Potassium Management of Cotton

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Introduction

Potassium is required in large amounts by cotton for normal crop growth and fiber development, with a typical high yielding crop containing about 200 kg K ha^{-1}. Plant uptake of K follows a pattern similar to dry weight accumulation except that K uptake peaks at 2.2 to 5.0 kg ha^{-1} day^{-1} a few weeks after the start of flowering (Halevy *et al.*, 1987). Cotton is 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 (Cassman *et al.*, 1989). When soil analysis calls for additional K, the cotton crop is usually fertilized with a single preplant broadcast application of K fertilizer. Mid-season applications are infrequently applied, and foliar applications are used occasionally to correct K deficiencies during fruiting.

However, despite soil analyses and subsequent soil applications of fertilizer prior to planting, K deficiencies have occurred sporadically and somewhat unpredictably across the US Cotton Belt. This has prompted a renewed focus on K management in cotton with some emphasis on understanding K fertilizer requirements and use by the cotton plant. The occurrence of a complex of K-deficiency symptoms in cotton (*Gossypium hirsutum* L.) was first recognized in California during the early 1960's (Ashworth *et al.*, 1982; Brown *et al.*, 1973). These deficiencies have manifested themselves during the latter half of the season in a range of soils and cotton cultivars. There is still some speculation about the causes of the deficiencies which are related to the relative inefficiency of cotton at absorbing K from the soil compared to most other crop species, soil K fixation, the incidence of diseases such as *Verticillium* wilt, and the use of higher-yielding and faster-fruiting cotton cultivars and the increased use of nitrogen in cotton management (Oosterhuis, 1975).

Applications of K fertilizer in the US Cotton Belt, when called for, are surface applied or shallowly incorporated into the topsoil. Potassium deficiencies are corrected by preplant soil applications and occasionally by mid-season sidedress applications of K. Foliar applications of K offer the opportunity of correcting mid-season deficiencies quickly and efficiently, especially late in the season when soil application of K may not be effective. The practice of foliar fertilization has only caught on in cotton production in the last two decades, but 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 (e.g. Kerby and Adams, 1985), there are no definitive studies available on the usefulness of foliar-applied K. Earlier research (Oosterhuis, 1976) 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 (Pettigrew, et. al. 1996; Oosterhuis *et al.*, 1990). With the national emphasis on lint quality (Sasser, 1991) 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 nutritional and fertility requirements of cotton. The review focuses on the importance of K in plant growth, its uptake and distribution in the plant, K deficiency symptoms, and the causes of K deficiency. The review also covers the K fertilization of cotton including soil and foliar fertilization. The review concentrates on plant nutrition rather than soil nutrition.

Importance of Potassium for Cotton Growth

Potassium is an essential macroelement for all living organisms required in large amounts for normal plant growth and development (Marschner, 1995). In higher plant cytoplasm, K is the dominant cation and is commonly found to be in concentrations ranging from 80 to 150 mM (Blevins, 1985). It is absorbed by roots from the soil as the monovalent cation K^+ usually by active uptake. The element is very mobile in the plant and can be translocated against strong electrical and chemical gradients (Hoagland, 1948). 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 (Evans and Sorger, 1966) 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 (Epstein, 1972). These two functions of K are manifest in its role in stomatal opening (Humble and Raschke, 1971) when stomatal conductance and turgor are coupled. Another major role of K is in photosynthesis (Huber, 1985) by directly increasing leaf growth and leaf area index, and therefore, CO_2 assimilation (Wolf *et al.*, 1976). Potassium increases the outward translocation of photosynthate from the leaf (Ashley and Goodson, 1972).

There have been a number of reviews of the K nutrition cotton (e.g. Hearn, 1981; Kerby and Adams, 1985). In cotton, K plays a particularly important role in fiber development, and a shortage will result in poorer fiber quality and lowered yields (Cassman *et al.*, 1990). Potassium is a major solute in the fiber (single cells) involved in providing the turgor pressure necessary for fiber elongation (Dhindsa *et al.*, 1975). 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 (Oosterhuis and Bednarz, 1997), it is likely implicated with secondary wall deposition in fibers and, therefore, related to fiber strength and micronaire. Xi *et al.* (1989) 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 (Hafez *et al.*, 1975) although the physiological reasons for this are not clear.

