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Europ. J. Agronomy 24 (2006) 282–290
European Journal of Agronomy
www.elsevier.com/locate/eja

Yield and fiber quality of Upland cotton as influenced by nitrogen and potassium nutrition

John J. Read [a,*], K. Raja Reddy [b], Johnie N. Jenkins [a]

[a] *USDA-Agricultural Research Service, Crop Science Research Laboratory, 810 Highway 12 East, Mississippi State, MS 39762-5367, USA*
[b] *Department of Plant and Soil Sciences, Box 9555, Mississippi State University, Mississippi State, MS 39762-9555, USA*

Received 6 January 2005; received in revised form 30 September 2005; accepted 24 October 2005

Abstract

Nutrient stress in Upland cotton (*Gossypium hirsutum* L.) depresses lint yield, particularly of late-season fruit (bolls), and may disrupt fiber development. A 2-year (1999 and 2000) study was conducted outdoors in large pots to determine individual effects of nitrogen (N) and potassium (K) stress at flowering stage on lint yield and fiber quality. Treatments were half-strength nutrient solution from emergence to crop maturity (control), 20% and 0% of control N from first flower onward, and 20% and 0% of control K from first flower onward in 1999 and first square onward in 2000. Leaf N and K were determined every 2–3 days from an uppermost, fully expanded leaf on the main-stem of five plants selected at random. Mature bolls were harvested from sympodial (fruiting) branches only and grouped according to week of anthesis across a 35-day flowering period, providing five flowering groups, from which fiber length, strength, and micronaire were determined. Fiber length was not consistently altered by stress, suggesting early stages of fiber development were indirectly affected by plant N and K status. Nitrogen deficiency decreased yield through early termination of reproductive growth. In 1999, although flowering group four of N-deficient cotton had low length, strength, and micronaire, values for weighted-sum micronaire (whole-plant micronaire) increased under N stress by about 12% in 0% N treatment and about 18% in 20% N treatment. In general, N and K stress had opposite effects on weighted-sum micronaire. The year by N treatment interaction was significant for weighted-sum strength, due to weak fibers in N-deficient cotton in 1999, but no treatment difference in 2000. Apparently, crop response to N stress was influenced by environment, as flowering groups with low quality fiber also comprised a large fraction of total lint, and thus placed heavy demands on plant N and carbohydrate reserves. Severe K deficiency in 2000 decreased yield and lint weight boll^{-1}, and micronaire values of 3.7 or less were evident in flowering groups two, three and four. Results support evidence that N stress indirectly affects cotton growth, as N deficiency decreased fiber length, strength and micronaire primarily in flowering groups with large percentage of bolls. Results from 2000 support evidence that K deficiency adversely affects reproductive growth, boll weight, and sugar translocation in cotton.
Published by Elsevier B.V.

Keywords: Cotton; Fiber development; Micronaire; Nitrogen deficiency; Potassium deficiency; 2.5% span length; Yarn strength

1. Introduction

Yield and quality in Upland cotton (*Gossypium hirsutum* L.) are influenced by genetics and environmental conditions (Ramey, 1986; Reddy et al., 1999). Because nitrogen (N) or potassium (K) deficiency in cotton limit yield similarly through decreased leaf area expansion and CO_2 assimilation capacity, low productivity is often associated with low fiber quality (Bradow and Davidonis, 2000; Reddy et al., 2004). Fruiting structures (bolls) have a high requirement for N, and N-deficient cotton will exhibit a more determinate growth and flowering pattern (Gerik et al., 1998). The developing boll is also a major sink for K, especially the seeds (Usherwood, 2000). Because K is involved in plant water relations and carbohydrate translocation, K deficiency, unlike N deficiency, restricts fruit production to a greater extent than vegetative growth (Kerby and Adams, 1985; Pettigrew, 1997). Pettigrew et al. (1996) reported K deficiency decreased lint yield, fiber elongation, 50% span length, and micronaire in eight genotypes of differing relative earliness and regional adaptation. In that study, varying N fertilization did not affect yield or fiber quality.

Reports of fiber property trends in studies of cotton nutrition are sometimes contradictory due to the interactive effects of genotype, weather, and soil (Minton and Ebelhar, 1991;

* Corresponding author. Tel.: +1 662 320 7420; fax: +1 662 320 7544.
E-mail address: jjread@msa-msstate.ars.usda.gov (J.J. Read).

1161-0301/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.eja.2005.10.004

Pettigrew, 2003; Reddy et al., 2004). Additionally, the indeterminate growth habit of cotton, and cultivar variation in development rate, may cause fiber properties to vary in different studies (Jenkins et al., 1990; Jones and Wells, 1998). On the same day, individual bolls may be just starting fiber elongation, others starting fiber thickening and others may be completely mature (Davidonis et al., 2004). Because cotton plants continuously produce bolls that are strong sinks for plant nutrients, the onset of N or K deficiency that disrupts fiber development can be greatly influenced by plant growth and stage of development (Bradow and Davidonis, 2000; Boquet and Moser, 2003). Consequently, it is difficult to predict the effects of N or K deficiency on fiber development and lint quality without knowledge of the timing and intensity of stress (Ramey, 1986).

