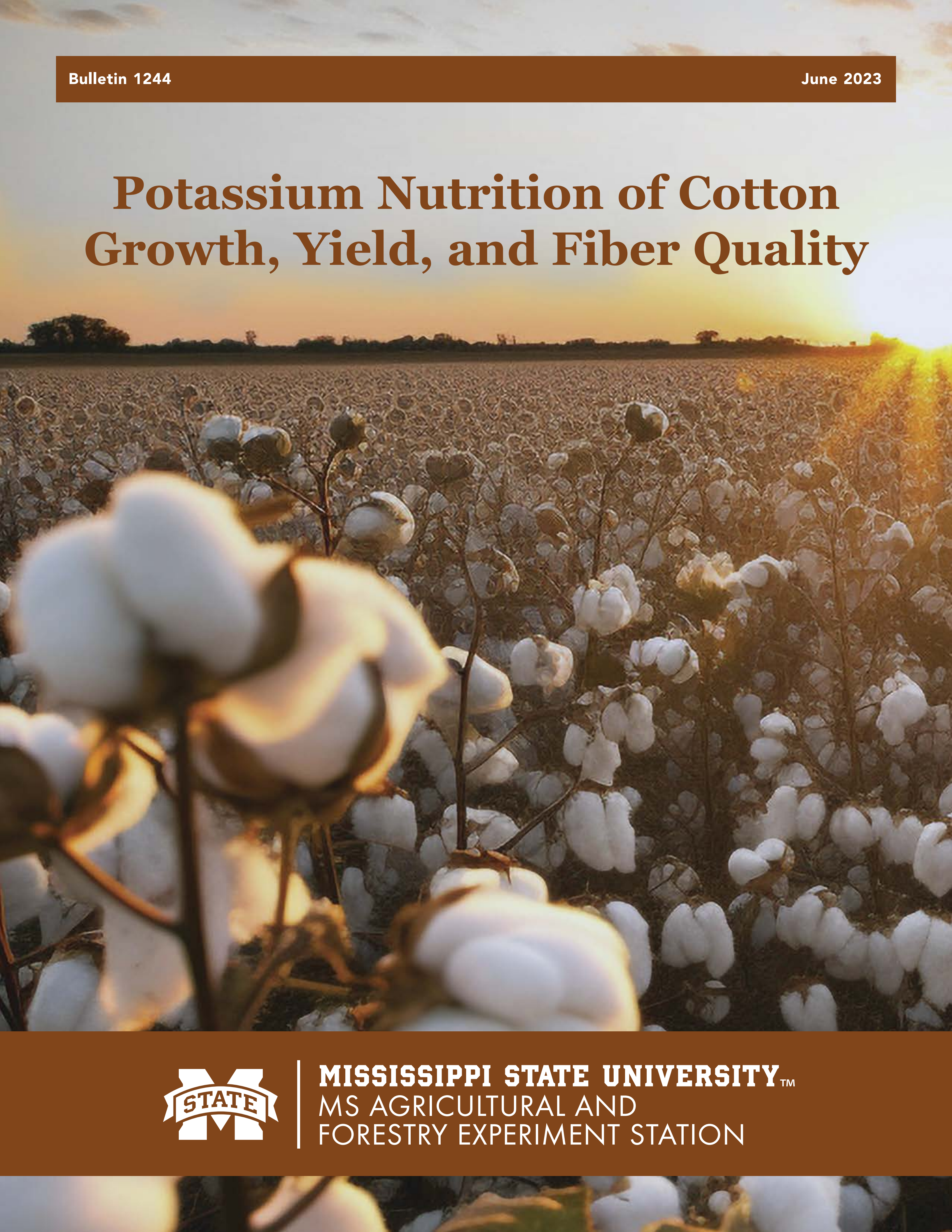
Bulletin 1244 June 2023

Potassium Nutrition of Cotton Growth, Yield, and Fiber Quality



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Potassium Nutrition of Cotton Growth, Yield, and Fiber Quality

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This document was approved for publication as Bulletin 1244 of the Mississippi Agricultural and Forestry Experiment Station. It was published by the Office of Agricultural Communications, a unit of the Mississippi State University Division of Agriculture, Forestry, and Veterinary Medicine.

Bulletin 1244 is a revision of Bulletin 1094, *Potassium Nutrition of Cotton*, which was published in March 2000.

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INTRODUCTION

A greater understanding of potassium (K) requirements and factors influencing supply for growth and development is needed for efficient production. Insufficient K supply can limit yield and fiber quality of a high value and costly crop to produce resulting in a decline in the return on investment. However, late-season K deficiency symptoms can be found routinely in cotton throughout the 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 commonly occurs during a 6-week period beginning at early flowering.

With the continued adoption of precision-agriculture practices, more effort has been devoted understanding why crop yield varies spatially across fields. It is well known that high yields require good growing conditions. Knowing specific plant nutrient requirements needed to sustain highly productive growth throughout the season is essential to managing and sustaining high levels of crop productivity.

Fertilizing cotton with K is a rather complex issue because soils vary widely in their K supplying capacity and absorption of K fertilizer. Potassium is a constituent of some primary minerals from which many soils 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. A portion of the K comes into equilibrium with soil water and is often attached or bound elctrostatically to organic matter and the surfaces of clay particles. When K fertilizer is applied to soil, a portion of the fertilizer may be bound or trapped in or on the mineral so that only a portion of it is either unavailable or slowly available to plants. Thus, K-bearing minerals maintain only a portion of their K in an exchangeable form that can be absorbed by plant roots, but which may at other times be held in a non-exchangeable form by the mineral. Routine soil tests primarily account for soluble and exchangeable K forms and not mineral or non-exchangeable forms.

Potassium concentration in cotton leaves is highly correlated with extractable soil K (Hsu, 1976). It will accumulate in cotton leaves and other plant parts above the concentration at which any measurable responses can be found. This trait allows the crop to "bank" a small portion of its total seasonal K requirement during vegetative growth. It uses that deposit later in the growing season when nutrient requirements are high or its uptake by roots cannot keep up with growing needs.