Cotton K Requirements

Potassium is required in large quantities by cotton, from 3 to 5 kg K ha^{-1} day^{-1} (Halevy, 1976). The total quantity of K taken up by the plant is related to the level of available soil- and fertilizer K (Bennett *et al.*, 1965; Kerby and Adams, 1985) and yield demand of the crop. An average mature cotton crop is estimated to contain between 110 and 250 kg ha^{-1} of K, of which about 54% is in the vegetative organs and 46% is in the reproductive organs (Rimon, 1989). 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 (Hodges, 1992; Rimon, 1989). Therefore, after several years of application, there should be a buildup of soil K.

Plant uptake of K follows a pattern similar to dry weight accumulation, 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 (Halevy *et al.*, 1987). Potassium was absorbed more rapidly than dry matter was produced, as evidenced by the higher concentration of K in young plants (Bassett *et al.*, 1970). The rate of K uptake was slow during the seedling stage (**Fig. 1**), about 10% of the total, but increased rapidly at flowering and reached a maximum of 4.6 kg ha^{-1} day^{-1} between 72 and 84 days (Halevy, 1976). Mullins and Burmester (1991) reported maximum daily uptake rates of 2.24-3.47 kg ha^{-1} day^{-1} 63 to 98 days after planting. Bassett *et al.* (1970) reported corresponding values of 2.1 to 3.4 kg ha^{-1} day^{-1} between 90 and 127 days after planting for older late maturing varieties.

The need for K increases dramatically when bolls are set on the plant because bolls are a major sink for K (Leffler and Tubertini, 1976). 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 56 days after flowering at boll maturity. This appears low compared to the 126 mg K $boll^{-1}$ reported by White (1991). An average cotton crop contains about 150 kg K ha^{-1} (Hodges, 1992) with about 50-65% of the K in the reproductive unit (Rimon, 1989; Mullins and

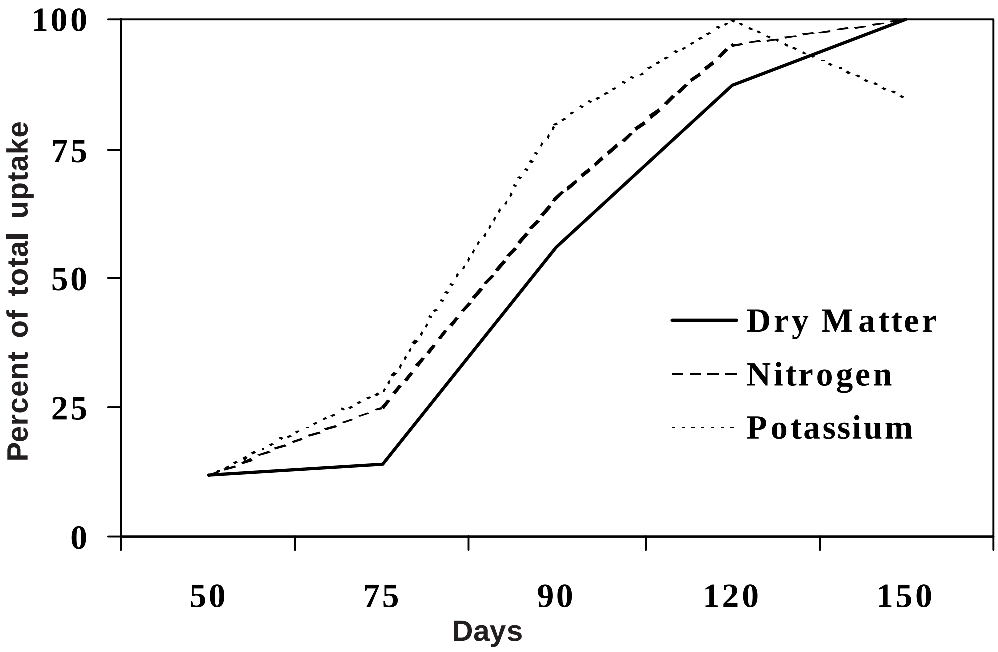

Figure 1. Pattern of Dry matter and Potassium and nitrogen uptake by the cotton crop. (adapted from Mullins and Burmester, 1991).

