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Potassium Nutrition of Cotton

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Introduction

Knowledge of potassium (K) requirements for cotton growth and development is needed for efficient production. It makes little sense to limit production and profitability with late-season K starvation. However, late-season K deficiency symptoms can be found routinely in cotton throughout the U.S. Midsouth. Many modern varieties flower early and require a readily available supply of nutrients during the fruiting period. Approximately two-thirds of the total K uptake occur during a 6-week period beginning at early flowering.

As site-specific agriculture becomes more widely practiced, there will be greater interest in understanding why certain areas produce less than others. It is well known that high yields require good growing conditions. Knowing the plant nutrient requirements needed to sustain highly productive growth throughout the season will be essential to managing the crop for overall greater productivity.

Fertilization of cotton with K is a rather complex issue, because soils vary widely in terms of K-supplying capacity and K fertilizer adsorption. Potassium exists as a constituent of some primary minerals from which many soils were originally formed. It is a part of the interlayer of clay minerals such as hydrous mica, and it may become available due to freezing and thawing or wetting and drying. Potassium dissolved in soil solution is in equilibrium with K^+ attached or bound electrostatically to organic matter and the surface of clay particles. Thus, only a portion of total soil K is soluble, in an exchangeable form, and readily available to plant roots. However, at other times K held in a nonexchangeable form in soil minerals can become exchangeable. When K fertilizer is applied to soil, some fertilizer may be bound or trapped within soil minerals so that part of it is either not available or slowly available to plants. Routine soil tests primarily account for exchangeable and soluble K forms.

Potassium concentrations in cotton leaves are highly correlated with extractable soil K (Hsu 1976). If K is readily available to the roots, it accumulates in cotton leaves and other plant parts. This trait allows the crop to “bank” a small portion of its total seasonal K requirement during vegetative growth and use these reserves later in the growing season when nutrient requirements are high or uptake by roots cannot keep up with growth needs.

Plant tissue analyses have been used to diagnose the nutrient status of plants and to guide fertilizer recommendations. The use of chemical analysis of plant material for diagnostic purposes in farmer fields is based on the assumption that causal relationships exist between crop growth rates and nutrient concentrations. The results presented in Figure 1 support and reinforce this assumption.

To improve plant tissue analysis as an aid in making fertilizer recommendations or diagnosing plant nutrient status, the relationship between plant nutrient composition and crop yield needs to be better defined. The relationship between plant nutrient status and soil test K levels is also useful information. Often, however, the correlation between plant nutrient status and yield is relatively low because many other factors can limit crop yields (Adeli 1994). This fact could diminish growers’ enthusiasm for tissue analysis. Unless a crop has adequate nutrients, yield can be limited and much of the other crop-production expenses will be wasted. In an attempt to diagnose spatial variability in yields, the crop nutrient status should be determined and deficiencies eliminated.

This bulletin has four main goals: (1) to show the effects of leaf K concentrations on plant-growth-related processes; (2) to show and describe leaf K deficiency symptoms in the absence of other nutritional, water, or disease stresses; (3) to discuss the relationship between leaf K concentrations and root uptake; and (4) to discuss tissue sampling for K analysis.

Materials and Methods

We conducted an experiment in which all the known factors limiting cotton growth were eliminated. The *Bt*-resistant cotton variety, DP NuCOTN 33B, was grown in a medium-fine sand, and plants were watered with a half-strength nutrient solution three times per day (Hewitt 1952). The plants were grown under natural solar radiation conditions in temperature-, water-, and nutrient-controlled growth chambers at the optimum temperature for growth, 86°F (day) and 72°F (night). All other essential nutrients (those known to be beneficial) were supplied in a nutrient solution. The plants were grown under these optimum conditions until first square. At that stage, the solution was changed to provide varying amounts of K. Removing or reducing K from the nutrient solution resulted in dilution of K in the plant tissues because of subsequent growth.