The blooming period in cotton is about 6 weeks and is associated with increased uptake of soil-applied nutrients (Boquet and Breitenbeck, 2000). Under ideal growing conditions (e.g., average air temperature of 30 °C), flowers are produced at 3-day intervals on the first nodes of successive fruiting (sympodial) branches up the plant and at 3–4-day intervals at successive nodes out a sympodial branch (Gerik et al., 1998). Fibers originate from the outer seed coat of the developing seed and their development occurs in three distinct processes of elongation, secondary wall thickening or maturation and then drying (Davidonis et al., 2004). Fiber elongation begins around anthesis, with maximum length occurring at approximately 20–25 days after anthesis (DeLanghe, 1986). Potassium malate is used to increase turgor pressure for growth and elongation (Ramey, 1986). The fiber begins to thicken 15–20 days after anthesis, as rings of cellulose are deposited in secondary wall formation until about 50 days after anthesis. Cellulose is deposited at slightly different angles during this thickening process, a feature that ultimately has a role in giving strength to that fiber (Davidonis et al., 2004). The degree of secondary wall deposition determines fiber maturity. Micronaire is a composite measure of maturity and fiber fineness since fiber cells with the same wall width can have different micronaire values (Davidonis et al., 2004). Micronaire tends to increase when there is ample supply of carbohydrate to mature bolls set on the plant (Pettigrew, 2001). Micronaire was linearly related to the amount of canopy photosynthesis that occurred from 15 to 45 days after flowering (Bauer et al., 2000). Thus, seasonal shifts in plant growth and metabolism are manifest in higher levels of fiber maturation in bolls from July flowers, as compared to fibers in bolls from August flowers (Jenkins et al., 1990; Davidonis et al., 2004).

Fiber length has always been important to cotton manufacturing and since the introduction of rotor spinning technology to cotton manufacturing in 1970, micronaire and strength both have increased in importance relative to other quality characteristics (Deussen, 1986). Studies of N and K nutrition in Upland cotton have usually emphasized increased yield and fruiting efficiency (Boquet and Breitenbeck, 2000; Pettigrew and Meredith, 1997), though several have been extended to include fiber quality (Minton and Ebelhar, 1991; Reddy et al., 2004; Reddy and Zhao, 2005). Pettigrew et al. (1996) found N and K supplements did not affect fiber strength, but added K increased fiber elongation. Few studies have addressed the effects of N and K deficiency on cotton quality (Bradow and Davidonis, 2000), although Heitholt (1994) examined effects of nutrient stress on percent boll retention and fiber properties in cotton. Cotton producers may be able to enhance overall profitability through utilization of agronomic practices that optimize lint quality without sacrificing yields. In precision farming research, Johnson et al. (2002) demonstrated cotton yield and fiber quality are spatially correlated; however, Bradow et al. (1999) found no meaningful correlation between fiber strength and spatial variations in levels of K or percent organic matter in the soil. Still, there is opportunity to direct cultural-input strategies during the production season and minimize effects of nutrient stress on seed cotton yield and fiber quality. The objective of this study was to determine the independent effects of N or K nutrition on cotton yield and fiber quality in the cohort of bolls from five fruiting zones, grouped according to week of anthesis, and hence, when fibers are elongating. Results should guide further research on the impacts of N and K deficiency and timing of plant nutrient stress on cotton fiber development.

2. Materials and methods

The experiment was conducted at the R.R. Foil Plant Science Research Center at Mississippi State University, Mississippi State, MS, USA (Lat. 33.416; Long. 88.782 W) with NuCotn 33B, a mid-season Upland Bt (*Bacillus thuringensis*) cultivar. Plants were grown outdoors in large, free-draining polyvinyl chloride (PVC) pots (15 cm diameter × 65 cm depth) filled with sand and supplied water and nutrients via plastic pipe and dripper system (Netafim,[1] Fresno CA). Pots were set side-by-side in 3-m long rows spaced 1 m apart in a wooden rack that was arranged in an east-west direction. Seeds were sown 17 May 1999 and 15 May 2000. Seedlings were emerged on 24 May 1999 and 21 May 2000, and thinned to one plant pot^{-1} on 11 June 1999 and 6 June 2000. Each treatment (control, N stress and K stress) was comprised of three, 1-m wide rows with plants spaced 0.15 m on center, providing 20 plants per row (replicate). This arrangement of potted plants was equivalent to a population of 65,605 plants ha^{-1}. Insects were controlled as necessary using conventional practices.

Daily thermal units (TU) were calculated each year by the following equation:

$$\mathrm{TU} = \left[\frac{T_{\max} + T_{\min}}{2}\right] - 15.5\,^{\circ}\mathrm{C} \quad (1)$$

where $T_{\max}$ and $T_{\min}$ were the maximal and minimum daily temperatures in degrees Celsius, respectively. Daily temperatures were recorded from a weather station adjacent to the field site. Thermal units are sometimes used to predict the attainment of different crop growth and development events, because cot-

[1] Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or Mississippi State University, and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

ton growth increases linearly as temperature increases between 15.5 and 31.1 °C (Jones and Wells, 1998; Reddy et al., 1999).