Burmester, 1991). During the development of a boll the K concentration increased from 19 g/kg at 10 days to 55 g/kg at maturity, while K concentration in the fiber decreased from 22 to 6 g kg^{-1} and seed K concentration remained nearly constant (Leffler and Tubertini, 1976). 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 (Dhindsa *et al.*, 1975). Potassium is the most abundant cation in cotton fiber (Leffler and Tubertini, 1976). The capsule wall of the boll contains approximately 4% K and accounts for between 32 to 60% of all the K accumulated by the boll (Bassett *et al.*, 1970; Kerby and Adams, 1985).

Luxury Consumption of K by Cotton

Potassium can be taken up in luxury amounts (Kafkafi, 1990), i.e. uptake and accumulation of K above levels needed for normal growth, and this could possibly confuse tissue diagnostic recommendations (Bednarz and Oosterhuis, 1996). Bennett *et al.* (1965) 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, there is evidence that luxury consumption of K is actually beneficial and a relatively cheap insurance policy against environmental stress (Kafkafi, 1990). Potassium is the most abundant cation in the phloem sap (Hall and Baker, 1972) amounting to about 80% of the total cation sum. It is usually stored in the vacuoles in large quantities. Recent reports by Bednarz and Oosterhuis (1996) 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. Kerby and Adams (1985) reported that the amount of K needed for high yield conditions was about 125 kg K ha^{-1}, and if plant K uptake exceeded this amount such that the ratio kg K/kg lint exceeded 0.13, then luxury consumption has occurred.

Sensitivity of Cotton to K 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 (Cassman *et al.*, 1989). Cope (1981) 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 (Barber, 1984). The rate of plant uptake of K depends on root length density and total root surface area (Brouder and Cassman, 1990). However, the cotton root system is notable by its low density relative to other major row crops (Gerik *et al.*, 1987). 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 (Kerby and Adams, 1985). 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 (Sprague, 1964). The leaf tip and margin curl downwards as the tissue breakdown continues. Finally the whole leaf becomes rust coloured, brittle and drops prematurely, stopping boll development which results in dwarfed and immature fruit, some of which may not open. These 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 (Kerby and Adams, 1985). The symptoms of K deficiency have been mistaken for *Verticillium* wilt symptoms as they seem to occur under similar environmental conditions (Weir *et al.*, 1986). Furthermore, the growth and yield of cotton varieties less susceptible to *Verticillium* wilt are often less affected by late-season K deficiency (Ashworth *et al.*, 1982; Mikkelsen *et al.*, 1988).

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 (Stromberg, 1960; Weir *et al.*, 1986; Maples *et al.*, 1988) 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.

Reasons for Potassium Deficiency in Cotton

Much speculation has surrounded the widespread occurrence of apparent "potassium deficiency" symptoms that have occurred in recent times in the US Cotton Belt. It has been proposed that the deficiencies are related to soils with K availability problems (Cassman *et al.*, 1990), the relative inefficiency of cotton at absorbing K from the soil compared to most other crop species (Cassman *et al.*, 1989), or the incidence of *Verticillium* wilt (Wakeman *et al.*, 1993). 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 (Oosterhuis *et al.*, 1991b).

The decrease in root activity after the start of flowering (Cappy, 1979) 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 assimilates 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 during early season in the Mississippi delta. Recent evidence indicates that modern cotton cultivars have less K in storage prior to boll development (Bednarz and Oosterhuis, 1996) 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 (Kerby and Adams, 1985).

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, 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, (iv) possible relationships with diseases such as *Verticillium* wilt, and possibly, (v) 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.

Estimating Cotton Fertilizer Potassium Requirements

Accurate soil analysis coupled with mid-season plant tissue analysis are needed to formulate a suitable K fertilizer program. Soil sampling and analytical methods of assessing soil available K are reviewed by Sabbe and Zelinski (1990).

