cotton yield and fiber quality. However, more information is needed on the underlying physiological explanation of cotton K requirements and K deficiencies to better predict the need for, and the response to, foliar application of K.

Foliar Fertilization of Cotton Seedlings with Potassium

Adverse environmental conditions are often experienced in the Mississippi Delta during seedling development. Producers have, therefore, become interested in foliar fertilization of seedlings to enhance their growth during this critical stage. However, little is known about the benefits of foliar fertilization of cotton seedlings, even though foliar application of urea or B to cotton during flowering is a widely used practice to enhance boll development. Field research at five sites in Alabama showed that cotton yield was not influenced at all by the application of foliar N-P_2O_5-K_2O (12-48-8) fertilizer made in one to three applications at 10 to 14 day intervals[24].

It has been speculated that foliar sprays of K could have a positive effect on droughted cotton seedlings because of the important role that K plays in the water relations of plants. This theory was tested in a series of pot experiments in the growth room where conditions could be carefully controlled[41]. These studies and associated field tests indicated that foliar-applied K did not improve the drought tolerance of seedlings, i.e., plant water relations were not improved for continued growth during the stress. Therefore, the potential benefit from such applications is not sufficient to warrant their use. Recent research has suggested that applying foliar fertilizers after relief of the drought stress to stimulate recovery and enhance growth may be beneficial (E.M. Holman, unpublished data), and a similar response may occur with K.

Leaf Uptake of Foliar-Applied Potassium

Understanding the absorption and translocation of foliar-applied K in the cotton plant is important in order to be able to predict how rapidly, and in what amounts, the foliar-applied K is taken up by the leaf and how quickly it moves to the developing boll. Using $^{42}KNO_3$ applied to the midrib of cotton by micro pipette, Kafkafi[48] in Israel showed that foliar-applied K moved into the leaf and to the boll within 20 hours. However, no information was provided on the quantity taken up by the leaf or the time intervals for translocation to the boll. Preliminary studies in Arkansas in 1990, using Rubidium to monitor K movement into the leaf, indicated that K first entered the leaf within 6 hours and then in greater quantities between 6-48 hours after application and was translocated to the developing bolls with little delay during the same period (Oosterhuis and Hurren, unpublished data). Further evidence that foliar-applied K is translocated to the boll was provided by Oosterhuis et al.[71], who demonstrated in field studies that foliar-applied KNO_3 increased K concentration, K content of the fibers, and fiber dry weight (**Figure 2**) compared to the untreated check. More detailed information on the time course of K uptake by the leaf and translocation to the developing boll, as well as factors that effect this process, is still needed.

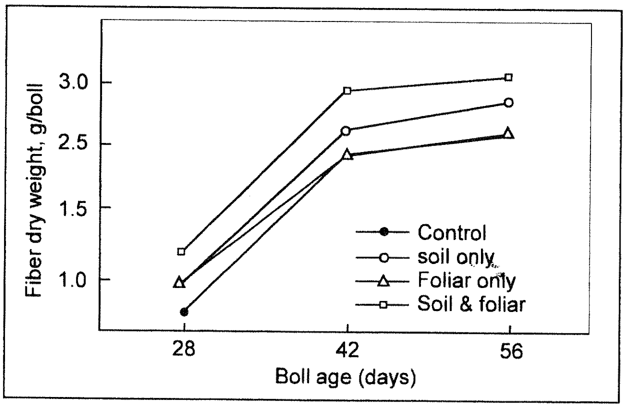

Figure 2. Effect of soil- and foliar-applied KNO_3 on fiber dry weight during boll development (from Oosterhuis et al., 1991b).

Use of Adjuvants with Foliar-Applied Potassium

It has been speculated that the use of adjuvants with the K spray may improve the efficacy of the foliar-applied K fertilizer and thereby provide the potential for decreasing the quantity of K applied per application. Howard et al.[42] showed that the uptake of K from foliar-applied KNO_3, as reflected in cotton petioles, was increased significantly when surfactants were added to the K solution. However, the final yield of lint was not increased. Similar results have been found in Mississippi (Heitholt, unpublished data) and Arkansas (Oosterhuis, unpublished data). Recent growth room studies by Chang and Oosterhuis[19] showed that lowering the pH of the foliar K solution to between 4 and 6 significantly increased the absorption of K, its subsequent accumulation in the boll, and the seedcotton yield. Additional research is obviously needed to understand the principles involved and, if necessary, to implement these findings into production practices.

Tissue Diagnoses of Potassium

Analysis of soil and plant samples offer a means of determining the K status of a crop. In cotton, tissue tests have become a valuable diagnostic tool for assessing the nutrient status of a crop, for determining fertilizer recommendations during the growing season, and for detecting potential K deficiency[5]. The petiole is generally considered more indicative of plant K status than the leaf blade, partly because of the more rapid decline in K concentration in the petiole, compared to the leaf, during the boll development period[4, 43] (**Figure 3a**). Hsu et al.[43] reported that, although the rates of K decline in both leaf blade and petiole were dissimilar, each was a function of maturity and not a function of K fertilization rate. Although the K concentration of the uppermost mature main-stem leaf petiole is considered to provide a reliable indication of plant K status at the time of sampling[43, 52], Weir and Roberts[91] cautioned that the result may not always provide adequate warning of impending K deficiency. Bednarz and Oosterhuis[9] suggested petioles sampled lower in the canopy than the currently recommended fourth node from the terminal may be more indicative of a pending K deficiency. There is also some concern about the validity of petiole analysis and the resulting recommendations from samples taken later than three weeks after the start of the flowering and boll development period[55].