All control and border rows were fed a favorable supply of water and nutrients using half-strength nutrient solution (Hewitt, 1952), containing 85.7 mg N L^{-1} and 138.1 mg K L^{-1}, via one Netafim dripper per pot rated at 1 L liquid h^{-1}. Plants were irrigated three times each day to provide 120% of daily pan evaporation, measured at the nearby weather station, in order to maintain optimum water conditions throughout the experiment. The different N and K treatment solutions were contained separately in mixing tanks and pumped through plastic lines to each 3-row treatment plot. All timing and duration of flows was under computer-controlled switches and solenoid valves. At various phenological stages, the plants in some three-row plots were supplied nutrients with an osmotically balanced nutrient solution (Hewitt, 1952). The three N treatments were: (1) control, a half-strength nutrient solution supplied from plant emergence to maturity; (2) 20% N at first flower stage, a moderate stress imposed from first flower stage (52 DAE) to maturity; and (3) 0% N at first flower, a severe stress imposed by completely withholding N from first flower (52 DAE) to maturity. The three K treatments were: (i) control from plant emergence to maturity; (ii) 20% of control K commenced either 52 DAE in 1999 or 31 DAE in 2000; and (iii) 0% of control K commenced either 52 DAE in 1999 or 31 DAE in 2000. The K-stress treatments were initiated at an earlier growth stage in 2000 in order to elicit K deficiency sooner in plant development, as visible symptoms were observed late in the season in 1999 when K was withheld at flowering stage. Reducing the amount of N or K available would dilute the amount of nutrient in plant tissues due to continued growth.

Plant nutrient status was assessed every 2–3 days by excising an uppermost, fully expanded leaf on the main-stem of five plants selected at random. Total N in these leaves provides an estimate of the N accumulated by the plant prior to sampling (Gerik et al., 1998). Although plant K is typically assessed from petiole K (Kerby and Adams, 1985), we used leaf blades because of their importance to light interception and dry matter production and to minimize environmental effects on water and nutrient uptake. The five leaves were combined, dried at 70 °C and ground to pass a 0.5-mm (40 mesh) screen in a small Wiley mill. Leaf N was determined according to standard micro-Kjeldahl methods (Nelson and Sommers, 1972), and K was measured on nitric-perchloric acid digests using inductively coupled plasma optical emission spectrometry. Because leaves were pooled prior to nutrient analysis, the number of observations on each sampling date is equivalent to the number of treatments. While pooling across reps precluded any statistical analysis of treatment differences, one of the primary objectives of this study was to determine if temporal changes in leaf N and K under nutrient stress are related to yield and quality of a cohort of bolls in different fruiting zones, based on week of anthesis. Several samples of NIST-certified standards of dried apple (N = 22.5 g kg^{-1}; K = 16.1 g kg^{-1}) and spinach (N = 59.0 g kg^{-1}; K = 29.0 g kg^{-1}) leaves (U.S. Department of Commerce, NIST, Gaithersburg, MD, USA) were included during laboratory analyses. The sample standard deviation for leaf N was 2.0 g kg^{-1} for apple and 4.2 g kg^{-1} for spinach. The sample standard deviation for leaf K was 2.2 g kg^{-1} for apple and 2.5 g kg^{-1} for spinach.

Daily during the reproductive period, sympodial-branch position white blooms (flowers at anthesis) were tagged with a jeweler tag bearing the current date. Bolls from monopodial branches were also tagged, but were not used for fiber analysis. Tagging white blooms for all treatments on the same day insured that the tagged blooms were of equivalent metabolic and developmental ages for each treatment (Ramey, 1986; Pettigrew, 2001). Lint from only sympodial branches was grouped according to week of anthesis across a 35-day flowering period, giving five flowering groups, from which lint yield and fiber properties were measured.

Irrigations were terminated on 29 September 1999 and on 22 September 2000 when more than 60% of bolls were opened. At harvest, the remaining tagged bolls (those not lost by injury or natural fruit abortion) were harvested by hand and their specific node and sympodial-branch position recorded. Lint yield was determined from mature bolls that were each ginned individually using a roller gin. Lint from each flowering group (week of flowering for sympodial-branch fruit) was pooled across 20 plants in each replicate and a 10-g sample was sent to Starlab (Knoxville, TN, USA). Individual, traditional instruments (digital fibrograph, stelometer, and micronaire instrument) were used to measure length (2.5% span length), strength (tenacity) and micronaire. Length and strength were determined twice and the values averaged for statistical analysis. The 2.5% span length is the length spanned by the longest 2.5% of the fibers in the test sample and was measured with a digital fibrograph. Fiber bundle strength was measured by stelometer. While additional factors of length uniformity, maturity index, color, trash and sample preparation also establish quality, this paper will deal only with 2.5% span length, fiber strength and micronaire.