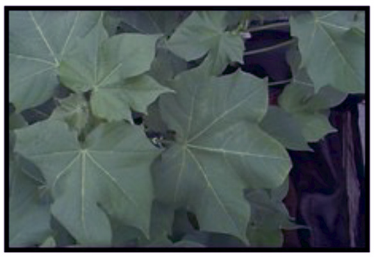
Plant tissue analyses have been used to diagnose plants' nutrient status and guide fertilizer recommendations. The use of chemical analysis of plant material for diagnostic purposes in farmer fields assumes that causal relationships exist between crop growth rates and tissue nutrient concentrations.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

The utility of plant tissue analysis as a useful aid in making fertilizer recommendations or diagnosing plant nutrient status, requires a thorough understanding of the relationship between plant nutrient composition and crop yield. The relationship between plant nutrient status and soil test results is also helpful information. Adeli and Varco (2002) found strong relationships between lint yield, soil test K levels, and leaf blade K concentration. Leaf tissue analysis has become an essential service available to growers to monitor spatially across fields plant nutrient status at specific growth stages and serves as an alert to warn of potential deficiencies. Unless a crop has adequate nutrients, its yield will be limited, resulting in a decrease in the return on investment of all inputs. When attempting to diagnose reasons for yield differences within a field, determine the crop nutrient status as well as observe for any natural or man-made factors contributing to variability including changing soil texture, drainage, and compaction. The purpose of this bulletin is to: (1) show the effects of leaf K concentrations on plant-growth related processes; (2) show and describe leaf K deficiency symptoms in the absence of other nutritional, water, or disease stresses; (3) discuss the relationship between K leaf concentrations and root uptake; (4) discuss tissue sampling for K analysis, and (5) discuss the possibilities of correcting deficiencies with foliar applications.

Figure 1. Potassium Nutrition and Cotton Growth.
Appearance of cotton leaf K deficiency symptoms, related K levels, and relative rates of growth or development expressed as a percentage of optimum K (>3%) in the leaves (Reddy and Zhao, 2005).

Leaf K content %	Leaf development %	Leaf growth %	Stem growth %	Photosynthesis %
>3.05	98	100	100	99

Leaf K content %	Leaf development %	Leaf growth %	Stem growth %	Photosynthesis %
1.90	90	86	100	93



Leaf K content %	Leaf development %	Leaf growth %	Stem growth %	Photosynthesis %
1.15	86	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

Growth, development, and photosynthesis are expressed as a percent of the maximum or optimum.

MATERIALS AND METHODS

Data are based on three large experiments. In the first two experiments, the Bt-resistant cotton variety, DPL NuCot 33B, was grown in medium-fine sand. Plants were watered three times per day using Hoagland's solution, which supplies all macronutrients and micronutrients needed by the plant (Reddy and Zhao, 2005). The exception to the complete nutrition supply consisted of sets of plants that received one of four levels of reduced potassium. Reduced potassium treatments consisted of 40%, 20%, 5%, and 0% of normal potassium levels (or 100%). The amount of potassium deprivation varied by trial. This method of removing or reducing K from the nutrient solution resulted in the dilution of K in the plant tissues with continued crop growth and development. Reduced potassium levels were imposed from around first flower, but cessation of reduced potassium feeding varied between the trials.

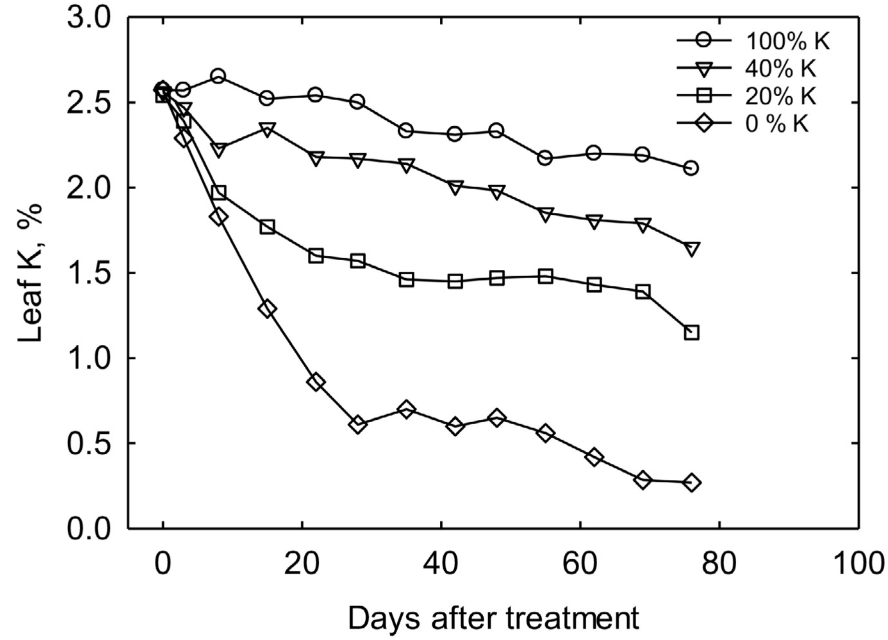


Figure 2. Temporal trends in average leaf potassium levels during the treatment period for four levels of K treatments, 100%, 40%, 20%, and 0% of control, imposed during the reproductive period of cotton, 2011 growing season. Each potassium level was represented by lines in curves (Lokhande and Reddy, 2015).

Plants in the first trial were grown in full sun inside precisely controlled plexiglass chambers that maintained the optimum temperature for cotton growth, 86°F (day) and 72°F (night), and excluded all pests (insects, diseases, weeds). Optimum nutrients were supplied until first square (23 days postemergence). Then, five K treatments were imposed (control with 100% K, 40%, 20%, 5%, and 0%) and continued until 85 days postemergence.

Leaf K concentrations from the recently fully expanded topmost leaves was measured weekly and interpolated so that actual K in the leaves was estimated daily. As the concentration of K in the plant tissues changed, the growth rates of leaves and stems were measured. Also, photosynthesis was measured daily, and the photosynthetic 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. Pictures were taken of plants and individual leaves at various stages of K deprivation.

In study two, cotton plants were grown outdoors in 26-inch-deep pots. At the first square, one set of plants was deprived of K (0% potassium). Two sets of plants were allowed to grow with full nutrients until almost the 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 the other essential nutrients and water, so only K was deficient during K deprivation. This experiment provided K to plants in varying stages of K deficiency, providing information on recovery from deficient conditions.