Obtaining a representative sample from a cotton field is essential for reliable estimates of crop K status. This necessitates a sufficient number of petioles per sample for analysis (usually about 10 to 20), an adequate number of samples to account for field variability, and consistency in sample selection, i.e., the same time of day and position on the plant. A gradient exists of increasing K concentration in the petioles of leaves at progressive main-stem nodes down the plant (Bednarz, unpublished data) which is presumably related to the age of the leaf[43] and its physiological activity. Samples taken after two days of overcast weather may exhibit a 10 percent decrease in K concentration from the previous day (Oosterhuis, unpublished data).

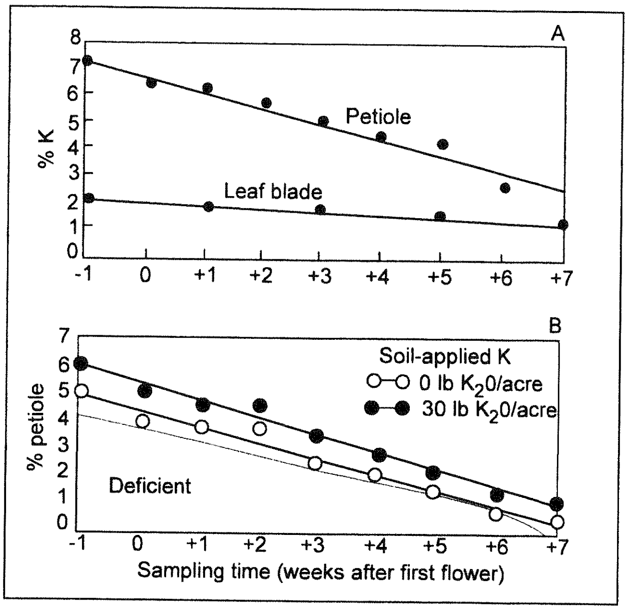

Figure 3. Cotton petiole K status from one week before first flower until boll maturation showing (A) a comparison between the decline in petiole K and leaf blade K, and (B) suggested critical cotton petiole K levels; Marianna, Arkansas (from Baker et al., 1992).

There is still some question about the appropriate critical or threshold levels for K concentration in the leaf or petiole, as these values may be appreciably altered by the environment, plant genetics, and sampling procedure. The sufficiency levels of K in petioles for a cotton crop are generally in the range of 4.0 percent at first flower, 3.0 percent during peak flower, 2.0 percent by first open boll, and 1.0 percent prior to harvest[7, 83, 84]. The critical tissue level for K in cotton leaf blades in mid-to-late season is between 0.9 and 1.2 percent[4] and may be as low as 0.6 to 0.9 percent for significant decreases in leaf photosynthesis[9].

Foliar applications of KNO_3 to cotton on soils moderate to low in K have been reported to significantly increase K concentration of petioles compared to control plants not receiving foliar-applied K[70]. The changes in plant K status from a single foliar application of K may not always be large enough to be detected by petiole analysis[93]. However, the early detection of K deficiency by in-season monitoring using weekly petiole analysis will allow some limited response by producers if yield potentials warrant additional K[4].

Recent developments with small portable selective ion meters using expressed leaf or petiole sap may provide another practical means of obtaining estimates of plant K status[60]. However, it is difficult to obtain a representative sample with such instruments (W.H. Baker, personal communication). Hodges and Baker[40] reported difficulties in expressing sufficient sap for the test, even under non water-stressed conditions. Additional research is required before these instruments can be used with any accuracy or dependability.

Luxury consumption of K , defined as uptake and accumulation of K above levels needed for normal growth, can occur in cotton[47], and this could possibly confuse tissue diagnostic recommendations[9]. Bennett et al.[10] showed that cotton plants continue to accumulate K at rates above that needed to produce maximum yields, with the highest K content occurring in older leaves and petioles. However, Kafkafi[47] suggested that luxury consumption of K can be beneficial for high yields and a cheap source of insurance against possible K deficiency problems.

Optimum Rate and Timing of Applying Foliar Potassium

The timing of foliar sprays, particularly in regard to the growth stage, can be critical in relation to the optimum efficacy of the foliar treatment, and more attention should be given to it[1]. It has been suggested that the recommended growth stages in cotton for foliar-applied K are at the pinhead and first flower stages and at peak boll development[20]. More recent evidence suggests that the optimum timing was during the boll development period starting soon after flowering and continuing at 7 day intervals for 5 weeks (Oosterhuis, unpublished data). Weir and Roberts[93] showed that the optimum stage of response to foliar application of KNO_3 was three weeks after first flower.

In a field study on a Loring-Calloway silt loam soil in Arkansas, six weekly applications of 2.8 kg/ha, 5.6 kg/ha or 11.2 kg/ha of KNO_3 were applied starting at first flower (Oosterhuis, unpublished data). The soil had a low preplant soil K level of 188 kg K/ha. Results suggested that weekly applications of 2.8 kg KNO_3/ha had no significant effect on lint yield compared to the untreated control. Whereas weekly applications at the 5.6 kg KNO_3/ha rate caused a 121 kg/ha (12.5 percent) yield increase, and weekly applications of 11.2 kg KNO_3/ha resulted in a 298 kg/ha (30 percent) increase in yield. Applying KNO_3 according to the K use uptake curve of the developing boll load (e.g. 2.8, 2.8 5.6 11.2, 11.2, 5.6, 5.6, and 5.6 kg KNO_3/ha at weekly intervals from flowering to 8 weeks after flowering, respectively) resulted in the largest increase in yield of 398 kg/ha (41 percent).

No visible injury of cotton leaves was observed at foliar application rates of up to 22.4 kg KNO_3/ha[70] in 94 L water/ha. However, solubility in cold water may be a problem at rates near 10 kg KNO_3/ha.