Soil Analysis for Potassium Fertility: Analysis of the soil to determine current soil fertility status as a means of formulating fertilizer requirements is a standard practice in cotton production in the USA. However, this is not always done every year and farmers often rely on the results of neighboring farmer fields. Soil sampling recommendations have been published for most U.S. states and the techniques are well described in the literature (e.g. Sabbe and Marx, 1987; Kerby and Adams, 1985). Generally, samples are taken in a zigzag pattern across the field so as to obtain a representative sample. Sampling is usually done in the furrow slice at a depth of 15 cm. There are a number of analytical procedures used, although the most common methods used are the ammonium acetate extraction procedure (0.05 M HCl + 0.0125 M NH_4OAc) and Mehlich's extractant method (Weir *et al.*, 1996). Other methods consider the K^+ as a ratio of Ca^{2+} + Mg^{2+}. In fields where K deficiency symptoms have been observed, it was suggested that separate soil samples should be taken from affected and unaffected areas (Snyder *et al.*, 1991), because results of a single field-wide sample are likely to mask the lower K in affected areas, resulting in a recommendation for less K fertilizer than needed. Development and use of precision fertilizer application based on variable soil analyses is a useful method of tailored fertilization gaining in popularity.

Although predictions of cotton fertilizer requirements are usually based on the nutrient concentration in the soil sample analyzed, the expected yield level should also be taken into consideration when determining the amount of fertilizer K to apply to the soil. In all interpretations of soil K fertilizer requirements, the method of extraction of K used in the analytical test needs to be taken into consideration. Recommended rates of potassium for soil application in Arkansas are presented in **Table 1**.

Table 1. Recommended rates of soil-applied K in Arkansas based on University of Arkansas soil tests[1].

Soil test K[2] mg kg^{-1}	*Recommended K kg ha^{-1}*
Above 175[3]	0
125-175	27.5
75-124	55.1
Below 50	82.7

[1]*Snyder et al., 1991; McConnell and Krist, 2000.*
[2]*15 cm depth*
[3]*Mehlich 3 extractant.*

The above rates were formulated for high yielding cotton production, e.g. 1000 kg lint ha^{-1}. Typical rates of K used in cotton in Arkansas are about 0-80 kg K ha^{-1}. This compares with higher rates in California of 0-460 kg K ha^{-1} (Weir *et al.*, 1996). This is because the soils in California are more prone to K fixation. The recommended soil sufficiency level for K varies across the US Cotton Belt. Most states use a range in their recommendations. In Arizona soil sufficiency level for K is 5 ppm (NaHCO3 extraction). In Arkansas, when soil K status is below 92 kg K ha^{-1}, application of 110 kg K ha^{-1} is recommended. However, if calcium is below about 1,350 kg ha^{-1}, reflecting low cation exchange capacity, possible salt injury should be avoided by splitting the rate between a preplant and a postplant application. The recommendations given in **Table 1** have been developed based on research over the past thirty years. However, the recommendations have not been fully calibrated for new varieties and higher yields, and possible differences in dryland and irrigated production systems need to be taken into consideration (Coker *et al.*, 2001).

Tissue Diagnoses of Plant Potassium Status: 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 (Baker *et al.*, 1992). 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 (Hsu *et al.*, 1978; Baker *et al.*, 1992). Hsu *et al.* (1978) 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. 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 (Maples *et al.*, 1977; Hsu *et al.*, 1978). However, Weir and Roberts (1993) cautioned that the result may not always provide adequate warning of impending 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 (Mascagni *et al.*, 1992). This may be related to dry conditions which are taken into consideration in the diagnostic recommendation.

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 10-20), 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 and Oosterhuis, 1996) which is presumably related to the age of the leaf (Hsu *et al.*, 1978) and its physiological activity. Samples taken on an overcast day may exhibit a 12% decrease in K concentration from the previous day (Zhao and Oosterhuis, 1998).

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% at first flower, 3.0% during peak flower, 2.0% by first open boll, and 1.0% prior to harvest (Bassett *et al.*, 1970; Singh *et al.*, 1992; Snyder *et al.*, 1991). The critical tissue level for K in cotton leaf blades in mid-to-late season is between 0.9 and 1.2% (Baker *et al.*, 1992) and maybe as low as 0.88% for significant decreases in leaf photosynthesis (Bednarz and Oosterhuis, 1999).

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 (Oosterhuis et al, 1990). 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 (Weir *et al.*, 1996). 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 (Baker *et al.*, 1992).