In the third experiment, four levels of potassium stress treatments (100%, 40%, 20%, and 0%) were imposed from flowering to crop maturity (Lokhande and Reddy, 2015). We used cotton variety Texas Marker-1, a genetic standard, in this experiment. Plants were harvested in each treatment when over 80% of the harvestable bolls opened. Leaf K content and flowering dates of bolls were measured from the first day of treatment to maturity to keep track of leaves in each K-stressed treatment. For each K stress treatment, based on flowering dates, open bolls were divided into different groups. Based on this criterion, we obtained several groups in the various K treatments. The bolls developed from flowers that were produced in the first 3 days of flowering constituted the first group and similarly, the rest of the groups of bolls were classified by a successive interval of 3 days in each treatment. Overall, from all K stress treatments, 40 groups of boll and lint samples were obtained. The average midday leaf K for each group was estimated by fitting regression equations for each treatment and the running average of leaf K over the boll maturation period for each group (Figure 2).

The information provided by these studies should be particularly useful to those 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. One factor that should be checked as a yield-limiting variable is leaf K. Soil fertility status is essential, but soil test results may not be an adequate indicator because of the interaction of K availability and other factors limiting the plant's ability to take up the nutrient. Tissue analysis is a reflection of plant uptake, which depends on the integration of a number of soil and environmental factors.

POTASSIUM DEFICIENCY SYMPTOMS IN COTTON

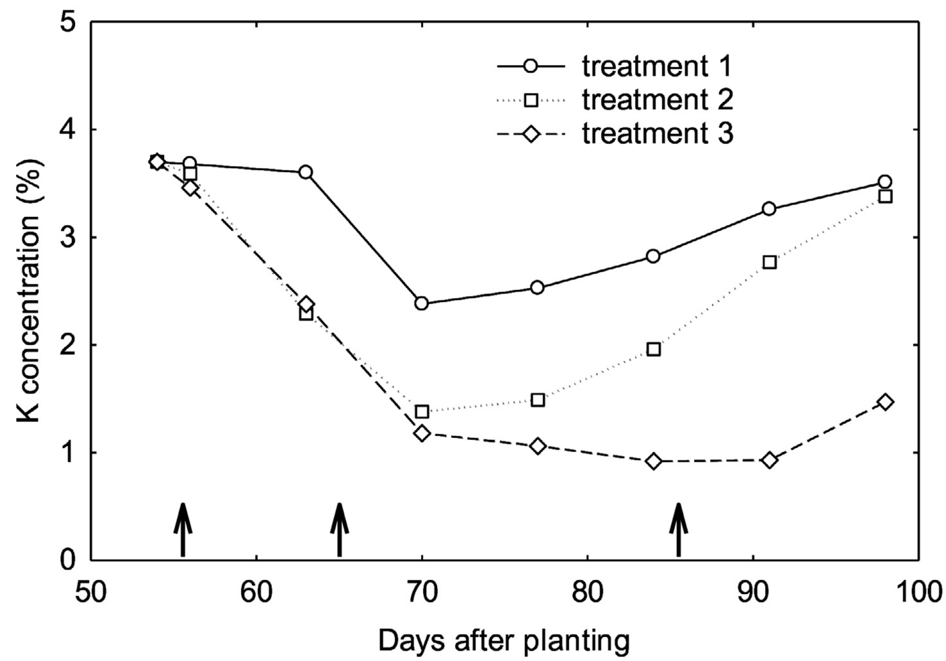


Figure 3. Influence of potassium nutrition on leaf K concentrations for plants grown in pots outdoors. The plants were grown in optimum water and nutrient solution culture up to flowering, and then potassium from the nutrient solution was withdrawn at various stages. The arrow on the left indicates the beginning of K starvation for treatments 2 and 3. The arrows in the middle and at the right indicate the restoration of K to normal nutrient solution for treatments 2 and 3, respectively (Reddy and Zhao, 2005).

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 the production of dry matter diluted K content. As K became scarcer, much of the K in old leaves was translocated to the young, actively growing structures, but even with this reuse of K, it became limiting within a few days. Older leaves remained green and appeared healthy, but photosynthesis measurements on individual leaves showed that older leaves with much of the K removed were essentially nonfunctional. This point contrasts with earlier observations that the K deficiency appears first in mature leaves. Older leaves with deficiency symptoms were produced with inadequate available K. It seems that if leaves were produced in an adequate-K environment, they did not develop deficiency symptoms even though most of the K was subsequently translocated out of those mature leaves. It 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.

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 downward curling or cupping of the upper leaves. (2) This was followed by mild mottling and eventually 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. (4) Severely deficient cotton leaves without the 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.

The crop needs to have high K concentrations in its leaves early in the season because having only sufficient K at that time can result in shortages later. Later in the season, it is difficult to maintain enough K in the leaves because of the heavy requirements for boll growth, which is also complicated by the limited root growth relative to the size of the total plant (Figure 4). As cotton plants age, the ratio of roots to above-ground parts decreases. This appears to continue after flowering and contributes to the difficulty associated with meeting K uptake needs during the fruiting period (data not shown). 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 help grow new absorbing surfaces, but during the boll-producing period, root growth slows, and nutrient absorption cannot keep up with the demands.

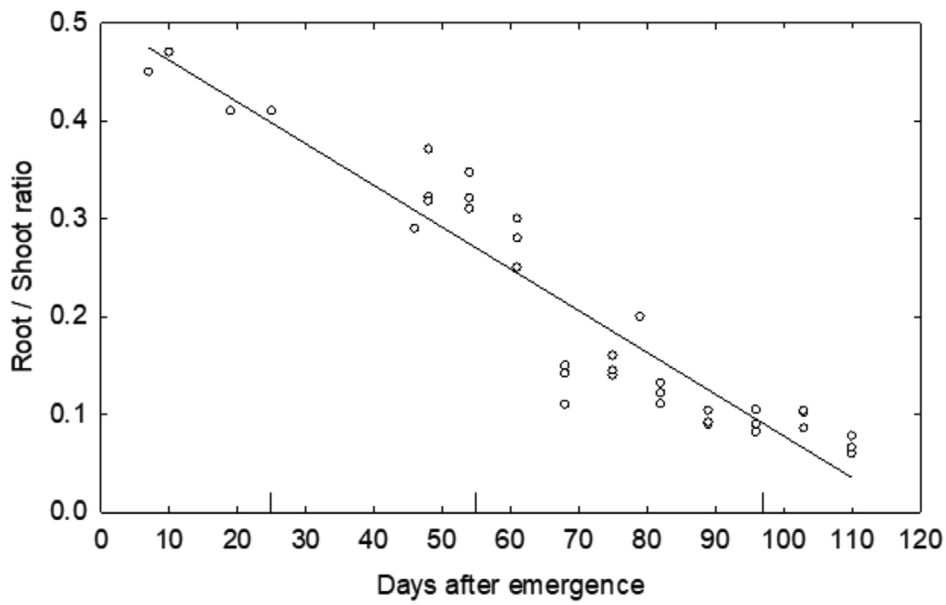


Figure 4. Seasonal trends in root: shoot ratio of cotton. Vertical lines indicate the beginning of squaring, flowering, and boll opening from left to right, respectively, for plants grown outdoors in large pots.