Sources of Potassium for Foliar Fertilization

A 3-year field comparison of the major K fertilizers was conducted in Arkansas on a Loring-Calloway silt loam[57] with a moderate soil K status (Mehlich 3 extractant) of 200 to 237 kg K/ha in the surface 15 cm and 176 to 197 kg K/ha at 16 to 30 cm of the soil. Salts of K used included nitrate, sulfate, thiosulfate, chloride and carbonate, applied at a rate equivalent to 11.2 kg KNO_3/ha in 93 liters of solution/ha. For the control and each treatment containing a source other than KNO_3, 1.5 kg N/ha as urea was applied to equal the N rate supplied by the KNO_3 treatment.

Results showed a trend for KNO_3 to increase yield the most, followed closely by potassium thiosulfate and potassium sulfate (K_2SO_4; **Table 3**). Potassium chloride (KCl) and potassium carbonate (K_2CO_3) had no effect on yield, and K_2CO_3 significantly decreased yield in 1992[57]. The detrimental effects of K_2CO_3 on yield and the lack of effect on yield of KCl were related to physiological effects on leaf photosynthesis and cell membrane integrity (Oosterhuis, unpublished data).

Only very minor and non-significant visual symptoms of foliar burn were observed following foliar application of any of the K fertilizers. Symptoms consisted of a few small spots on the leaf, particularly with K_2CO_3. A recent study by Chang and Oosterhuis[19] confirmed these findings and showed clear differences among foliar applied K sources in affect on leaf burn, leaf expansion, K absorption, and yield.

Recently there has been some interest across the Cotton Belt in using KCl because it is a cheaper source of K. Pettiet[74] reported that KCl dissolved more easily than KNO_3 and was more easily absorbed by the leaf; however, the effects on yield were not recorded. There have been six field tests across the Cotton Belt in recent years comparing KNO_3 and KCl and in all but one test, KCl had

Table 3. Effects of foliar applications of five K sources on cotton yield and boll weight (from Miley and Oosterhuis, 1994).

Potassium Source [1]	Yield 1991	Yield 1992	Yield 1993	Boll weight 1991	Boll weight 1992	Boll weight 1993
	kg lint/ha			g/boll		
K sulfate	1,186 a[2]	1,146 bc	588 a	4.64 a	4.20 ab	3.85 ab
K nitrate	1,160 a	1,257 a	625 a	4.81 a	4.33 a	3.84 ab
K thiosulfate	1,154 a	1,185 b	552 a	5.05 a	4.28 ab	3.84 ab
K chloride	1,107 a	1,150 bc	569 a	4.84 a	4.27 ab	3.91 a
Check	1,091 a	1,164 b	585 a	4.82 a	4.24 ab	3.84 ab
K carbonate	1,066 a	1,095 c	553 a	4.82 a	4.12 b	3.64 b

[1] Treatments were applied at 2, 4, 6, and 8 weeks after the start of flowering in 1991 and at 2, 4, 6, 7, and 8 weeks after the start of flower in 1992.

[2] Numbers within columns followed by the same letter are not significantly different (P=0.05).

either no effect on yield or decreased yield (W.R. Thompson, personal communication). A salt index has been used as a measure of the effect of a fertilizer on the osmotic potential of the soil solution[76] and may give some insight into the possible effect that a fertilizer could have on leaf tissue. The salt index is defined as the ratio of the increase in osmotic potential produced by a fertilizer material as compared to that produced by an equal weight of sodium nitrate based on the relative value of 100. The salt index for KNO_3 is 73.6 compared to 116.2 for KCl, further indicating that KCl in large concentrations could possibly have a negative influence on leaf tissue. In support of this it has been shown that foliar-applied KCl adversely affected membrane integrity of leaf discs compared to the untreated control and the foliar KNO_3 treatment (Oosterhuis, unpublished data).

Genotypic Differences in Response to Foliar-Applied Potassium

Most of the research on genotypic responses to K fertilization has been conducted using soil-applied K, with only one reference to foliar-applied K. Significant genotypic differences in response to soil-applied K have been reported. Cassman et al.[18] demonstrated significant genotypic differences between two Acala cultivars in K requirement and response to late-season K deficiency. These authors related this to differences in root growth after peak flowering and root-growth response to bulk density. Furthermore, on soils with K problems, it has been suggested that cultivars tolerant to K deficiency will have reduced symptoms and will produce 12 to 40 percent higher yields than more-sensitive cultivars[3, 92]. It is curious that Weir et al.[92] reported no differences in petiole K between two Acala cultivars in response to soil-applied K.

In contrast to the reports on genotypic differences in Acala cottons, Mullins and Burmester[61] reported a lack of difference among cultivars in their total nutrient uptake. Pettigrew et al.[75] suggested that the same genotypes should be used under both K deficient and K sufficient conditions.

A study of genotypic responses to foliar-applied K[46] indicated that there were no significant differences among cotton cultivars in response to foliar applied KNO_3. In their studies, foliar-applied K increased the K concentration in all plant parts of all cultivars studied although this was not always reflected in increased yield.

Effect of Foliar-Applied Potassium on Disease

Soil-applied K has been reported to reduce the incidence of Verticillium wilt (*Verticillium dahliae* Kleb.)[30], although the physiological reasons for this are not clear. In California, K deficiency symptoms have often been associated with the occurrence of Verticillium wilt[56], and the symptoms may be limited to cotton fields infested with Verticillium wilt[92]. Also, soil fumigation to reduce the incidence of Verticillium wilt eliminated the foliar symptoms of K deficiency and Verticillium wilt[92]. Furthermore, varieties more tolerant of Verticillium wilt are often more tolerant of late-season K deficiency[3, 92]. Verticillium wilt blocks the vascular system of cotton, preventing movement of K to the developing boll load or upper canopy leaves[3], causing the K shortage as manifested in K deficiency symptoms. Minton[59] and Ebelhar[58] reported that in soils infested with Verticillium wilt and root knot nematode (*Meloidogyne incognita*), soil-applied K could be used to reduce the Verticillium wilt-K deficiency symptoms.