All data were subjected to analysis of variance using PROC GLM procedures in SAS (SAS Institute, 1999). Year and the interactions with year were designated as random effects in the various models. In terms of lint yield, data for each flowering group were summed across 20 plants in each replicate in order to determine whole-plant responses to N and K deficiency. Lint weight $boll^{-1}$ was expressed as the ratio of total lint produced to total number of bolls in each replicate. In regards to fiber quality on a whole-plant basis, values for length, strength and micronaire in each flowering group were weighted by the fraction of lint produced, based on the summation of lint in each 20-plant replicate, year, treatment combination. Then these weighted fiber quality values were averaged across the five flowering groups. Thus, fiber quality expressed as a weighted-sum average was weighted toward where (or more precisely when) on an average plant the most amount of lint was produced. Analysis of variance was performed within each flowering group to determine the effects of treatment and year by treatment interaction on yield fraction, boll number and fiber quality. Treatment means were separated using Fisher's protected least significant difference (LSD) test at $P < 0.05$.

Table 1
Week of anthesis, total number of mature bolls (number of plants harvested is in parentheses), and average lint weight boll^{-1} in five flowering groups of cotton grown outdoors in large pots supplied half-strength Hoagland's solution (control) in irrigation water throughout the experimental period

Flowering group	Week of anthesis		Bolls (no. three reps^{-1})		Lint weight (g boll^{-1})	
	1999	2000	1999	2000	1999	2000
One	11–17 July	9–16 July	135 (52)	231 (53)	1.44	1.71
Two	18–24 July	17–23 July	219 (55)	308 (57)	1.45	1.61
Three	25–31 July	24–30 July	188 (56)	229 (54)	1.92	1.59
Four	1–7 August	1–6 August	253 (56)	125 (47)	2.00	1.47
Five	8–14 August	7–15 August	48 (30)	42 (29)	1.62	1.22

Note: Data are for sympodial (fruiting) branches only from 60 control plants. Open bolls were first observed 22 August 1999 and 17 August 2000. Irrigations stopped at 29 September 1999 and 22 September 2000. Including vegetative branches, the total number of bolls harvested was 924 in 1999 and 976 in 2000.

3. Results

3.1. Plant and environment effects

Among control plants, the anthesis dates of each flowering group were similar in both years, although flowers occurred about 1 day sooner in 2000 than 1999 (Table 1). A large number of bolls was harvested from flowering groups two and three (mainstem nodes 6–12 and 8–14, respectively), which corresponded to nodes that are typically the most productive fruiting branches for cotton in the mid-south (Jenkins et al., 1990). Among all treatments, flowering groups two and three made up a large fraction, from about 50–65%, of the total lint yield in both years (Table 2). Analysis within each treatment found a significant ($P < 0.01$) effect of year by flowering group interaction for yield fraction. This interaction was influenced by boll number, because a large number was harvested from flowering groups two, three and four in 1999; whereas, groups one, two and three were generally most productive in 2000 (Table 3).

While temperature conditions were not excessive, differences in environmental conditions between years had potential to alter plant development (Fig. 1). Thermal units (Eq. (1)) accumulated between planting and harvest, 17 May to 31 October, were similar in 1999 and 2000 (1515 versus 1543), but the distribution differed between years. In 1999, warm temperature conditions

Table 2
Effects of nitrogen (N) and potassium (K) stress at flowering stage on percentage of final lint weight in mature cotton bolls harvested in five flowering groups from sympodial branches only of cotton grown outdoors in large pots in 1999 and 2000

Stress treatment	Group one		Group two		Group three		Group four		Group five	
	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
Control	13.2	26.5	21.9	33.2	24.6	24.5	34.8	12.3	5.4	3.4
20% N FF	16.2	26.4	36.9	34.9	28.2	29.7	18.3	7.9	0.4	1.1
0% N FF	17.3	33.7	40.9	44.4	23.5	19.5	18.4	2.5	nd	nd
20% K FF/FS	8.0	27.6	22.3	23.6	25.4	26.6	37.8	15.0	6.6	7.2
0% K FF/FS	13.7	40.6	24.3	33.0	24.4	21.6	34.5	3.6	3.1	1.9
Average S.E.	1.1	2.1	1.7	2.0	2.6	1.8	2.5	1.2	0.7	1.0

Note: Values represent the mean of three replicate rows with 20 plants in each row. Control, half-strength nutrient solution at plant emergence onward; 20% N FF, 20% of control N at first flower onward; 0% N FF, 0% of control N at first flower onward; 20% K FF/FS, 20% of control K at first flower (1999) or first square (2000) onward; 0% K FF/FS, 0% of control K at first flower (1999) or first square (2000) onward. Average S.E., experimental standard error of the mean. nd, no data.

Table 3
Effects of nitrogen (N) and potassium (K) stress at flowering stage on number of mature cotton bolls harvested in five flowering groups from sympodial branches only of cotton grown outdoors in large pots in 1999 and 2000

Stress treatment	Group one		Group two		Group three		Group four		Group five	
	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
Control	45	77	73	103	63	76	84	42	16	14
20% N FF	55	71	105	96	74	91	50	26	2	3
0% N FF	47	70	96	98	56	55	46	7	nd	nd
20% K FF/FS	42	80	78	79	76	88	105	48	26	24
0% K FF/FS	38	65	71	70	55	52	83	11	11	5
Average S.E.	4.0	6.0	4.9	7.4	6.8	6.1	5.3	3.4	2.1	3.0

Note: Values represent the mean of three replicate rows with 20 plants in each row. Control, half-strength nutrient solution at plant emergence onward; 20% N FF, 20% of control N at first flower onward; 0% N FF, 0% of control N at first flower onward; 20% K FF/FS, 20% of control K at first flower (1999) or first square (2000) onward; 0% K FF/FS, 0% of control K at first flower (1999) or first square (2000) onward. Average S.E., experimental standard error of the mean. nd, no data.