POTASSIUM EFFECTS ON PHYSIOLOGY AND GROWTH

The rate of leaf area expansion is reduced by K deficiency. The leaf area expansion rate increases with increasing leaf K concentration up to a maximum that occurs at about 3% (Figure 1 and 5). Although higher concentrations of leaf K were observed in some conditions, there was no additional advantage as far as the leaf area expansion rate was concerned. In a production environment, there appears to be some advantage in early or midseason 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 provides a brief 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. Leaf expansion rates declined even more as K concentration decreased and were only 59% as great in plants that had approximately 1% leaf K. Additionally, the importance of adequate K to N utilization by cotton was shown by Fridgen and Varco (2004).

The rate of photosynthesis was 7% less in cotton plants with 1.9% leaf K compared to well-fertilized plants (Figure 1 and 5). 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 to 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. Research in Arkansas (Zhao et al., 2001) found seedling cotton leaves had their maximum photosynthesis with approximately 1% K. They measured photosynthesis of individual leaves, whereas we measured photosynthesis of plants in a closed canopy. A negative relationship between K fertilizer rates and leaf senescence has been documented, indicating the importance of maintaining leaf health for continued photosynthesis as boll maturity progresses (Adeli and Varco, 2002).

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

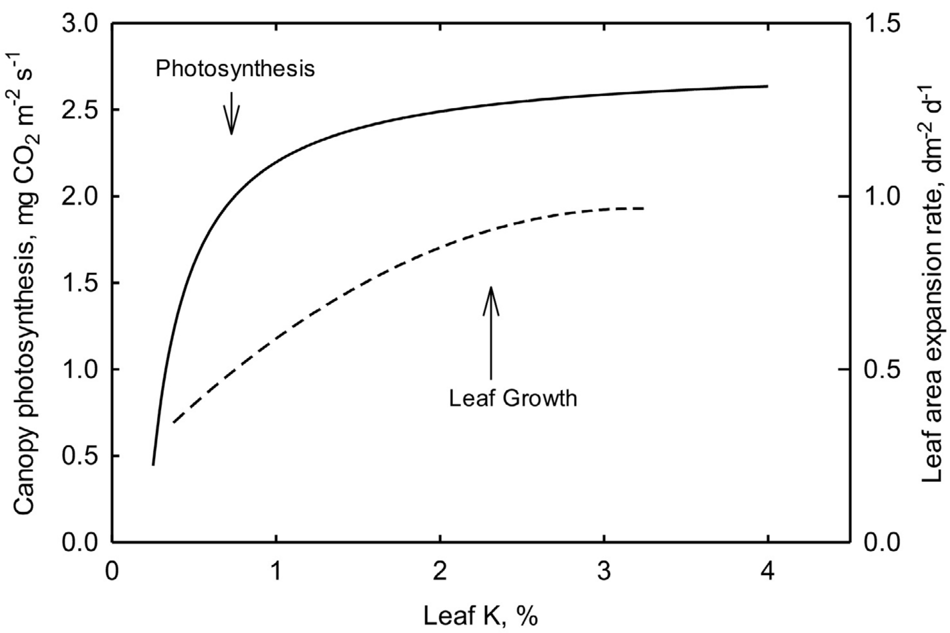


Figure 5. Cotton canopy net photosynthesis and leaf area expansion as a function of leaf K concentration. Plants were grown in optimum day/night (86/72 °F) temperatures in a range of K-deficient conditions but with sufficient water and other macro- and micronutrients. Potassium was determined in the uppermost fully expanded leaves (Reddy and Zhao, 2005).

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 and then declined rapidly. However, well-fertilized irrigated cotton 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 with optimum nutrient solutions. Apparently, in crops exposed to drought, the K nutrition during the fruiting period is closely linked to the water supply. Potassium uptake is associated with total root length and root growth rates. If water supply becomes limited during the fruiting period—when there is severe competition between roots and the increasing boll load for both K and photosynthates while uptake of K is insufficient to meet the fruit-load needs—it causes a withdrawal of K from the leaves and the related slowing of growth processes. The importance of maintaining high soil test K levels when growing season rainfall is limited was shown by Varco (2000) where fertilizer rates of 116 and 175 pounds of K per acre maintained yield across years of declining growing season rainfall, while lower fertilizer K rates generally resulted in a yield decline.

A good population of mature bolls was produced on those healthy plants that received a 100% K causing one to interpret the typical decline in leaf K during boll growth to be caused by insufficient K absorption. In a nutrient solution environment where minerals are not limiting, the K concentration in the leaves remains stable during growth. However, in field environments with drying soil, the K concentration changes in leaves during the season, increasing the complexity of interpreting the crop's nutritional status. According to Hsu (1979), the percentage K of field-grown cotton leaves increases with age until 3 weeks after the beginning of flowering. The plant's growth then becomes a major factor in cotton physiology. Since the fruit's nutritional requirements exceed the plants' ability to take up nutrients, the concentration of K in the leaves decreases. Presumably, this is caused by a combination of less available water and fewer roots to support a sizeable above-ground plant.

The relative amount of roots compared to the whole plant weight decreases throughout the season (Figure 4). 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, which may be because K is removed from the leaves to support growth when the K uptake is low, causing the leaf concentration to decline just as in our solution-culture-grown plants.