Recent research in Arkansas has indicated that foliar-applications of K reduced the incidence ($P=0.10$) of Verticillium wilt from 36.1 percent in the untreated control (no foliar applications of KNO_3) plots to 27.8 percent in the plots treated with foliar-applied KNO_3 during flowering.

In what may be a similar relationship, the incidence of Alternaria leaf spot was significantly reduced when treated with a fungicide and K[37]. This was also demonstrated in Tennessee, where an application of a foliar fungicide foliarly applied at 1.15 or 4.64 L/ha with KNO_3 at 11.9 kg K_2O/ha, significantly reduced the incidence of Alternaria leaf spot (M.A. Newman, personal communication). Obviously, additional research is needed to explain the relationship between the occurrence of disease, such as Verticillium wilt, and the appearance of K deficiency.

Factors Affecting Absorption of Foliar-Applied Potassium

Compatibility of potassium and insecticide mixtures.

Foliar applications of K are routinely added to foliar applications of pesticides. Questions have arisen about the compatibility of KNO_3 and insecticides[51]. These authors reported decreased efficacy and a 35 to 75 percent reduction in the amount of pyrethroid insecticide recovered when tank mixed with urea (23 percent N) solution. This was caused by separation of the pyrethroid out of suspension in the urea solution mixture and not due to chemical degradation of the pyrethroid (Graves, personal communication). It has been suggested that similar problems may occur with tank mixes of KNO_3 and insecticides. Recent studies by Baker et al.[5] reported that the pyrethroid insecticide Cymbush 3EC mixed with KNO_3 remained well dispersed with mild agitation and would not be expected to pose a physical compatibility problem. They did report some problems with urea-insecticide mixtures which could be lessened by first mixing the insecticide with water to provide a stable emulsion dispersion. Baker et al.[5] suggest that because of the unique behavior of specific emulsified insecticides, each insecticide/fertilizer combination should be evaluated separately for compatibility to obtain a high level of assurance of the mixture stability before use.

Urea and KNO_3 mixtures.

Foliar application of urea to cotton is a common practice in the U.S. Cotton Belt and questions have arisen concerning the mixing of urea and KNO_3 in foliar applications. In field studies in Arkansas, rates of up to 11.2 kg N/ha as urea and 11.2 kg KNO_3/ha were tank mixed and applied with a CO_2 backpack sprayer to the cotton in 93 liters of water. It was concluded that mixing KNO_3 with urea did not have any detrimental effect on yield (Oosterhuis and McConnell, unpublished data).

Water deficit stress.

The variable response to foliar K fertilization may also be related to the water status of the plant. Water deficit has been shown to significantly decrease the amount of foliar-applied ^{15}N absorbed by the cotton leaf[98]. Periods of water deficit stress can increase the thickness of the cotton leaf cuticle by up to 30 percent and also alter the composition of the cuticle to more long chain hydrophobic waxes[66] thereby reducing penetration of foliar-applied chemicals. Furthermore, the thickness of the cotton leaf cuticle also increases during ontogeny, while the uptake of foliar-applied ^{15}N decreased concomitantly[13]. The effect of water deficit and cuticle thickness on the absorption of foliar-applied K by cotton has not been documented.

Miscellaneous factors affecting the efficacy of foliar potassium sprays.

The absorption of K by leaves from foliar sprays can be affected by the choice of the salt, the concentration, additives such as adjuvants or insecticides, dew or surface moisture on the leaf, the site of application, leaf age, plant status, and root temperature. Experience in Arkansas has shown that excessively high midday temperatures and low humidity tend to decrease the amount of nutrient absorption by the leaf (Oosterhuis, unpublished data). Dew can enhance the uptake of residue from the foliar fertilizers remaining on the leaf after excessive evaporation[98].

Yield Enhancement Using Foliar-Applied KNO_3 and Plant Growth Regulators

Earlier work at the University of Arkansas has shown a consistent and significant increase in cotton yields from the plant growth regulator PGR-IV[69, 89]. This growth regulator is purported to increase boll retention. In theory, this should further increase the need for additional K. In a field test in Arkansas[64], the following treatments were compared: (a) an untreated control, (b) KNO_3 foliar applied at 11.2 kg/ha at 2, 4, 6, and 8 weeks after first flower (c) KNO_3 at 292 ml/ha at pinhead square and first flower, and (d) PGR-IV followed by KNO_3 (treatments b and c). Results showed that foliar KNO_3 increased seedcotton yields significantly by 61 kg/ha, PGR-IV increased yields by 107 kg/ha, whereas the PGR-IV plus KNO_3 treatment increased yields by 256 kg/ha. A similar trend was recorded with the plant growth regulators, Pix™ and Cytokin™ [67].

Advantages and Disadvantages of Foliar Fertilization with Potassium

The advantages of using foliar feeding with K include low cost, a quick plant response (increased tissue K concentration and fewer new deficiency symptoms), use of only a small quantity of the nutrient, quick grower response to plant conditions, compensation for the lack of soil fixation of K, independence of root uptake problems, increased yields, and improved fiber quality.

On the other hand, the disadvantages are that only a limited amount of nutrient can be applied in the case of severe deficiencies, and the cost of multiple applications can be prohibitive unless incorporated with other foliar applications such as pesticides. Other disadvantages when using high concentrations of K include the possibility of foliar burn, compatibility problems with certain pesticides, and low solubility of certain K salts, especially in cold water. Another restraint is the lack of a full understanding of this technology, specifically the optimum rate and timing, tissue threshold levels to predict the need for foliar-applied K, the physiological mechanism of absorption, and the effect of plant condition and environmental factors on absorption.