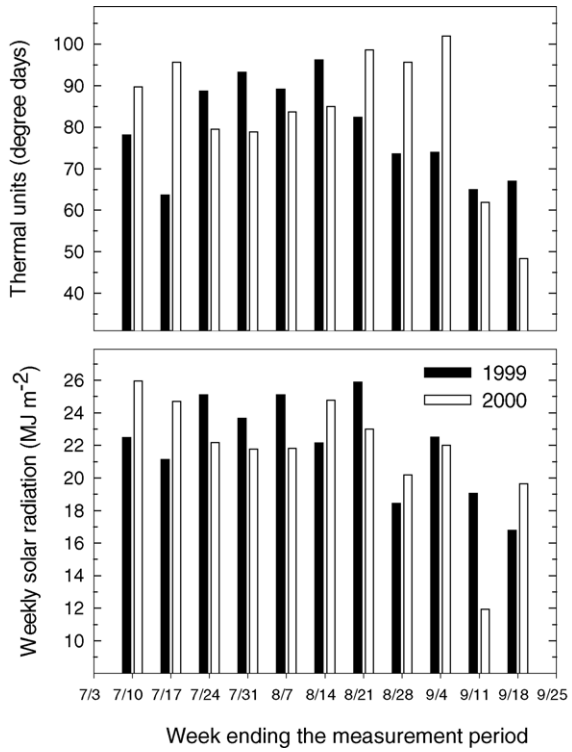

Fig. 1. Total weekly thermal units and average weekly solar radiation in July, August and September 1999 and 2000 based on daily weather data collected at Mississippi State, MS, USA.

and high solar radiation from about 17 July to 7 August, the peak-flowering period, may have contributed to less boll retention of flowering group one (Table 3), as well as group two in control (Table 1). In 2000, warm temperature conditions from about 21 August to 4 September may have contributed to low yield fraction and less retention of bolls in flowering group four (Tables 2 and 3).

Weighted-sum fiber length averaged significantly less in 1999 than 2000 (28.2 mm versus 29.0 mm, Tables 4 and 5). Fiber length of flowering group one was consistently less in 1999 than 2000, averaging from 1.0–2.2 mm shorter in the different treatments. Low fiber length in 1999 was associated with somewhat warmer conditions in July and somewhat lower leaf N under N stress in 1999, as compared to 2000 (Fig. 2). Among control plants in 1999, micronaire values increased linearly across flowering groups one to four (Table 4), and was associated with increased lint weight boll^{-1} (Table 1). The opposite trend was observed in 2000, as micronaire and lint weight boll^{-1} decreased as flowering group increased.

3.2. Nitrogen stress effects

In 1999, the decline in leaf N in 20% N treatment resulted in plants considered low in N (25–30 g kg^{-1}; Gerik et al., 1998) on most sampling dates in August. Leaf N levels in 0% N treatment in 1999 ranged from 25 to 30 g kg^{-1} following 23 July, and were below 25 g kg^{-1} on most sampling dates in August (Fig. 2). Boll demand for N was evident from changes in leaf N in 1999, which increased in the first week of boll-filling (about 7–14 August) before declining to about 25 g N kg^{-1} on 16 August 1999. Leaf N declined rapidly under stress in 2000, but only 0% N treatment was considered low or deficient in N by mid-August (Gerik et al., 1998).

Lint yield was significantly lower in 0% N treatment than control and 20% N treatments, and averaged about 9% and 20% lower than control in 1999 and 2000, respectively (Fig. 3). Nitrogen deficiency (leaf N < 25 g kg^{-1}; Gerik et al., 1998) generally had an opposite effect on average lint weight boll^{-1}, which

Table 4
Effects of nitrogen (N) stress treatments on selected fiber quality characteristics in five flowering groups and for weighted-sum treatment means of cotton grown outdoors in large pots in 1999 and 2000