Leaf K concentration from the recently fully expanded topmost leaves was measured weekly and interpolated so that actual K in the leaves was estimated on a daily basis. As the concentration of K in the plant tissues changed, the growth rates of leaves and stems were measured. Also, photosynthesis was measured throughout each day, and the rate was related to the K concentration of the leaves. The data collected in this manner provided information on the rate of various production-related processes, including leaf and stem growth, leaf addition rate, and photosynthesis, as functions of leaf K concentration when other growth-limiting factors were kept at an optimum. This is a very sensitive methodology to measure cotton responses to K, because other growth-limiting factors were eliminated. Pictures were taken of plants and individual leaves at various stages of K deprivation.

In a concurrent study, cotton plants were grown outdoors in 26-inch-deep pots containing sand and were watered three times per day with a nutrient solution containing all the essential nutrients for plant growth. At first square, one set of plants was deprived of K. Two sets of plants were allowed to grow with full nutrients until almost first flower and then deprived of K for either 12 days or 29 days. Following those periods of K deprivation, the full-strength solution was restored to the plants. As in the first experiment, the plants received all of the other essential nutrients and water, so that only K was deficient during the period of K deprivation. This experiment provided K to plants that were in varying stages of K deficiency, therefore providing information on recovery from deficient conditions.

The information provided by these studies should be particularly useful to those who are attempting to diagnose the reasons for crops not performing as well as expected. Fields in which yields are being monitored will have considerable variability, and the reasons for the variability often will not be apparent. Leaf K content is one factor that should be checked as a yield-limiting variable. Soil fertility status is important, but soil test results may not provide all the needed answers because of the interaction of K availability and other factors limiting the plant's ability to take up the nutrient. Tissue analysis reflects an integration of all factors influencing growth and nutrient uptake.

Results

A Closer Look at Potassium Deficiency Symptoms in Cotton

When K was withheld from the nutrient solution after first square, the plants continued to grow but at a progressively slower rate (Figure 1). The leaf K concentration became progressively lower as K content was diluted by production of dry matter. As K became more limiting, much of the K in older leaves was translocated to younger actively growing structures, but even with this reuse of K, it became limiting within a few days. The old leaves remained green and appeared healthy, but measurements of photosynthesis on individual leaves showed that older leaves with much of the K removed were essentially nonfunctional. Older leaves expressing deficiency symptoms were produced with inadequate available K. If leaves were produced in an adequate-K environment, they apparently did not develop deficiency symptoms even though most of the K was subsequently translocated out of those mature leaves. This finding illustrates the widely held view that "hidden hunger" can indeed be a production problem. Marginal K concentration in the upper leaves is hardly detectable by visual symptoms.

The crop needs to have high K concentrations in its leaves early in the season, because having only sufficient K at that time could result in shortages during boll formation. Later in the season, it is difficult to maintain adequate K in the leaves because of the heavy requirements for boll growth. Plant development at this stage is also

Figure 1. Potassium Nutrition and Cotton Growth - Appearance of cotton leaf K deficiency symptoms, related K levels, and the relative rates of growth or development expressed as a percentage of optimum K (≥ 3%) in the leaves.

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
≥ 3.05%	100%	100%	100%	100%

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
1.9%	90%	86%	100%	93%

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
1.15%	88%	66%	100%	85%

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
0.94%	85%	59%	98%	80%

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
0.39%	83%	37%	42%	45%

Leaf K content	Leaf development	Leaf growth	Stem growth	Photosynthesis
0.30%	82%	32%	5%	25%

complicated by limited root growth relative to the size of the total plant (Figure 2). As cotton plants age, the ratio of roots to above-ground parts decreases. This ratio appears to continue after flowering and contributes to the difficulty associated with meeting K uptake needs during the fruiting period. Other studies have found that most nutrients are absorbed by young, recently formed roots. As roots age, they become more coarse, heavily suberized, and lignified. Highly functional roots must continuously grow new absorbing surfaces, but during the boll-producing period, root growth slows and nutrient absorption cannot keep up with the demands.