Suggestions for Optimum Foliar Fertilization with Potassium

The requirement for foliar-applied K varies greatly with geographical area and even within a single field, and it is difficult to provide a standard recommendation for the practice. Furthermore, the explanation for the cause(s) of the K deficiency syndrome is still not clear. However, research results and practical experience in commercial fields have indicated the following general principles for foliar fertilization with K.

Foliar application of K during boll development may be beneficial when the soil K level is inadequate, from K fixation, low soil test K status, or poor root growth, and when petiole analysis indicates a pending shortage of K. The petiole threshold level of K will decrease from about 4.0 percent at first flower to about 2.0 percent near open boll. Three to four foliar applications of K should be made during the first five weeks of boll development at 7 to 10 day intervals starting at the commencement of flowering. A minimum rate of approximately 4.5 kg/ha of K should be used at each application. The recommended source of K for foliar fertilization is KNO_3, although K_2SO_4 or $K_2S_2O_4$ appear to work almost as well. Attention should be given to possible solubility problems in cold water. The use of an adjuvant with the foliar spray will increase leaf K uptake but may not necessarily result in increased yields, although it may permit the use of a lower rate of K per application. Further insight into the practical applications of foliar fertilization of cotton with K are give by Roberts et al.[79].

Conclusions

Potassium deficiency has occurred widely across the U.S. Cotton Belt in recent years. The occurrence of these outbreaks of K deficiency has been somewhat unpredictable and the explanations not clear. The K-deficiency syndrome appears to be a complex anomaly related to low soil K status, K fixation in the soil, a greater demand for K by modern cultivars, less storage of K prior to flowering by modern cultivars, the inability of the root system to supply the needed K during boll development, and possible relationships with diseases such as Verticillium wilt. Interest has focused on the possibility of foliar feeding with K to supplement traditional soil application methods. Foliar applications of K offer the opportunity of correcting these deficiencies quickly and efficiently, especially late in the season when soil application of K may not be effective. Research during the last five years has shown that foliar-applications of KNO_3 can alleviate K deficiency and significantly increase yield and fiber quality. However, results from across the Cotton Belt have been variable and unpredictable, and additional research is needed to fully explain this phenomenon. There is sufficient evidence that foliar application of KNO_3 appears to be a useful production practice for supplementing preplant soil applications of K fertilizer, especially when K deficiency symptoms occur and soil and petiole tests show a low K status.

Synopsis of Future Research Imperatives

Additional work is still required to elucidate the chain of events occurring during the onset of K deficiency. This is certainly the case in cotton, where, by the time a deficiency is detected, it is often too late to remedy the situation, and reduced yields and fiber quality result. An improved understanding of K deficiency in cotton could ultimately lead to more reliable indicators of a pending deficiency for more timely management inputs for optimum yield and fiber quality. A better knowledge of the physiology of K deficiency should also help to explain the inconsistent response to foliar-applied K. Lastly, the effect of water deficit on K partitioning and response to soil and foliar applications of K needs to be quantified.

Literature Cited

1. Alexander, A. 1986. Optimum timing of foliar nutrient sprays. p. 44-60. *In* Alexander, A. (ed.). Foliar Fertilization. Martinus Nijhoff Publishers, Dordrecht.
2. Ashley, D.A. and R.D. Goodson. 1972. Effect of time and plant potassium status on C-labeled photosynthate movement in cotton. Crop Sci. 12:686-690.
3. Ashworth, L.J., A.D. George, and O.D. McCutcheon. 1982. Disease-induced potassium deficiency and Verticillium wilt in cotton. Calif. Agri. 36(9-10):18-20.
4. Baker, W.H., J.S. McConnell, R.L. Maples, and J. Varvil. 1992. Soil and plant methods for diagnosing K deficiency in cotton. p. 67-70. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
5. Baker, W.H., J.S. McConnell, S.J. McConnell, J.J. Varvil, R. Bagwell and N.P. Tugwell. 1994. The physical stability of insecticide mixed with foliar urea nitrogen and potassium nitrate fertilizers. Proc. 1993 Cotton Research Meeting and Research Summaries, Univ. of Arkansas, Ark. Agri. Exp. Stn., Special Report 162:56-61.
6. Barber, S.A. 1984. Soil Nutrient Bioavailability. A Mechanistic Approach. John Wiley, New York.
7. Bassett, D.M., W.D. Anderson, and C.H.E. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum* L.). Agron. J. 62:299-303.
8. Bednarz, C.W., and D.M. Oosterhuis. 1996. Partitioning of potassium in the cotton plant during the development of potassium deficiency. J. Plant Nutr. 19:1629-1638.
9. Bednarz, C.W., and D.M. Oosterhuis. 1995. Plant potassium partitioning during the progression of deficiency symptoms in cotton (*Gossypium hirsutum* L.). Better Crops with Plant Food, Potash & Phosphate Institute, Atlanta, Georgia. Vol 80(1):12-14.
10. Bennett, O.L., R.D. Rouse, D.A. Ashley, and B.D. Doss. 1965. Yield, fiber quality and potassium content of irrigated cotton plants as affected by rates of potassium. Agron. J. 57:296-299.
11. Beyrouty, C.A., J. Keino and D.M. Oosterhuis. 1995. Cotton root response to water management. p. 84-92. *In* Oosterhuis, D.M. (ed.). Proc. 1994 Cotton Research Meeting and Summaries of Cotton Research in Progress. Arkansas Agric. Exp. Stn. Univ. of Arkansas, Fayetteville. Special Report 166.
12. Blevins, D.G. 1985. Role of potassium in protein metabolism in plants. p. 413- 424. *In* Potassium in Agriculture. American Society of Agronomy, Madison, Wisconsin.
13. Bondada, B.R., D.M. Oosterhuis, and R.J. Norman. 1997. Cotton leaf age, epicuticular wax, and nitrogen-15 absorption. Crop Sci. 37:807-811.
14. Brouder, S.M. and K.G. Cassman. 1990. Root development of two cotton cultivars in relation to potassium uptake and plant growth in vermiculitic soil. Field Crops Research 23:187-203.
15. Brown, A.L., J. Quick, and G.J. DeBoer. 1973. Diagnosing potassium deficiency by soil analysis. California Agriculture 27:13-14.
16. Cappy, J.J. 1979. The rooting patterns of soybean and cotton throughout the growing season. Ph.D. Dissertation, University of Arkansas, Fayetteville.
17. Cassman, K.G., T.A. Kerby, B.A. Roberts, D.C. Bryant, and S.L. Higashi. 1990. Potassium nutrition effects on lint yield and fiber quality of Acala cotton. Crop Sci. 30:672-677.
18. Cassman, K.G., B.A. Roberts, T.A. Kerby, D.C. Bryant, and S.L. Higashi. 1989. Soil potassium balance and cumulative cotton response to annual potassium additions on a vermiculitic soil. Soil Sci. Soc. Am. J. 53:805-812.
19. Chang, M.A. and D.M. Oosterhuis. 1995. Response of cotton to foliar application of various potassium compounds at different pH levels. Better Crops with Plant Food. Phosphate & Potash Institute. Vol 79(2):20-21.
20. Chokey, S. and N.K. Jain. 1977. Critical growth stages of American rainfed cotton for foliar feeding of nitrogen. Indian J. of Agron. 22(2):87-89.
21. Cope, J.T., Jr. 1981. Effects of 50 years of fertilization with phosphorus and potassium on soil test levels and yields at locations. Soil Sci. Soc. Am. J. 45:342-347.
22. Davis-Carter, J.G., S.H. Baker, and S.C. Hodges. 1992. Potassium fertilization of irrigated cotton on sandy soils. p. 1147-1150. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
23. Dhindsa, R.S., C.A. Beasley, and I.P. Ting. 1975. Osmoregulation in cotton fiber. Plant Physiol. 56:394-398.
24. Edmisten, K.L., C.W. Wood, C.H. Burmester, and C.C. Mitchell. 1993. Foliar fertilization of seedling cotton. p. 1304-1305. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
25. Epstein, E. 1972. Mineral nutrition of plants: Principles and Perspectives. Wiley, New York.