N-stress treatment	Group one		Group two		Group three		Group four		Group five		Weighted sum	
	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
2.5% span length (mm)												
Control	28.2	29.7	28.8	29.4	29.1	28.5	29.6 a	27.6	31.6	28.1	28.5	28.9
20% FF	27.9	29.6	28.4	29.4	29.1	28.4	28.4 a	28.3	28.7	28.2	28.4	29.0
0% FF	27.8	29.9	28.4	29.5	29.3	28.0	26.2 b	27.8	nd	nd	28.1	29.3
Year × treatment	0.853		0.833		0.798		0.002		0.073		0.682	
Strength (kN m kg^{-1})												
Control	220.2	205.5	224.2 a	199.9	230.3 a	198.6	221.8 a	186.0	232.4	191.4 b	219.3 a	199.2
20% FF	206.3	218.2	211.3 a	210.5	220.7 a	199.2	207.2 a	200.4	211.8	219.4 a	212.1 b	207.7
0% FF	210.4	210.5	193.2 b	203.8	207.4 b	197.8	189.4 b	201.7	nd	nd	198.8 c	204.6
Year × treatment	0.105		0.177		0.233		0.031		0.045		0.009	
Micronaire												
Control	3.4 b	4.5	4.2 b	4.3	4.4	4.1	4.8 ab	4.0	4.2	3.4 b	4.3 b	4.2
20% FF	4.8 a	4.5	5.3 a	4.2	5.2	4.5	4.9 a	4.1	4.3	4.7 a	5.1 a	4.4
0% FF	4.8 a	4.8	5.2 a	4.8	4.8	3.9	4.2 b	3.7	nd	nd	4.8 a	4.6
Year × treatment	0.034		0.022		0.530		0.689		0.024		0.069	

Note: Weighted sums were calculated by weighting each fiber property by the amount of lint produced in each flowering group. Control, half-strength nutrient solution at plant emergence onward; 20% FF, 20% of control N at first flower onward; and 0% FF, 0% of control N at first flower onward. Within a flowering group and year, means followed by a different letter are significantly different by Fischer's protected LSD test at $P = 0.05$. Year × treatment, probability of F-statistic for year by N treatment interaction. nd, no data.

Table 5
Effects of potassium (K) stress treatments on selected fiber quality characteristics in five flowering groups and for weighted-sum treatment means of cotton grown outdoors in large pots in 1999 and 2000

K-stress treatment	Group one		Group two		Group three		Group four		Group five		Weighted sum	
	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
2.5% span length (mm)												
Control	28.2	29.7	28.8	29.4	29.1	28.5	29.6	27.6	31.6	28.1	28.5	29.0
20% FF/FS	28.4	29.4	28.9	28.7	30.1	28.4	29.6	28.0	31.8	29.2	28.3	28.7
0% FF/FS	27.7	29.9	29.1	29.2	30.1	28.0	27.9	27.7	29.2	26.7	28.4	29.1
Year × treatment	0.224		0.452		0.387		0.220		0.787		0.970	
Strength (kN m kg^{-1})												
Control	220.2	205.5	224.2	199.9	230.3	198.6	221.8	186.0 b	232.4	191.4 b	219.3	199.2
20% FF/FS	201.5	223.4	217.2	216.6	221.2	220.6	216.1	210.0 ab	249.1	230.6 a	207.9	219.6
0% FF/FS	221.4	225.9	226.0	219.0	228.5	184.9	218.9	221.6 a	210.4	194.2 b	221.6	212.5
Year × treatment	0.182		0.540		0.132		0.063		0.280		0.075	
Micronaire												
Control	3.4 b	4.5	4.2	4.3 a	4.4	4.1	4.8	4.0 ab	4.1	3.4	4.3	4.2 ab
20% FF/FS	4.4 a	4.7	4.3	4.3 a	4.1	4.6	4.7	4.7 a	3.2	4.5	4.2	4.6 a
0% FF/FS	4.4 a	4.0	4.3	3.2 b	3.5	3.7	4.4	3.6 b	2.8	4.0	4.0	3.7 b
Year × treatment	0.049		0.021		0.496		0.149		0.089		0.126	

Note: Weighted sums were calculated by weighting each fiber property by the amount of lint produced in each flowering group. Control, half-strength nutrient solution at plant emergence onward; 20% FF/FS, 20% of control K at first flower (1999) or first square (2000) onward; 0% FF/FS, 0% of control K at first flower (1999) or first square (2000) onward. Within a flowering group and year, means followed by a different letter are significantly different by Fischer's protected LSD test at $P = 0.05$. Year × treatment, probability of F-statistic for year by K treatment interaction. nd, no data.

was significantly greater than that of controls in both years, and greater than 20% N treatment in 2000. In three out of four comparisons between control and 20% N treatments, both lint yield and weight boll^{-1} were significantly greater in 20% N treatment.

As compared to control plants, weighted-sum micronaire in 1999 was about 12% greater in 0% N treatment and 18% greater in 20% N treatment (Table 4). Flowering groups one and two, and to a lesser extent group three, contributed to high micronaire observed under N stress. In 20% N treatment, values for weighted-sum micronaire and the micronaire of flowering groups two, three and four exceeded 4.9 (in other words, were