Recent developments with small portable selective ion meters (Cardy meter^{TM}, Spectrum Technologies, Plainfield, IL) using expressed leaf or petiole sap may provide another practical means of obtaining estimates of plant K status (Morse *et al.*, 1992). However, it is difficult to obtain a representative sample with this instrument (W.H. Baker, personal communication). Hodges and Baker (1993) reported difficulties in expressing sufficient sap for the test, even under non water-stressed conditions. There use may be for “spot” tests, but additional research is required before these can be used with any accuracy or dependability.

Fertilization With Potassium

The goal of fertilizer programs for cotton should be to achieve maximum economic return for the fertilizer investment (Kerby and Adams, 1985), even though this may not necessary 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 (Hake *et al.*, 1991). An effective economic fertilizer program must also keep in mind 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 the cotton is well documented (Bassett *et al.*, 1970; Halevy 1976) with the need for K rising dramatically when the boll load begins to develop (Halevy, 1976) because the bolls are the major sinks for this element. However, most fertilizer programs utilize a single preplant application of K with KCl being the predominant fertilizer.

However, this preplant application 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). In the Mid-South, growers sometimes make an automatic application by air during squaring and water in with sprinkler or furrow irrigation. 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 (Roberts, 1992). Accurate soil analysis coupled with mid-season plant tissue analysis are needed to formulate a suitable K fertilizer program.

Potassium fertilizer may be broadcast preplant, drilled preplant, or sidedressed while plants are still small (Kerby and Adams, 1985). Most fertilizer applications of K in the Cotton belt are surface applied or shallowly incorporated into the topsoil. Previous research in California by Gulick *et al.* (1989) 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.* (1992) 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^{-1} 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 river Delta has shown increased yields on some soils as a result of deep placement of K fertilizer at a depth of 15-30 cm (Tupper *et al.*, 1988). Yield increases from deep placement of fertilizer K have not consistently resulted in yield increases (T. Keisling, personal commun.) 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

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 (Gris, 1844). 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 US 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 (e.g. Kerby and Adams, 1985), there are fewer studies available on the usefulness of foliar-applied K. Foliar applications of K offer the opportunity of correcting deficiencies quickly and efficiently, especially late in the season when soil application of K may not be effective or possible (Oosterhuis, 1995; Weir *et al.*, 1996). Foliar feeding of a nutrient may actually promote root absorption of the same nutrient (Keino *et al.*, 1999;Thorne, 1957). The boll weevil eradication program currently in place in the US Cotton Belt is tending to decrease insecticide sprays and thereby limit opportunities for combining foliar K (or N) with insecticide treatments.

Effect of Foliar-Applied Potassium on Yield: Earlier research (Oosterhuis, 1976) indicated that foliar-applications of K significantly increased seedcotton yield. Halevy and Markovitz (1988) 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 recently Oosterhuis *et al.* (1990, 1991b, 1992, 1993) showed that foliar-applications of KNO_3 can increase yields and improve lint quality, i.e., by an average of 26 kg ha^{-1} compared to the standard soil K treatment. This research showed that in some cases it appeared possible to achieve the same effect as the foliar K by doubling the initial recommended soil-applied K. However, this may not be practical due to possible salt buildup and K fixation in some soils and because excessive K application to the soil can induce magnesium deficiency and reduce yield (Davis-Carter *et al.*, 1992). However, well-irrigation water in the Mid-south contains sufficient Mg to prevent any possible deficiency problems. Boll weight (seed + fiber) was increased from 3.52 g $boll^{-1}$ in the soil-applied KCl control plots to 3.87 g $boll^{-1}$ in the soil-plus-foliar K plots (Oosterhuis *et al.*, 1990). 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. 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, 1995), although in some cases responses to foliar fertilizer on cotton growing in soils with a higher K status have been recorded. A three-year study from 1991 to 1993 at twelve sites from North Carolina to California evaluated the effect of foliar-applied KNO_3 compared to soil-applied KCl on cotton yield and fiber quality (Oosterhuis, 1994). Yield demands varied widely in these tests and response to foliar-applied KNO_3 were variable with significant yield increases recorded about 40% of the time. 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.