26. Evans, H.J. and G.J. Sorger. 1966. Role of mineral elements with emphasis on univalent cations. Annual Review of Plant Physiol. 17:47-76.
27. Gerik, T.J., J.E. Morrison, and F.W. Chichester. 1987. Effects of controlled-traffic on soil physical properties and crop rooting. Agron. J. 79:434-438.
28. Gris, E. 1844. Nouvelles experiences sur l'action des composis ferrugineux solubles, appliques a la vegetation et specialment au traitement de la chlorose at a la debilite des plant. Compt. Rend. (Paris) 19:1118-1119.
29. Gulick, S.H., K.G. Cassman, and S.R. Grattan. 1989. Exploitation of soil potassium in layered profiles by root systems of cotton and barley. Soil Sci. Soc. Am. J. 53:146-153.
30. Hafez, A.A.R., P.R. Stout, and J.E. DeVay. 1975. Potassium uptake by cotton in relation to Verticillium wilt. Agron. J. 67:359-361.
31. Hake, K., K. Cassman, and W. Ebelhar. 1991. Cotton nutrition - N, P and K. Physiology Today. National Cotton Council, Memphis, TN. Vol. 2(3):1-4.
32. Halevy, J. 1976. Growth rate and nutrient uptake of two cotton cultivars grown under irrigation. Agron. J. 68:701-705.
33. Halevy, J. and T. Markovitz. 1988. Foliar NPKS application to cotton from full flowering to boll filling. Fertilizer Research 15:247-252.
34. Halevy, J., A. Marani, and T. Markovitz. 1987. Growth and NPK uptake of high-yielding cotton grown at different nitrogen levels in a permanent-plot experiment. Plant and Soil 103:39-44.
35. Hall, S.M. and D.A. Baker. 1972. The chemical composition of *Ricinus* phloem exudate. Planta 106:131-140.
36. Hearn, A.B. 1981. Cotton nutrition. Field Crop Abstracts. 34(1):11-34.
37. Hillocks, R.J. and R. Chinodya. 1989. The relationship between *Alternaria* leaf spot and potassium deficiency causing premature defoliation in cotton. Plant Path. 38:502-508.
38. Hoagland, D.R. 1944. Lectures on the inorganic nutrition of plants. Chronica Botanica. p. 48-71. Waltham, Massachusetts.
39. Hodges, S.C. 1992. Nutrient deficiency disorders. p. 355-403. *In* Herber, D.J. and D.A. Richter (eds.). Proc. Beltwide Cotton Conferences. National Cotton Council of America, Memphis, TN.
40. Hodges, S.C. and S. Baker. 1993. Correlation of plant sap extracts of nitrate-N and K with dried petiole extracts. p.1335-1337. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
41. Holman, E.M., D.M. Oosterhuis, and R.G. Hurren. 1992. Effect of foliar-applied N and K on vegetative cotton. Arkansas Farm Res. 41(1):4-5
42. Howard, D.D., P.E. Hoskinson, and P.W. Brawely. 1993. Evaluation of surfactants in foliar feeding cotton with potassium nitrate. Better Crops with Plant Food. 77(3):22-23, 1993. Potash & Phosphate Institute.
43. Hsu, H.H., J.D. Lancaster, and W.F. Jones. 1978. Potassium concentration in leaf-blades and petioles as affected by potassium fertilization and stage of maturity of cotton. Commun. in Soil Sci. and Plant Anal. 9:265-277.
44. Huber, S.C. 1985. Role of potassium in photosynthesis and respiration. p. 369-396. *In* Potassium in Agriculture. Am. Soc. Agron., Madison, WI.
45. Humble, G.D. and K. Raschke. 1971. Stomatal opening quantitatively related to potassium transport. Plant Physiol. 48:447-453.
46. Janes, L.D., D.M. Oosterhuis, F.M. Bourland, and C.S. Rothrock. 1993. Foliar-applied potassium nitrate effects on cotton genotypes. Arkansas Soil Fertility Studies 1992. Arkansas Agri. Exp. Stn., Research Series 425. p. 77-79.
47. Kafkafi, U. 1990. The functions of plant K in overcoming environmental stress situations. p.81-93.*In* Proceedings 22nd Colloquium, International Potash Institute, Bern, Switzerland.
48. Kafkafi, U. 1992. Foliar feeding of potassium nitrate in cotton. Better Crops with Plant Food. 76(2)16-17. *In* Proc. 22nd Colloquium, Potash & Phosphate Institute, Norcross, GA.
49. Kerby, T.A. and Adams, F. 1985. Potassium nutrition of cotton. p. 843-860. *In* Potassium in Agriculture. Am. Soc. Agron. Madison, WI.