The lower K concentration in the leaf affects several physiological processes (Figures 1 and 5). When mineral nutrients are depleted in the leaves, the need for photosynthetically produced sugar is also reaching its peak because energy is needed to support fruit growth. Additional flowers and bolls require both minerals and sugar. As their requirements exceed the supply, less K is available to support the growth and functioning of roots. Healthy cell membranes are effective barriers to nutrient passage; 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, supporting their growth becomes progressively more difficult. The reproductive parts appear to have a higher priority for available carbon and other nutrient resources. They survive at the expense of root growth 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). We observe this annually and call it "cutout." The cutout occurs earlier when nutrients or water are limited, causing fewer young bolls to survive. A cutout also occurs earlier in hot weather because bolls are formed faster; higher temperatures cause higher respiration or higher burning rates of the energy-consuming processes. However, excessively hot weather causes young bolls to drop because of high-temperature injury, and all 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 the sand with nutrient solutions added daily. We found that increasing the potassium concentration above that which resulted in additional growth caused the increased concentration of K in the leaves. This is called "luxury consumption." When the 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 removed entirely 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. This suggests that if plants have a marginal K nutritional status and the growing conditions worsen, immediate management action is needed. Delaying the response, hoping rain will restore conditions, is the wrong tactic. Delaying restoration of K status results in a worsening condition, and the plants require longer to recover. A longer recovery time wastes the productive time of the growing season and results in lower yields.

This discussion is to help increase understanding of the timing of tissue sampling for K analysis, as well as appropriate interpretation of the results. We believe leaves should be checked for K concentration at the beginning of flowering to minimize the number of samples. Young mature leaves should have at least 3% K at that time. 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.

It has been inferred that good K nutrition delays maturity. We did not find that to be true. Potassium-deficient plants sometimes die prematurely because they are more susceptible to diseases and nematodes. They may also "cutout" because inadequate K limits growth, so such plants appear to mature earlier. Also, plants grown in high K produce flowers and set more bolls over a more extended period, and therefore are later to mature the last bolls produced, but they do not produce bolls slower. We determined the length of the time required from flowering to open bolls on hundreds of bolls and found no delays caused by high K nutrition.

LEAF K AND COTTON YIELDS

Bennett et al. (1965) reported on a study in which up to four-bale 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 leaf K and yield (Figure 6). Even with the high yields, they reported severe K deficiency symptoms in leaves containing less than 1.5% K. Their results are consistent with the responses we observed between leaf K and photosynthesis (Figure 5). Adeli and Varco (2002) noted maximum lint yield across 3 years on a high-yielding site was predicted at a leaf K concentration of 25 grams of K per kilogram at first week of bloom, while Baker et al. (1991) reported a value of 21 grams per kilogram as a minimum sufficiency level in Arkansas.

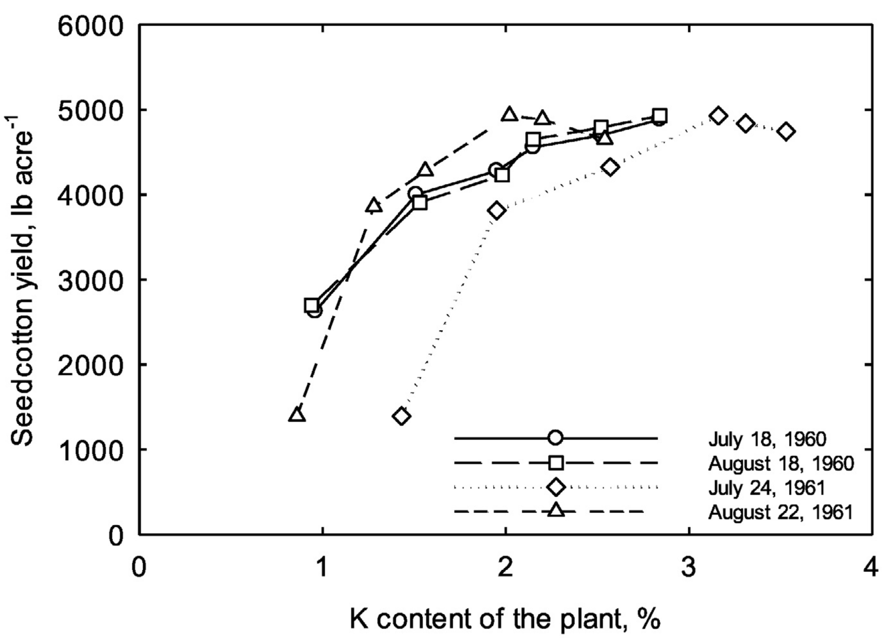


Figure 6. Relation between yield and potassium content of above-ground cotton plants (redrawn from Bennett et al. 1965).

LEAF K AND FIBER QUALITY

The cotton genus, *Gossypium*, contains about 53 species, but only four species are cultivated that produce lint of any commercial value: *G. hirsutum*, *G. barbadense*, *G. arboreum*, and *G. herbaceum* (Fryxell, 1992; Wendel and Grover, 2015; Gallagher et al., 2017; Wang et al., 2018). The Upland cotton (*G. hirsutum*) is the most extensively cultivated due to its wide adaptability to the environment, high production, better yield potential, and medium fiber length (about 0.87 to 1.83 inches), accounting for greater than 95% of global and U.S. cotton production and yield (Chen et al., 2007). Sea Island cotton (*G. barbadense*), also known as American Pima cotton, is highly desirable due to its high fiber quality with long (1.25 inches to 1.56 inches), strong, and fine fibers (Avci et al., 2013), accounting for about 5% of the United States cotton production. The other two species (*G. arboreum* and *G. herbacium*) with shorter fiber lengths (0.5 to 1 inch) are only cultivated in the southern and southeastern Asian countries, with limited contribution to global lint supply.

A single pound of cotton may contain more than 100 million individual fibers (The Classification of Cotton, 2018). Each cotton fiber is a single complete cell that develops in the surface layer of the cottonseed. The fibers are composed of a cuticle, a primary wall, a secondary wall, and a central core or lumen. The cuticle is the cotton fiber's "very outside" or "skin." It is composed of a waxy layer (cotton wax). The lumen is a hollow canal running the fiber's length, providing nutrients while the plant is growing. Depending on the fiber's maturity, the lumen's dimensions vary enormously. Mature fibers will have a thick layer of cellulose in the secondary wall, resulting in a very small lumen. In contrast, an immature fiber has a fragile wall structure and a large lumen.