Figure 1 shows the appearance of cotton leaves, the percent K in those leaves, and the relative rate of growth or development functions expressed as percentages of the maximum rates attainable. As leaves on plants developed in low-K media, their appearance was influenced by their K content. Progressively more K-deficient leaves have the following symptoms:

(1) Early evidence of K deficiency was a downward curling or cupping of the upper leaves;

(2) This symptom was followed by mild mottling and eventually a severe interveinal chlorosis. It should be noted that these symptoms appeared in the absence of disease organisms or deficiencies of other nutrients;

(3) Necrotic areas at the margins of the leaves did not appear until the plants were in an extremely low-K condition for an extended period; and

(4) Severely deficient cotton leaves without disease have nearly yellow interveinal areas with pale-green veins. The margins are often brown. Diseases did not appear because these plants were isolated, but plants grown on similarly low-K media in the natural environment abscised most of their leaves because of foliar diseases. Potassium deficiency symptoms may be confounded with disease symptoms of various kinds because K-deficient plants have increased susceptibility to infection by microorganisms.

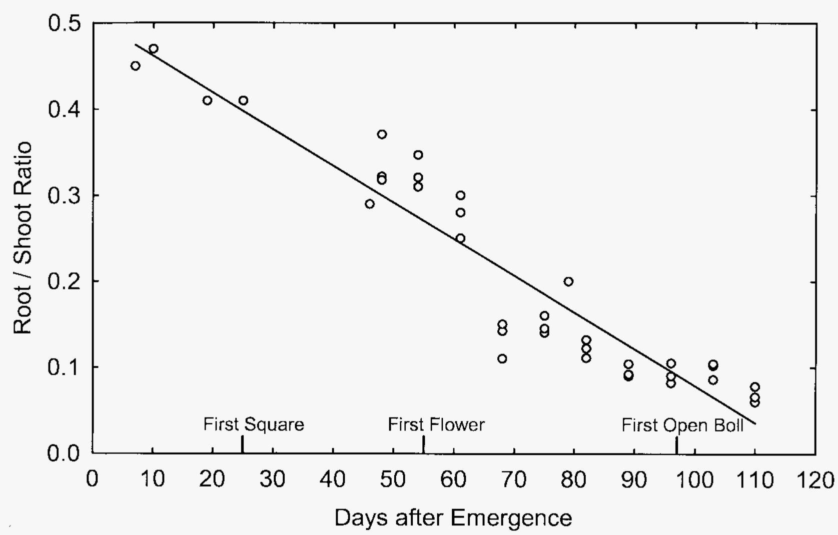

Figure 2. Seasonal trends in root:shoot ratio of cotton. Vertical lines indicate the beginning of squaring, flowering, and boll opening from left to right, respectively, for plants grown outdoors in large pots.

Potassium Effects on Physiology and Growth

The rate of leaf area expansion is reduced by K deficiency. The rate of leaf area expansion increases with increasing leaf K concentration to a maximum that occurs at about 3% K (Figures 1 and 3). Although higher concentrations of leaf K were observed in some conditions, there was no additional advantage as far as leaf area expansion rate was concerned. In a production environment, there may be some advantage in early or mid-season accumulation of K in plant tissue since it is mobile and can be utilized later in the season to support additional growth if drought interferes with absorption. Although the total amount of K that can be stored in this way is relatively small, the available K in the plant could provide a buffer during stress periods.

Leaf growth rates were 14% lower in plants that had only 1.9% K in the leaves compared to fully fertilized plants with 3% K in the leaves. Leaf expansion rates declined even more as K concentration decreased and were only 59% as great in plants that had approximately 1% leaf K.

The rate of photosynthesis was 7% less in cotton plants that had 1.9% leaf K compared with well-fertilized plants (Figures 1 and 3). Plants with 1.9% leaf K looked as healthy as plants containing more K. It has long been assumed that 2% leaf K concentration in plants was sufficient; however, this information suggests that this concentration is marginal. Both canopy photosynthesis and leaf growth were lower in plants with 1.9% leaf K compared with plants with higher concentrations of K. The young, fully expanded leaves that had only 1% K had

20% lower canopy photosynthesis rates relative to the well-fertilized plants (Figure 3). Research in Arkansas found seedling cotton leaves had maximum photosynthesis with approximately 1% K (Oosterhuis and Bednarz 1997). They measured photosynthesis of individual leaves, whereas we measured photosynthesis of plants in a closed canopy.