50. Leffler, H.R. and B.S. Tubertini. 1976. Development of cotton fruit. II. Accumulation and distribution of mineral nutrients. Agron. J. 68:858-861.
51. Long, D.W., J.B. Graves, B.R. Leonard, E. Burris, L.M. Southwick, and D.C. Rester. 1991. Effects of co-application of urea solutions and insecticides on chemical deposition and biological activity. p. 762-768. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
52. Maples, R.L., J.L. Keogh and W.E. Sabbe. 1977. Nitrate monitoring for cotton production in Loring-Calloway silt loam. Arkansas Agri. Exp. Sta. Bulletin 825.
53. Maples, R.L., W.R. Thompson, and J. Varvil. 1988. Potassium deficiency in cotton takes on a new look. Better Crops with Plant Food 73(1):6-9. Potash & Phosphate Institute.
54. Marschner, H. 1988. Mineral nutrition of higher plants. Academic Press, London. p. 674.
55. Mascagni, H.J., T.C. Keisling, R.L. Maples, W.E. Sabbe, and P.W. Parker. 1992. Response of fast-fruiting cotton cultivars to nitrogen rate on a sandy soil. p. 1178. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
56. Mikkelsen, D.S., B.L. Wier, A. Abshai, and A. Hafez. 1988. Disease induced potassium deficiency in cotton. p. 514-516. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
57. Miley, W.N., D.M. Oosterhuis, and L.D. Janes. 1994. Effects of foliar application of five potassium fertilizers on cotton yield and quality. Arkansas Soil Fertility Studies 1993. Arkansas Agri. Exp. Sta., Research Series 436:62-66.
58. Minton, E.B. and M.W. Ebelhar. 1991. Potassium and aldicarb-disulfoton effects on Verticillium wilt, yield and quality of cotton. Crop Sci. 31:209-212.
59. Minton, E. 1988. Potassium improves cotton quality and disease resistance. Better Crops with Plant Food 73(1):10. Potash & Phosphate Institute.
60 Morse, S.G., J.P. O'Connor, and M. Zick. 1992. The efficacy of diagnostic tools as tissue testing, selective ion meters, and plant mapping to determine the need and timing of foliar K-Power applications. p. 1158-1161. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
61. Mullins, G.L., and C.H. Burmester. 1991. Dry matter, nitrogen, phosphorus, and potassium accumulation by four cotton varieties. Agron. J. 82:729-736.
62. Mullins, G.L., C.H. Burmester, D.W. Reeves. 1992. Cotton response to surface and deep placement of potassium fertilizer. p. 77-79. Proc. 1992 Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
63. Oosterhuis, D.M. 1976. Foliar application of fertilizer. p. 11-12. *In* Annual Report Cotton Research Institute 1974-75, Gatooma. Government Printer, Salisbury, Rhodesia.
64. Oosterhuis, D.M. 1992. Cotton yield enhancement using foliar-applied potassium nitrate and PGR-IV. Better Crops with Plant Food 77(1):10-11. Potash & Phosphate Institute.
65. Oosterhuis, D.M. 1994. Foliar fertilization with potassium shows potential. Fluid J. Summer 1994, p. 24-26.
66. Oosterhuis, D.M., R.E. Hampton, and S.D. Wullschleger. 1991. Water deficit effects on cotton leaf cuticle and the efficiency of defoliants. J. Agron. Prod. 4:260-265.
67. Oosterhuis, D.M. and L.D. Janes. 1994. Research on plant growth regulators. Proc. 1993 Cotton Research Meeting and Research Summaries, Univ. of Arkansas, Ark. Agri. Exp. Stn., Special Report 162:196-199.
68. Oosterhuis, D.M. and W.N. Miley. 1992. Foliar fertilization of cotton with potassium nitrate, Arkansas 1989-1991. Arkansas Fertility Studies. Univ. of Arkansas, Ark. Agri. Exp. Stn., Special Report 421:135-139.
69. Oosterhuis, D.M. and D. Zhao. 1993. Physiological effect of PGR-IV on growth and yield of cotton. p. 1270. *In* Herber, D.J. and D.A. Richter (eds.). Proc. Beltwide Cotton Conferences. National Cotton Council of America, Memphis, TN.
70. Oosterhuis, D.M., S.D. Wullschleger, R.L. Maples and W.N. Miley. 1990. Foliar feeding of potassium nitrate in cotton. Better Crops with Plant Food. 74(3):8-9. Potash &