Recent rapid advances in spinning and fabric technologies are demanding better quality cotton. The fiber quality traits important for the textile, yarn, and fabric industries include fiber length, uniformity, strength, and micronaire value. Therefore, both quantity and quality contribute to the producers' prices for their crops. Fiber quality is generally assessed using precise High Volume Instruments (HVI), a process commonly referred to as high-volume instrument classification (The Classification of Cotton, 2018).

Fiber length, the average length of the longer one-half of the fibers, and fiber length uniformity, defined as the length variation of the fibers that is the strongest indicator of short fiber content, are considered the most important property traits affecting yarn quality, spinning efficiency, hairiness, evenness or imperfections, and strength. Fiber length and length uniformity are also very important for advanced spinning technologies in the textile industry as they affect fabric strength, pilling, and appearance (Felker, 2001). Fiber strength, defined as the force required to break a bundle of fiber, also affects yarn quality, spinning efficiency and strength, and fabric strength (Yang, et al., 2016; Rodgers et al., 2017). The strength is largely dependent on genetics but modulated by environment and management. The micronaire value, a measure of fiber fineness and maturity, influences yarn hairiness, strength, spinning efficiency and fabric appearance or evenness, white specs, dyeability, strength, appearance, and pilling of the fabric.

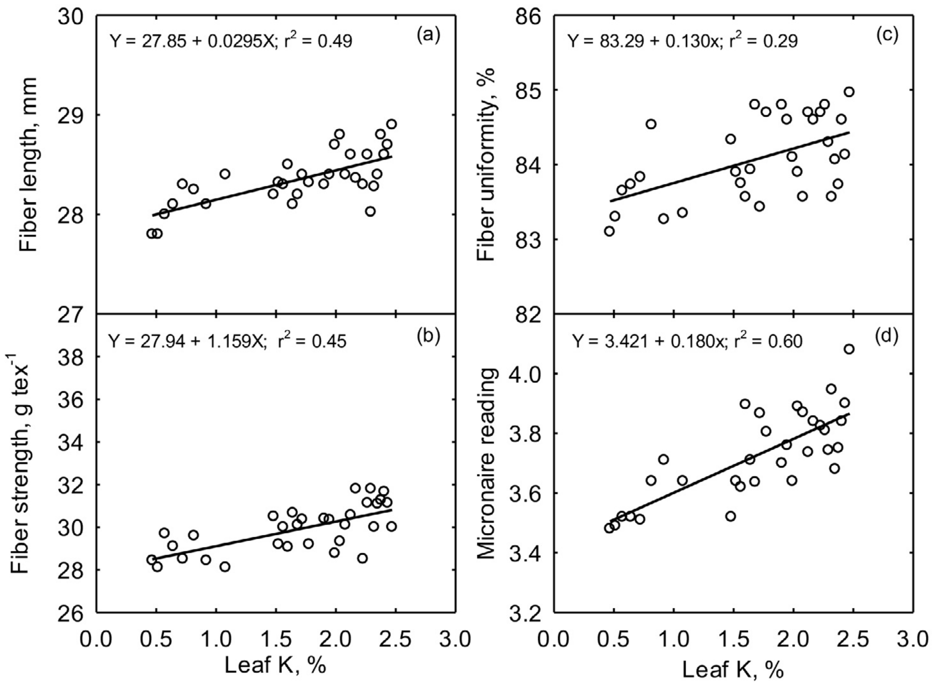


Figure 7. Relationships between cotton leaf K levels and fiber quality parameters — (a) length, (b) strength, (c) uniformity, and (d) micronaire — during fiber growth and development period. The K levels were averaged from flowering to boll opening, estimated by fitting regression analysis to estimate daily values. Cotton lint samples for fiber analysis were collected at the final harvest when 80% of the bolls opened in the treatments (Lokhade and Reddy, 2015).

Lokhade and Reddy (2015) determined the fiber quality trends with respect to leaf K, averaged across the boll maturation period beginning with anthesis. They reported that fiber length declined linearly with leaf K concentration ($r^2 = 0.49$, Figure 7a), and the longest fibers (28.9 mm) were recorded at optimum potassium (2.5%) levels. The decline in fiber length was 0.03 mm per unit of leaf K content. Despite this decrease in fiber length, the recorded values were within 24 to 28 mm, which is acceptable for mills (Bradow and Davidonis, 2000). Although fiber uniformity decreased linearly ($r^2 = 0.29$, Figure 7c) with a decrease in the leaf potassium content, the changes in the uniformity were not significant, and the uniformity remained within the range that is not penalized by the mill industry (83 to 85%) (Schleth and Peter, 2005).

The elongation period during the fiber development process is critical for fiber length. Potassium plays a vital role in sucrose uptake in the plasma membrane during this elongation period (Schleth and Peter, 2005). Our results corroborate the findings of Reed et al. (2006), who showed decreasing fiber length with declining leaf K levels in a pot-culture experiment. Although there is a significant decline in fiber length with an increase in K deficiency, the uniformity was not significantly affected. This is likely because very few late initiated bolls were retained for K-deficient treatments in this study. These results are in accordance with those reported by others (Pettigrew, 2003; Gormus and Yucel, 2002), that the fiber uniformity ratio remained unaffected under K stress treatments.

Like length, fiber strength also declined (r^2 = 0.45, Figure 7b) with a decrease in leaf K. Plants grown under optimum K levels (2.5%) produced fibers with values of 30.0 grams per tex, and these values declined to 28.3 grams per tex when leaf K levels decreased to 0.5%. The lower lint quality values recorded in this study, in combination with lower levels of leaf K (26 to 29 grams per tex) result in classification within medium-strength fiber which is required by mills (Ruan et al., 2005).