The rates at which main stem leaves and nodes were added were less in plants with lower K concentrations (Figure 1). Leaves were added to the main stem only 90% as fast in plants whose sampled leaves contained 1.9% K compared with plants with higher K concentrations. Cotton leaf area expansion and development, however, are very sensitive to temperature when water and nutrients are not limiting (Hodges et al. 1993; Reddy et al. 1996). This small difference in association with lower K concentration would not be detected in most field situations, which is another example of plants' "hidden hunger" being masked by other environmental factors.

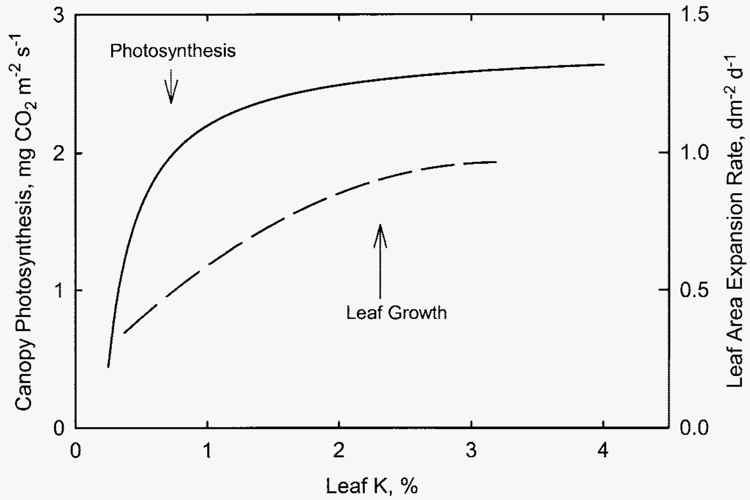

Figure 3. Cotton canopy net photosynthesis and leaf area expansion as a function of leaf K concentration. Plants were grown in optimum day/night (86/72°F) temperatures in a range of K-deficient conditions but with sufficient water and other macro and micro nutrients. Potassium was determined in the uppermost fully expanded leaves.

Other research has found that in well-fertilized fields that were not irrigated, the K concentration of cotton leaves increased until about 3 weeks after flowering, then declined rapidly (Hsu 1976). However, irrigated cotton that was well-fertilized did not show a decline in leaf K concentration throughout the fruiting period (Bennett et al. 1965). We observed a similar phenomenon in a well-fertilized crop grown with optimum nutrient solutions. In crops exposed to drought, K nutrition during the fruiting period is apparently closely linked to water supply. Potassium uptake is associated with total root length and root growth rates. During the fruiting period, there is severe competition between roots and the increasing boll load for both K and photosynthates. If water supply becomes limited during that period, the uptake of K is insufficient to meet fruit-load needs. This deficit causes a withdrawal of K from leaves and a related slowing of growth processes.

In a non-limiting nutrient solution environment, K concentration in the leaves remained stable during growth even to maturity. This finding was true even with a large population of bolls on all the plants. However, under field conditions in which dry soil is sometimes a problem, the K concentration in leaves changes during the season. When leaf concentrations of potassium are low during dry conditions, interpretation of fertility needs becomes more complicated; it is unclear whether low leaf K is caused by low soil K or drought. According to Hsu (1979), field-grown cotton leaf K concentrations increased with age until 3 weeks after flowering began. At that time, the nutritional requirements of the bolls exceeded the ability of the plants to take up nutrients, causing the leaf K concentration to decrease. Presumably, this phenomenon was caused by a combination of less available water and the fact that there were fewer fine roots to support the above-ground plant. As the boll load increased, there were fewer energy-bearing compounds available to support growth of new roots capable of taking up the nutrients needed.

The relative amount of roots compared with the whole plant weight decreases throughout the season (Figure 2). As K becomes limiting, its concentration in the mature leaves (both old and young) decreases. The K concentration in the immature leaves follows the same trend. One possible cause for this trend was seen in our solution-culture-grown plants when K was not provided. In those plants, when uptake was low, K was removed from the leaves to support growth, causing leaf concentration to decline.