Effect of Foliar-Applied Potassium on Fiber Quality: Foliar-applications of K have also been shown to improve fiber quality (Oosterhuis *et al.*, 1990). The increase occurred primarily in fiber length uniformity and strength, with micronaire increased only occasionally. In these studies, soil application of KCl alone did not enhance any of the fiber quality components. With the national emphasis on lint quality (Sasser, 1991) and the introduction of high volume instrumentation classification, the positive effect of K on lint quality may be of paramount importance.

Leaf Absorption 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 micropipette, Kafkafi (1992) 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. 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 subsequently 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.*, (1991b) who demonstrated in field studies that foliar-applied KNO_3 increased K concentration, K content of the fibers, and fiber dry weight compared to the untreated check.

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 paid to it (Alexander, 1986). It was suggested earlier that the optimal growth stages in cotton for foliar-applied K were pinhead square and first flower stages, and at peak boll development (Chokey and Jain, 1977). However, recent research has indicated that the optimum response to foliar applications of K was during the period of boll growth starting soon after flowering and continuing at weekly intervals past peak boll development (Oosterhuis, 1995) with the optimum stage occurring three weeks after first flower (Weir and

Roberts, 1993). Application rates have averaged about 4 kg K ha^{-1} (Oosterhuis, 1995) with no visible injury of cotton leaves observed at foliar application rates of up to 22 kg KNO_3 ha^{-1} (Oosterhuis et al, 1990) in 94 L water ha^{-1}. However, solubility in cold water may be a problem at rates near 10 kg KNO_3 ha^{-1}.

Sources of Potassium for Foliar Fertilization: Field studies by Miley *et al.* (1994) and Chang and Oosterhuis (1995) compared the K salts nitrate, sulfate, thiosulfate, chloride and carbonate, as foliar fertilizers applied at a rate equivalent to 11.2 kg KNO_3 ha^{-1} in 93 liters of solution per hectare. For the control and each treatment containing a source other than KNO_3, 1.5 kg N ha^{-1} as urea was applied to equal the nitrogen rate supplied by the KNO_3 treatment. Results showed a clear trend for KNO_3 to increase yield the most, followed closely by potassium thiosulfate and potassium sulfate. Potassium chloride and potassium carbonate had no effect on yield, and potassium carbonate significantly decreased yield. The detrimental effects of potassium carbonate on yield and the lack of effect on yield of potassium chloride were related to physiological effects on leaf photosynthesis and cell membrane integrity (Oosterhuis, unpublished data).

Factors Affecting Absorption and Efficacy of Foliar-Applied Potassium: 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, water deficit stress, and root temperature. Furthermore, the environmental conditions at the time of spraying can be expected to have an influence on the amount of K absorbed by the leaf. Drought has been shown to increase cuticular thickness and composition of cotton leaves and thereby reduce the penetration of foliar-applied chemicals (Oosterhuis *et al.*, 1991a). Excessively high midday temperatures and low humidity tend to decrease the amount of nutrient absorption by the leaf (Oosterhuis, unpublished). Dew can enhance the uptake of residue from the foliar fertilizers remaining on the leaf after excessive evaporation (Zhu, 1989). Questions have arisen about the compatibility of K added to foliar applications of pesticides as occurs with tank mixes of urea and pyrethroids (Long *et al.*, 1991). However, Baker *et al.* (1994) reported that pyrethroid insecticides mixed with KNO_3 remained well dispersed with mild agitation and would not be expected to pose a physical compatibility problem as found with urea-insecticide mixtures. Fertilizer mixtures of KNO_3 with urea did not have any detrimental effect on yield (Oosterhuis and McConnell, unpublished).

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 disadvantage is that the K in fertilizers prepared for foliar application may cost as much as three times more per pound of K than in ordinary soil-applied fertilizers (Snyder *et al.*, 1991).