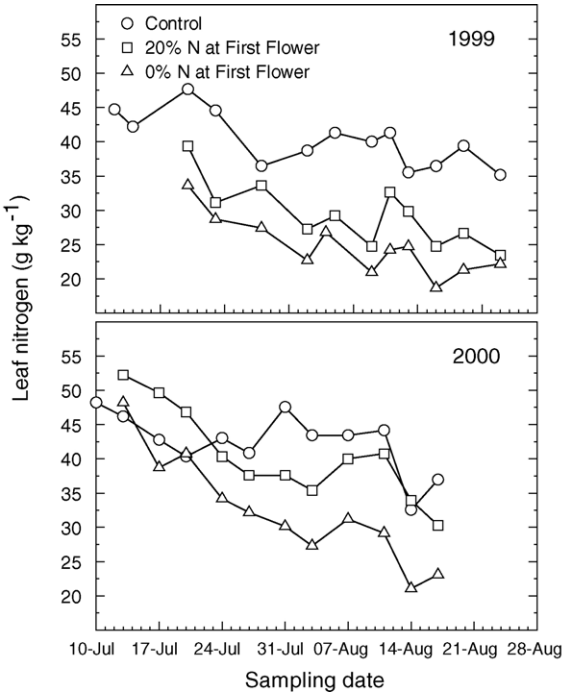

Fig. 2. Nitrogen concentration in uppermost, fully expanded leaves of cotton grown outdoors in large pots under three N treatments in 1999 and 2000. Values represent a single observation on each sampling date, based on a pooled sample of five leaves.

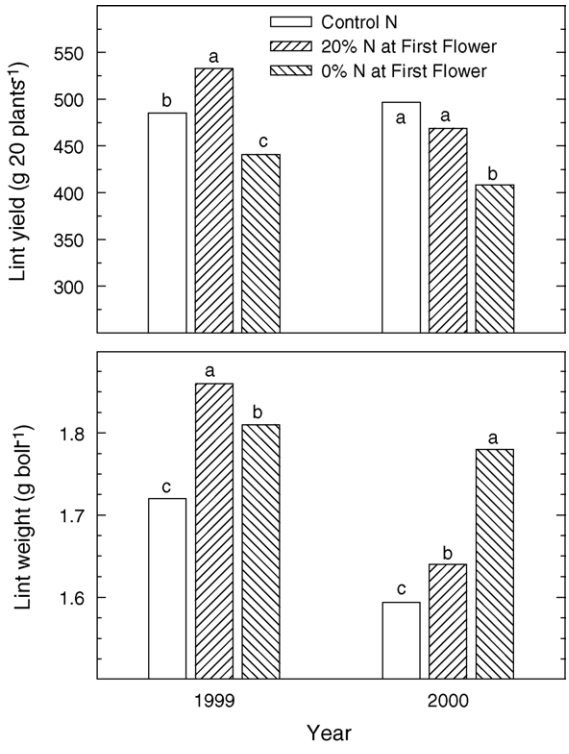

Fig. 3. Effects of N stress on lint yield and lint weight boll^{-1} of mature bolls harvested from sympodial branches of cotton grown outdoors in large pots. Values represent the mean of three observations, and were obtained by first summing across five flowering groups in each 20-plant replicate.

penalty grade). Nitrogen deficiency, however, did not consistently increase fiber micronaire. In 1999, flowering group four in 0% N treatment had significantly lower micronaire, as well as fiber length and strength, than 20% N treatment. A similar, but nonsignificant trend was observed in 2000, when micronaire of flowering group four averaged 3.7 in 0% N treatment. The year by treatment interaction was significant for micronaire of flowering groups one, two, and five.

The 0% N treatment in 1999 significantly decreased weighted-sum fiber strength and fiber strength of flowering groups two, three and four, as compared to control or 20% N treatment (Table 4). Analysis of variance found a highly significant ($P < 0.01$) effect of year by N treatment interaction for weighted-sum strength, due to weak fibers under N stress in 1999, but similar fiber strength among treatments in 2000. The year by treatment interaction was significant for fiber strength of flowering groups four and five.

3.3. Potassium stress effects

As expected, symptoms of K deficiency, including yellowing and premature leaf drop, were more pronounced in 2000 than 1999 because K was withheld sooner. In general, cotton is K deficient when its leaf concentration falls below 15 g kg^{-1} at early bloom (Kerby and Adams, 1985). The 20% K treatment lowered leaf K to about 10 g kg^{-1} in 1999 and 12.5 g kg^{-1} in 2000 (Fig. 4). Severe K stress was possibly manifested in 0% K treatment in both years, as K in uppermost leaves dropped below 5 g kg^{-1} in mid August 1999 and late July 2000.

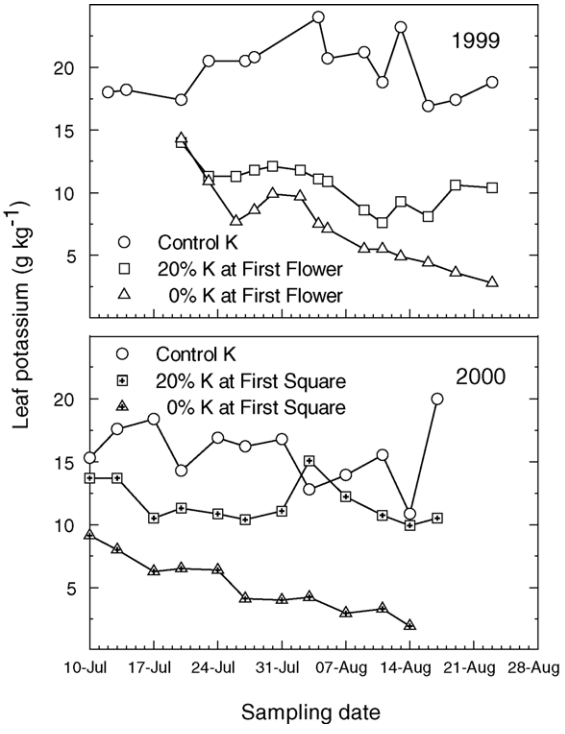

Fig. 4. Potassium concentration in uppermost, fully expanded leaves of cotton grown outdoors in large pots under three K treatments in 1999 and 2000. Values represent a single observation on each sampling date, based on a pooled sample of five leaves.