Lower leaf K concentration affects several physiological processes (Figures 2 and 3). At the time mineral nutrients are being depleted in the leaves, the need for photosynthetically produced sugar is also reaching a peak for the same reason: energy is needed to support fruit growth. Additional flowers and bolls require both minerals and sugars. As their requirements exceed the supply, less K is available to support growth and functioning of roots. Healthy root cell membranes are effective barriers to nutrient passage, and therefore energy is also required for K uptake. Thus, energy provided by the respiration of sugars is essential for K movement from the soil into the root.

As rapidly growing cotton plants develop more bolls, it becomes progressively more difficult to support their growth. The reproductive parts appear to have a higher priority for available carbon and other nutrient resources. They survive at the expense of roots and other vegetative plant parts. Stem growth becomes incrementally slower. The addition of new leaves slows, and the leaves also become progressively smaller due to the lack of nutrients (both minerals and sugar). This process is a natural maturing of cotton known as “cutout.” The cutout occurs earlier when nutrients or water is limiting, causing fewer young bolls to survive. Excessively hot weather also compounds nutrient-deficit problems in cotton. Hot weather causes bolls to form faster, which causes cutout to occur earlier. Higher temperatures also increase respiration, which requires the plant to consume even more energy. However, excessively hot weather causes young bolls to drop because of high-temperature injury, and the available energy may go into producing vegetative growth.

To determine the potential dynamics of K concentration in cotton plants, we also grew plants outdoors in sand with nutrient solution added daily. These studies showed that increasing K concentration above the amount that resulted in additional growth caused increased concentration of K in the leaves (Figure 4). This phenomenon is called “luxury consumption.” When K was withheld from the solution, the K concentration in the leaves decreased in relation to the degree and length of time of K starvation. If K was completely removed from the solution, the K concentration in the leaves decreased to 30% of the well-fertilized status within 10 days. If the starvation was continued for 29 days, the leaf K concentration decreased to only 17% of the well-fertilized condition. When K was restored to the nutrient media, the plants required about the same time to recover (10 or 29 days) as they did to deplete K in the starved environment (Figure 4). This finding suggests that if plants have a marginal K nutritional status and the growing conditions become worse, an immediate management action such as irrigation is needed.

These findings illustrate the need for timely tissue sampling for K analysis and the appropriate interpretation of the results. Our opinion is that leaves should be checked for K concentration at the beginning of flowering. Young mature leaves may require as much as 3% K at that time. This amount is higher than the critical values stated elsewhere in this bulletin (2.1% for photosynthesis and 2.5% for leaf growth), but 3% is considered a more reasonable value to have at flowering, because leaf K concentration decreases with age and boll growth. Oosterhuis (1993), extracting results from several published sources, reported petiole K concentrations decreased from 4% at first flower to 3% at peak flowering, 2% at first open boll, and 1% just before harvest. These petiole values are equivalent to only 1.38% leaf K at first flower, 0.99% at peak flowering, 0.71% at first open boll, and 0.56% at harvest calculated from the relationships shown in Figure 6. Obviously, metabolic rates at these lower values will be seriously limited by K late in the season. If plants are sufficiently well-fertilized and well-irrigated, they will not go through “cutout” unless insufficient sugar is available to support all the possible growth.

Potassium-deficient plants sometimes die prematurely, because they are more susceptible to diseases and nematodes. Inadequate K also limits growth, which may cause early “cutout” and give the appearance of early maturity. We determined the length of time required from flowering to open bolls and found no delays caused by high-K nutrition. However, plants grown under high-K nutrition continue to produce flowers and set bolls over a longer period, requiring more time to mature all the bolls.