Fiber micronaire readings as measured with the HVI instrument, similar to other fiber properties, declined as leaf K levels during fiber development declined (r^2 = 0.60, Figure 7d). Micronaire readings of 3.48 (discount range) were recorded at a leaf K concentration of 0.46%. The acceptable Upland cotton micronaire premium range was between 3.7 and 4.2, while base ranges were between 4.3 and 4.9. Micronaire values below 3.5 and above 4.9 are penalized by the mills, resulting in a price penalty (Bradow and Davidonis, 2000). Since micronaire is a measure of fiber maturity and fineness serving as an indirect measurement of air permeability (Moore, 1996), the recorded values in the discount range may be the result of K involvement in photosynthesis and subsequent transport to the seed and fibers during the development (Ruan et al., 2005). Typically, there will be a shift in sucrose metabolism beginning around 24 days after anthesis in cotton fibers (Ma et al., 2008). Potassium is involved in photosynthesis as it plays a role in plant water relations through the regulation of stomatal conductance and through carbohydrate transport related to the translocation capacity of photosynthate and carbohydrates to bolls (Pettigrew and Meredith, 1997). Studies have shown that there is a direct correlation between the amount of canopy photosynthesis and fiber micronaire values measured between 15 and 45 days of anthesis (Pettigrew and Meredith, 1997). Therefore, potassium levels during fiber development play a critical role in resulting cotton fiber micronaire values. Managing soil potassium and supplementing using the foliar application are important management strategies during crop production.

PROFITABILITY OF APPLYING K AS A FOLIAR SPRAY

If you have invested all the necessary resources for producing a highly productive cotton crop but become concerned in midseason that yields may be limited by lack of available K because of K-deficiency symptoms, what options are available? One possibility is the application of K to the foliage. Applying to the foliage is limited because high salt concentrations cause foliar burns. Too much fertilizer salt will injure the leaves and cause more damage than benefit. It has been determined that only about 10 pounds per acre of potassium nitrate or potassium sulfate per weekly application beginning the third week of flowering can be applied safely (Oosterhuis et al., 1991; Howard et al., 1998). This may be applied in multiple applications with insecticides.

A good soil fertility program is essential to producing high-yielding cotton. Howard et al. (1998) found that cotton yield response to foliar K was dependent on the choice of K source including potassium nitrate (KNO_3), potassium sulfate (K_2SO_4), potassium thiosulfate ($K_2S_2O_3$), and potassium chloride (KCl), solution buffering, and whether boron was included. They reported that yields from K_2SO_4, $K_2S_2O_3$, and KCl averaged 10% greater than the untreated check, and foliar application of KNO_3 augmented an additional 4% more yield than the other K sources. Also, buffering of the K solution (KNO_3) to pH 4 or adding a surfactant increased lint yield by 5% compared to the check. In addition, they also reported that including boron in the foliar K application further improved yields.

WHEN AND WHAT PLANT PARTS TO SAMPLE

Plant structures vary in the amounts of K they contain, so one must select an appropriate tissue for analysis. As a rule, young mature leaves have higher K concentrations than old or still-growing leaves. This is especially true in soils testing low or medium for K. As the plants grow and the amount of roots relative to above-ground parts decreases, the percentage of K in the above-ground parts increases, but the present K usually decreases. 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.

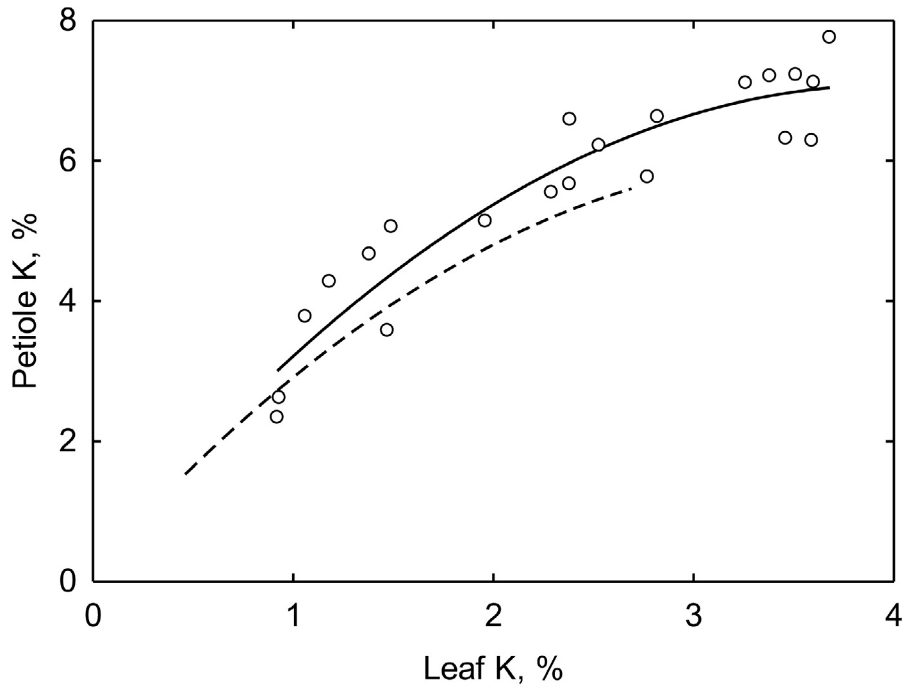


Figure 8. The relationship between cotton leaf blade K concentration and leaf petiole K concentration. The solid line represents data collected from plants grown in nutrient solutions ($Y = 0.174 + 3.476 * X - 0.437 * X^2$, $r^2 = 0.89$). The broken line represents 372 data points from 57 locations in 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 the complexity of the presentation.

Research has shown that leaf petioles have higher concentrations of K than leaf blades and the broadest range of K concentration of any structures (Hsu, 1979). This has led some researchers to recommend that leaf petioles are the most appropriate tissue to analyze for determining the K status of the crop. Petioles function as a nutrient conduit and temporarily store small amounts of K. There is a close correlation between leaf petiole K and leaf blade K concentrations (Figure 8). We believe, however, that the K concentration in petioles is more of a reflection of recent K uptake than a suitable indicator for estimating whole plant K status. Potassium concentrations in young mature leaves decreased slightly earlier than in old leaves in K-deficient field-grown plants (Hsu, 1979). Cotton leaf K concentration has been shown to vary from its greatest concentration early in the season to its lowest value late in the season (Mullins and Burmester, 1990). Thus, leaf sampling must be reported at very specific plant developmental stages to minimize natural variances in leaf K concentration. Since the leaf blades are so crucial to light interception and dry matter production, we have concluded that leaf nutritional status and health are primary concerns. 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 mainstem terminal is usually the youngest fully expanded leaf, is physiologically the most active leaf, and is, therefore, the appropriate leaf to sample. This conclusion is also in agreement with numerous other research reports. Also, mainstem leaves reach full size after about 16 days (the time required for four to five additional leaves to be added from the mainstem).