Effect of Potassium Fertilizer on Disease

Soil-applied K has been reported to reduce the incidence of *Verticillium* wilt (*Verticillium dahliae* Kleb.) (Hafez *et al.*, 1975), although the physiological reasons for this are not clear. In California, K deficiency symptoms have often been associated with the occurrence of *Verticillium* wilt (Mikkelsen *et al.*, 1988), and the symptoms may be limited to cotton fields infested with *Verticillium* wilt (Weir *et al.*, 1986). Also, soil fumigation to reduce the incidence of *Verticillium* wilt, eliminated the foliar symptoms of K deficiency and *Verticillium* wilt (Weir *et al.*, 1986). Furthermore, varieties more tolerant of *Verticillium* wilt are often more tolerant of late-season K deficiency (Ashworth *et al.*, 1982; Weir *et al.*, 1986). *Verticillium* wilt blocks the vascular system of cotton, preventing movement of K to the developing boll load or upper canopy leaves (Ashworth *et al.*, 1982), causing the K shortage as manifested in K deficiency symptoms. Minton and Ebelhar (1991) 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. Harris (1997) reported that leaf spot, caused by *Cercospora*, *Alternaria* and *Stemphylium*, in Georgia was associated with low soil K and low petiole K.

Recent research in Arkansas has indicated that foliar-applications of K during flowering reduced the incidence ($P \geq 0.10$) of *Verticillium* wilt by 23% in the plots treated with foliar-applied KNO_3 compared to the untreated control that did not receive foliar-applied K (Janes *et al.*, 1993). In what may be a similar relationship, the incidence of *Alternaria* leaf spot was significantly reduced in Tennessee when treated with a fungicide and K (Hillocks and Chinodya, 1989). An explanation is needed for the relationship between the occurrence of disease, such as *Verticillium* wilt, and the appearance of K deficiency.

Genotypic Differences in Response to Potassium Fertilization

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.* (1990) 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 12-40% higher yields than more-sensitive cultivars (Ashworth *et al.*, 1982; Weir *et al.*, 1986). In contrast to the reports on genotypic differences in *Acala* cottons, Mullins and Burmester (1991) reported a lack of difference between cultivars in their total nutrient uptake. Pettigrew *et al.* (1992) suggested that the same genotypes should be used under both K deficient and K-sufficient conditions. In a study of genotypic responses to foliar-applied K (Janes *et al.*, 1993) indicated that there were no significant differences among cotton cultivars in response to foliar-applied KNO_3.

Suggestions for Optimum Soil and Foliar Fertilization with Potassium

A sound fertility program is essential for optimum yields and profits. This begins with an understanding of the various facets of the cotton production system and the growth of the cotton plant. Predictions of cotton fertilizer requirements should be based on a preseason soil analysis. This involves taking representative soil samples, the selection of a reliable and accurate laboratory with an accepted analytical K extraction technique, and careful diagnosis of the results for a an appropriate recommendation based on experimental field tests. The expected yield level should also be taken into consideration when determining the amount of fertilizer K to apply to the soil. In all interpretations of soil K fertilizer requirements, the method of extraction of K used in the analytical test needs to be taken into consideration. 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. However, university and industry research results and practical experience make it possible to compile appropriate K fertilizer recommendations.

Foliar application of K during boll development may be beneficial when the soil K level is inadequate, either 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 5.0% at first flower to about 2.0% near open boll. To overcome suspected K deficiencies, three to four foliar applications of K should be made during the first five weeks of boll development at weekly intervals starting at the commencement of flowering. A minimum rate of approximately 4.5 kg K /ha should be used at each application. The recommended source of K for foliar fertilization is potassium nitrate, although potassium sulfate and potassium thiosulfate 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 necessary 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 given by Roberts *et al.* (1993).

Conclusions

Judicious use of K in a well conceived cotton fertilizer program is essential for optimum plant growth, yield development and fiber quality. Potassium is required in large amounts by cotton for normal crop growth and fiber development, with a typical high yielding crop containing about 200 kg K ha^{-1}. Uptake of K by the plant follows a pattern similar to dry weight accumulation and peaks at 2.2 to 5.0 kg ha^{-1} day^{-1} a few weeks after the start of flowering. The cotton crop is more sensitive to low K availability than most other field crops, and often shows signs of K deficiency on soils not considered K deficient. Deficiencies can occur from low soil K status, K fixation in the soil, and also from the greater demand for K by modern cultivars and the inability of the root system to supply this, and possibly due to relationships with diseases such as *Verticillium* wilt. When soil analysis calls for additional

K, the cotton crop is usually fertilized with a single preplant broadcast application of K fertilizer. Mid-season applications are infrequently applied, and foliar applications are used occasionally to correct K deficiencies during fruiting. 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.

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