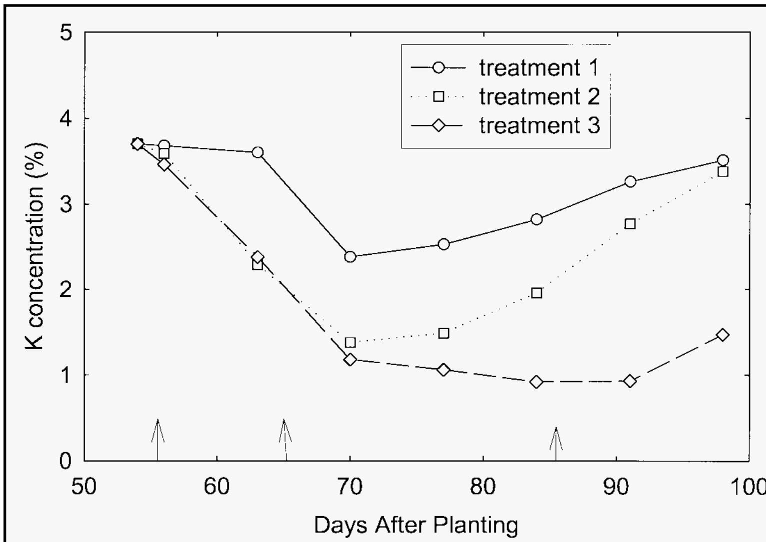

Figure 4. Influence of potassium nutrition on leaf K concentrations for plants grown in pots outdoors. The plants were grown in optimum water and nutrient solution culture up to flowering, and then potassium from the nutrient solution was withdrawn at various stages. The arrow on the left indicates the beginning of K starvation for treatments 2 and 3. The arrows at the middle and at the right indicate the restoration of K to normal nutrient solution for treatments 2 and 3, respectively.

Leaf K and Cotton Yields

Bennett et al. (1965) reported on a study in which cotton was grown with irrigation and six levels of K fertilization. The land had been subsoiled, fumigated to control nematodes, and fertilized with other elements to avoid deficiencies. Cotton was seeded early, sampled for K at approximately first flowering and 30 days after first flowering, and hand picked in early September. They found a close relationship between whole-plant K and yield (Figure 5). Even with the high yields (four bales), they reported severe K deficiency symptoms in leaves containing less than 1.5% K. Their results are very consistent with the responses we observed between leaf K and photosynthesis (Figure 3).

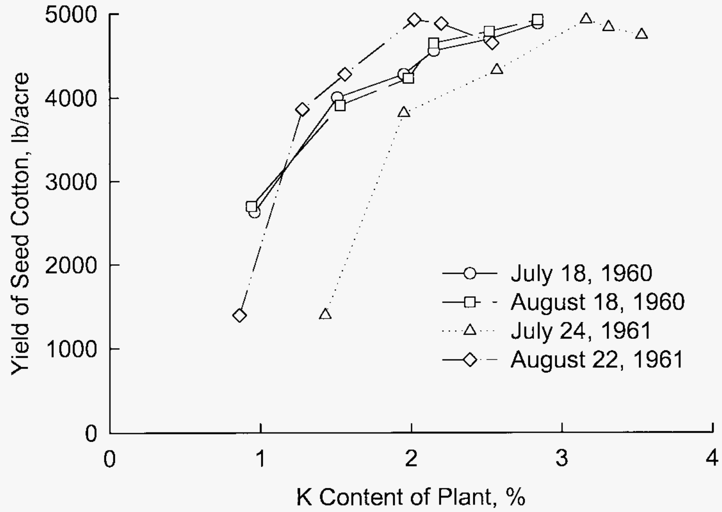

Figure 5. Relation between yield and potassium content of above-ground cotton plants (redrawn from Bennett et al. 1965).

When and What Plant Parts to Sample

Since plant structures vary in the amounts of K they contain, selecting an appropriate tissue for analysis is an important issue. Generally, young mature leaves have higher K concentrations than old leaves or leaves that are still growing. As plants grow and the amount of roots relative to above-ground parts decreases, the percentage of K in the above-ground parts increases. If the available K is high, the concentration in above-ground parts may remain about constant as plants age. The interpretation of plant analysis results depends on both the time of testing the samples and the parts analyzed.