Phosphate Institute.
71. Oosterhuis, D.M., R.G. Hurren, W.N. Miley, and R.L. Maples. 1991b. Foliar-fertilization of cotton with potassium nitrate. Proc. 1991 Cotton Research Meeting, Univ. of Arkansas, Ark. Agri. Exp. Stn., Special Report 149:21-25.
72. Oosterhuis, D.M., W.N. Miley, and L.D. Janes. 1993. A summary of foliar fertilization of cotton with potassium nitrate, Arkansas 1989-1992. Arkansas Fertility Studies. Univ. of Arkansas, Ark. Agri. Exp. Stn., Bulletin 425:97-100.
73. Oosterhuis, D.M., D. Albers, W.H. Baker, C. Burmester, J.T. Cothren, M.W. Ebelhar, D.S. Guthrie, M.G. Hickey, S.C. Hodges, D.D. Howard, L.D. Janes, G. Mullins, B.A. Roberts, J. Silvertooth, P. Tracy and B. Weir. 1993. A summary of a Beltwide study of soil and foliar potassium fertilization with potassium nitrate in cotton. Proc. Beltwide Cotton Conferences, National Cotton Council, Memphis, TN. p. 1351.
74. Pettiet, J.V. 1993. Potassium chloride as a source of foliar fertilizer. p. 1307-1309. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
75. Pettigrew, W.T., J.J. Heitholt, and W.R. Meredith, Jr. 1992. Potassium and nitrogen fertilization effects on cotton dry matter allocation and yield. Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN. p. 1071.
76. Rader, L.F., L.M. White, and C.W. Whittaker. 1943. The salt index: a measure of the effects of fertilizer on the concentration of the soil solution. Soil Sci. 55:201.
77. Rimon, D. 1989. Functions of potassium in improving fiber quality of cotton. p. 319-323. *In* Methods of potassium research in plants. Proc. 21st Colloquium, Potash and Phosphate Institute,
78. Roberts, B.A. 1992. Surface applications of potassium. p. 80-82. Proc. 1992 Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
79. Roberts, B.A., T.A. Kerby, and B.L. Weir. 1993. Foliar fertilization of cotton in California. p.64-76. *In* L.S. Murphy (ed.). Foliar Fertilization of Soybeans and Cotton. Special publication 1993-1. Potash & Phosphate Institute and Foundation for Agronomic Research, Norcross, GA.
80. Rosolem, C.A. and D.S. Mikkelsen. 1991. Potassium absorption and partitioning in cotton as affected by periods of potassium deficiency. J. Plant Nutr. 14:1001-1016.
81. Sabbe, W.E. and L.J. Zelinski. 1990. Plant analysis as an aid in fertilizing cotton. p.469-493. *In* Soil Testing and Plant Analysis. 3rd edition. Soil Sci. Soc. Am. Book Series, No. 3.
82. Sasser, P.E. 1991. The future of cotton quality: Trends and implications — Fiber quality measurements. p. 68-70. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
83. Singh, D., M.S. Brar, and A.S. Brar. 1992. Critical concentrations of potassium in cotton (*Gossypium hirsutum*). J. Agri. Sci. (Camb.) 118:71-75.
84. Snyder, C.S., W.N. Miley, D.M. Oosterhuis, and R.L. Maples. 1991. Foliar application of potassium to cotton. University of Arkansas, Coop. Ext. Serv. Cotton Comments. 4-91.
85. Sprague, H.B. 1964. Hunger Signs in Crops. A Symposium. David McKay Co., New York.
86. Stromberg, L.K. 1960. Potassium fertilizer on cotton. Calif. Agri. 14(4):4-5.
87. Thorne, G. 1957. The effect of applying a nutrient in leaf sprays on the absorption of the same nutrient by the roots. J. Exp. Bot. 8(24).
88. Tupper, G.R. and H.C Pringle, and M.W. Ebelhar. 1988. Cotton response to deep banding dry fertilizer in the subsoil. p. 498-501. Proc. 1992 Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
89. Urwiler, M., C. Stutte, S. Jourdan, T. Clark. 1987. Bioregulant field evaluations of agronomic crops. University of Arkansas, Agri. Exp. Stn. Research Series 358:30.
90. Wakeman, R.J., B.L. Weir, E.J. Paplomatas, and J.E. DeVay. 1993. Association of foliar symptoms of potassium deficiency in cotton (*Gossypium hirsutum*) with infection by *Verticillium dahliae*. p. 213-215. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
91. Weir, B.L., T.A. Kerby, B.A. Roberts, D.S. Mikkelsen, and R.H. Garber. 1986. Potassium deficiency syndrome of cotton. Calif. Agri. 40(5-6):13-14.
92. Weir, B.L. and B.A. Roberts. 1993. Nitrogen and potassium fertilization. California Cotton Rev. May 1993. p. 12-13.
93. Weir, B.L., B.A. Roberts, and T.A. Kerby. 1992. Effects of foliar N and K on cotton petiole levels and lint yields. p. 1162-1163. *In* Proc. Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.
94. White, C.C. 1991. Contrasting patterns of boll development in relation to potassium supply in two contrasting cultivars of Acala cotton. M.S. Thesis, University of California, Davis.
95. Wolf, D.D., E.L. Kimbrough, and R.E. Blaser. 1976. Photosynthetic efficiency in alfalfa with increasing potassium nutrition. Crop Sci. 16:292-294.
96. Xi, S., R. Lihua, Z. Yongsong, T. Qizhao, and Q. Lianxiang. 1989. Effect of potassium fertilizer application on physiological parameters and yield of cotton grown on a potassium deficient soil. Z. Pflanzenenerndhr. Bodenk. 152:269-272.
97. Zhao, D. and D.M. Oosterhuis. 1998. Influence of shade on mineral nutrient status of field-grown cotton. J. Plant Nutr. 21:1681-1695.
98. Zhu, B. 1989. The absorption and translocation of foliar-applied nitrogen in cotton. Ph.D. Dissertation. University of Arkansas, Fayetteville.