IS A CHLOROPHYLL METER RIGHT FOR DETECTING K DEFICIENCY?

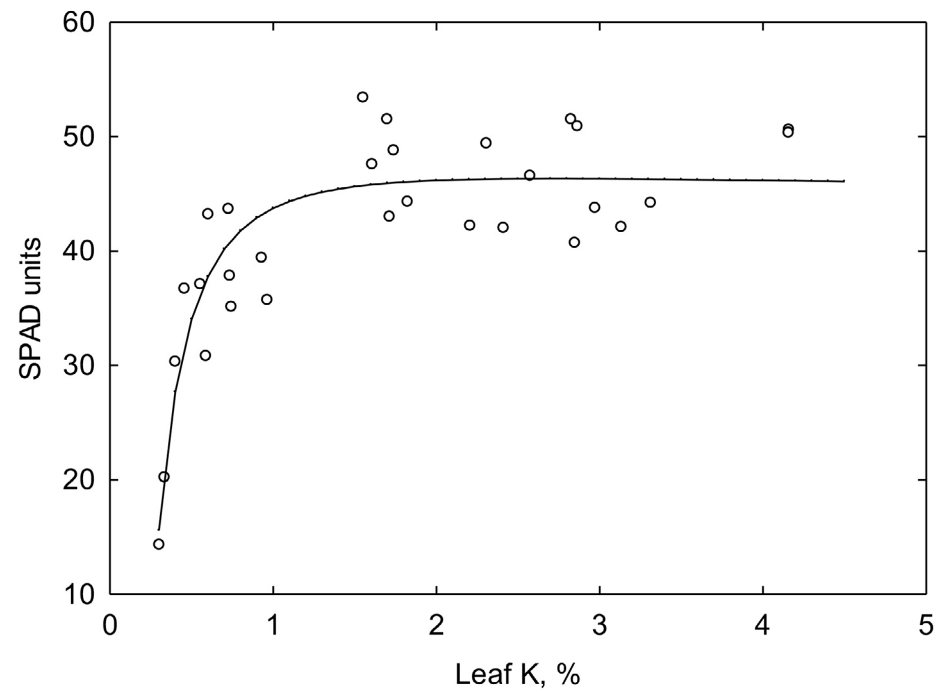


Figure 9. The relationship between SPAD readings and leaf K concentrations for plants grown in optimum day/night temperatures and at a range of potassium-deficient conditions (Reddy and Zhao, 2005).

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 walking crop fields to scout for crop health. The chlorophyll meter (SPAD-502) was developed by Minolta Company as a tool to manage the N status of crops. Several researchers found a strong correlation between the meter's leaf chlorophyll measurements and leaf N content. The instrument measures transmission of red light at 650 nm, at which chlorophyll absorbs light, and transmission of infrared light at 940 nm, at which no absorption occurs. Based on these two transmission values, the instrument calculates a SPAD (Soil Plant Analysis Development) value that is quite well correlated with chlorophyll content. We compared SPAD readings on plants varying widely in K content (Figure 9) and found the SPAD meter readings are not sufficiently sensitive to detect K deficiency symptoms in cotton. One can see differences with that instrument only when leaf K concentrations are below 1%; at that concentration, it is too late to correct the problem. In a field study, leaf reflectance measured with a spectrometer on most recently matured leaves sampled from first bloom to peak bloom did not show a difference between no applied K and 100 pounds of K per acre (Fridgen and Varco, 2004). However, detection of leaf N across N rates depended on adequate K supply. One can also visually detect the nutritional problem before the leaves reach a low concentration.

POTASSIUM DEFICIENCY AND DISEASES

The high yield and quality of cotton require healthy, vigorous plants throughout the season. Several investigators have reported an association between K deficiency symptoms and the incidence of verticillium wilt (*Verticillium* spp.) (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 says that the two symptoms are distinct and can be identifiable. Potassium deficiency symptoms are often recognized as leaves having a bronze color and necrosis occurring along the margins of the leaves 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 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

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 insufficient nutrients are available to the crop. Precision management tools can now be used to facilitate mapping and documentation of specific causes of depressed yield including inadequate tissue K. Recent advances in remote spectral imaging of crops should improve our capability of mapping K deficient areas within fields. This information may be coupled with variable-rate fertilizer applications and increase precision in fertilization. With the increased adoption of spatial tissue sampling by service providers for growers, sampling structures must account for varying soil textures and cation exchange capacities due to differences in K availability associated with these soil properties (Buscaglia and Varco, 2003). This study defined physiological processes as a function of leaf K concentration when other production factors were not limiting. One should expect crop productivity to 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 terminated before many healthy bolls reached maturity. However, in both experiments, the boll parameters (size, seed, and lint weight per boll), boll numbers and 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:

- Critical foliar K concentration required for optimum photosynthesis, and thus the productivity of cotton (95% of the maximum) is 2.1%. Many processes are severely affected below the critical foliar K levels. Growth processes are limited when leaf K concentrations are below 2%, and visual symptoms of K deficiencies are difficult to see.
- 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 increases with an increase in foliar K up to 3%. Leaf K concentration should be determined at early flowering. Select leaf blades (not including petioles) from the first mature leaf below the crop terminal. This is usually the fourth or fifth leaf from the top. Critical foliar K concentration is also 2.1% for optimum leaf growth.
- Fiber length, strength, micronaire, and uniformity declined linearly with a decrease in leaf K content during cotton boll and fiber development. Weaker fibers with medium length were produced under K-deficient conditions with micronaire values in the discount range. Fiber uniformity, however, did not decline with a decrease in leaf K.
- Potassium deficiency is aggravated by drought. Drought-stressed plants usually have lower leaf K concentrations even in highly fertile soil, and drought and insufficient K may limit yields. 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 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

Appreciation is expressed for the excellent technical assistance provided by Kimberly Gourley, former biological technician, USDA-ARS, and David Brand, senior research associate, MSU Department of Plant and Soil Sciences. We also thank Dr. Alan Henn and Dr. Cori Speights for their critical review and suggestions. Part of the research was funded by the USDA NIFA (2019-34263-30552, and MIS 043050) and the MAFES-SRI, Mississippi State, Mississippi.

We acknowlledge the contributions of Harry F. Hodges, professor emeritus (deceased), to the orginal publication, MAFES Bulletin 1094. This publication is the revised version of that bulletin with additional information.

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