Since the leaf blades are so important to light interception and dry matter production, we concluded that leaf nutritional status and function are of primary concern. Therefore, young mature leaves near the top of the plant should be sampled to represent the nutritional health of the crop. The fourth or fifth leaf from the main stem terminal is usually the youngest fully expanded leaf, is physiologically the most active leaf, and is therefore the appropriate leaf to sample. Main stem leaves reach full size after about 16 days (the time required for four to five additional leaves to be added from the main stem).

This conclusion is also in agreement with many other research reports, but it does conflict with the conventional wisdom. Previous research showed that leaf petioles have higher concentrations of K than leaf blades and that they have the widest range of K concentration of any structures (Hsu 1979). Based on this finding, many people use petiole samples to determine the K nutritional status of their crops. Petioles function as a nutrient conduit and apparently temporarily store small amounts of K. Indeed, there is a close correlation between leaf petiole K and leaf blade K concentrations (Figure 6). Potassium concentration in young mature leaves has been shown to decrease earlier than in old leaves in K-deficient, field-grown plants (Hsu 1979).

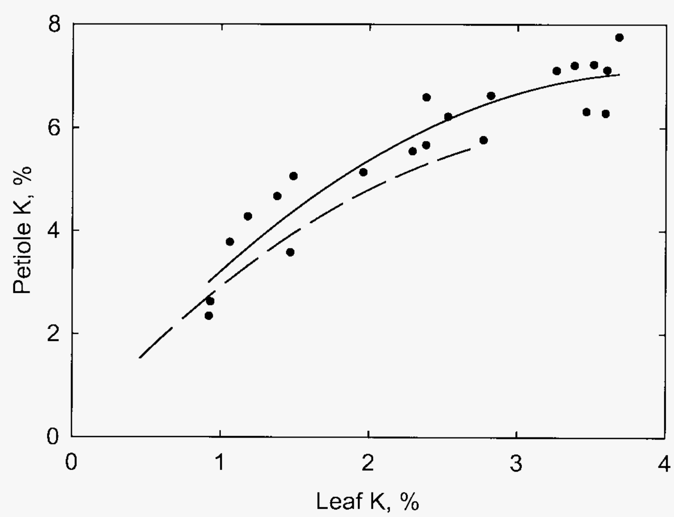

Figure 6. The relationship between cotton leaf blade K concentration and leaf petiole K concentration. The solid line represents data collected from plants grown in nutrient solutions ($y = 0.174 + 3.476 * X - 0.437 * X^2$, $r^2 = 0.89$). The broken line represents 372 data points from 57 locations in 2 years of field-grown plants ($y = 0.149 + 3.1974 * X - 0.434 * X^2$, $r^2 = 0.61$, Hsu, 1979). The field data points are not shown to avoid complexity of presentation.

Is a Chlorophyll Meter Right for Detecting K Deficiency?

Thurow (1997) points out that the lack of "on-the-go" soil sensors for nutrient management remains an important void in precision agriculture. New electronic field diagnostic tools are being developed for use in nutrient management, but there is no substitute for a knowledgeable person to scout fields for crop health. The chlorophyll meter (SPAD-502) was developed by Minolta Company as a tool to manage N status of crops. Several researchers found a strong correlation between the meter's leaf chlorophyll measurements and leaf N content. We compared SPAD readings on plants varying widely in K content (Figure 7) and found the SPAD meter readings are not sufficiently sensitive to detect K deficiency symptoms in cotton. This instrument detects differences only when leaf K concentrations are below 1%. At that concentration, it is too late to correct the problem. A person can visually detect the nutritional problem before the leaves reach such a low concentration.

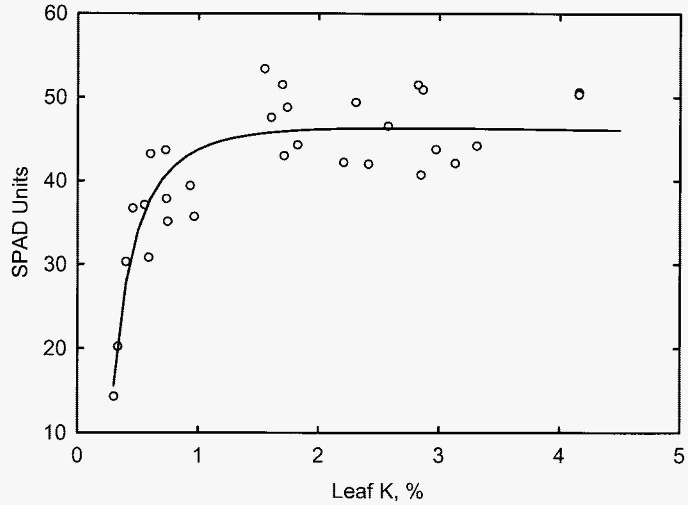

Figure 7. The relationship between SPAD readings and leaf K concentrations for plants grown in optimum day/night temperatures and at a range of potassium-deficient conditions.

Potassium Deficiency and Diseases

High yield and quality of cotton requires healthy vigorous plants throughout the season. Several investigators have reported an association of K deficiency symptoms and the incidence of verticillium wilt (Adeli 1994 and references cited therein). Cassman (1994) points out that the symptoms caused by K deficiency are sometimes mistakenly attributed to verticillium wilt. He believes the two symptoms are distinct and identifiable. Potassium deficiency symptoms are often recognized as bronze-colored leaves with necrosis occurring along the margins without a clear border (Figure 1). Conversely, verticillium wilt causes necrotic lesions with well-defined borders and rich brown color between leaf veins. Also, when the stems are split open with a knife, brown staining of the interior xylem indicates verticillium wilt. Broadcasting K fertilizer reduced verticillium wilt symptoms in one Mississippi Delta study. In our enclosed chambers, we did not find any disease symptoms even on severely K-deficient plants (Figure 1). Plants with similar K levels grown outdoors, however, prematurely lost all of their leaves due to foliar disease.

Summary and Conclusions

Potassium deficiency symptoms of cotton are often seen late in the growing season. It is well known that yield responses to other agronomic inputs are limited if any essential nutrient is insufficient. Since K is required by cotton in relatively large quantities and deficiency symptoms are common, a clear definition of crop sensitivity to tissue K concentration seems important. Also, as we become more concerned with identifying reasons for lower production in certain areas of a field, we will need to know if K is a limiting factor.

Recent advances in remote spectral imaging of crops should improve our capability for mapping K-deficient areas within fields. This information may be coupled with variable rate fertilizer applications to increase precision in fertilization. This study defined physiological processes as a function of leaf K concentration when other production factors were not limiting.

It is reasonable to expect crop productivity to closely reflect an integrated status of the various processes during the growing season. Reporting yield data directly from this study seems inappropriate, because the treatment area was small and the experiment was canceled before many healthy bolls reached maturity. However, in both experiments, boll parameters (size, seed, and lint weight per boll), boll numbers, boll weight per plant, and percent boll retention were closely related to the K nutrition treatments (data not shown). Therefore, it seems reasonable to interpret the vigor of the physiological processes and growth parameters directly influenced by leaf K concentration to yield. We reached the following conclusions:

- Growth processes are limited when leaf K concentrations are below 2%, and visual symptoms of K deficiencies are difficult to identify. Critical foliar K concentration required for optimum photosynthesis, and thus the productivity of cotton (95% of the maximum), is 2.1%. Several processes are severely affected below that critical foliar K level.

- Early evidence of K deficiency is a downward cupping of the upper leaves and a mild mottling of those leaves.

- Leaf growth is the most sensitive physiological process to K-deficient conditions, and it increased as foliar K increased up to 3%. However, 2.5% is the critical foliar K concentration, a requirement for optimum leaf growth and thus canopy development (95% of the maximum).

- The most practical way to avoid K deficiency is to provide adequate fertilizer to the soil. Only small amounts can be supplied by foliar feeding. Foliar feeding is essentially a stop-gap procedure that may be used in an emergency.

- Potassium-deficient plants are more susceptible to plant diseases and symptoms may be readily confused.

Acknowledgements

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