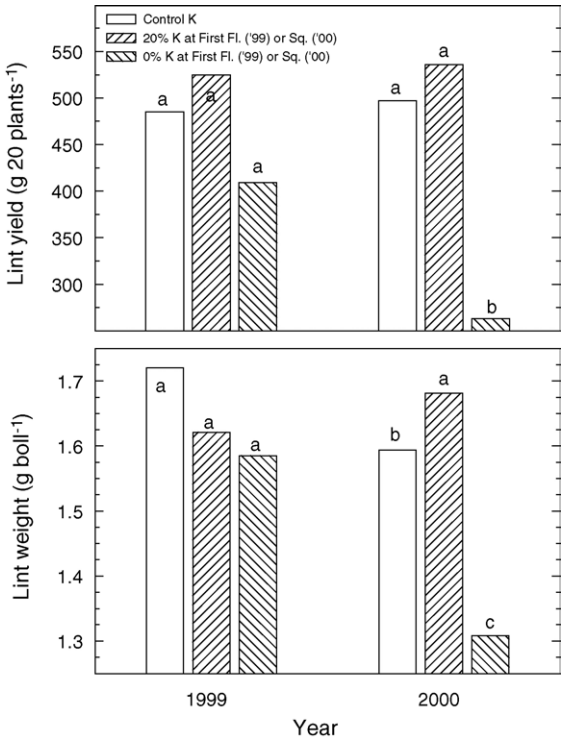

Fig. 5. Effects of K stress on lint yield and lint weight boll^{-1} of mature bolls harvested from sympodial branches of cotton grown outdoors in large pots. Values represent the mean of three observations, and were obtained by first summing across five flowering groups in each 20-plant replicate.

In 1999, lint yield and lint weight boll^{-1} did not differ among treatments, but yields were least in 0% K treatment (Fig. 5). This trend was highly significant in 2000, when K deficiency decreased lint yield by about 55% and weight boll^{-1} by about 20%, as compared to control. Decreased yield of K-deficient cotton in 2000 was associated with smaller number of bolls in all flowering groups (Table 3). The year by treatment interaction was significant for lint yield due to a large K-induced decrease in 2000 when K was withheld sooner.

Fiber length was not significantly affected by K stress (Table 5), although 0% K treatment in 1999 decreased fiber length of flowering group four by about 1.7 mm ($P < 0.20$), as compared to control or 20% K treatment. In flowering group five, K stress decreased fiber length by about 2.5 mm in 1999 ($P > 0.38$) and by about 1.4 mm in 2000 ($P > 0.11$), as compared to controls. Fiber strength of flowering group five decreased slightly in 1999, and was significantly lower in 0% K than 20% K treatment in 2000. Micronaire decreased significantly in 2000, and values nearly 1.0 unit less than those in 20% N treatment were evident in weighted-sum micronaire and in flowering groups two and four (Table 4). In 2000, weighted-sum micronaire and micronaire of flowering groups two, three, and four was 3.7 or less. Similarly, micronaire values below 3.7 were evident in 1999 in flowering groups three and five, but no significant treatment differences were detected. These results suggest severe K deficiency may decrease micronaire when leaf K falls below 10 g kg^{-1} for an extended period.

4. Discussion

The present study determined changes in lint yield and fiber quality, due solely to N or K stress, in mature bolls grouped according to week of anthesis. Cotton was grown outdoors in large pots and provided different levels of N or K in nutrient solution from flowering stage to crop maturity in order to determine the dynamics of stress development and if changes in leaf N or K are related to fiber quality. In agreement with other studies (Jenkins et al., 1990; Davidonis et al., 2004), difference between years in boll distribution within the crop had a marked effect on where (or more specifically when) a significant effect of nutrient stress was detected in the five flowering groups. The inconsistent effects of N and K stress on fiber quality across years, suggests that plants experienced different levels of stress because of what happened to boll development in the 2 years (Jones and Wells, 1998). Consequently, we were unable to determine quantitatively the relationships between changes in leaf N or K and the fiber quality of five flowering groups. The influence of environment was most evident under N stress in 1999, as the cohort of bolls with low length, strength and micronaire (flowering group four) also comprised a large fraction of total lint, and thus placed a large demand on the plant for nutrient and carbohydrate reserves. Because the N-stress treatments did not differ in yield fraction (Table 2) or boll number (Table 3), a possible explanation is 0% N treatment depressed photosynthesis enough to impact fiber quality (Reddy et al., 2004). Fiber quality of flowering group four was not affected by N stress in 2000, when comparatively more lint was produced from earlier flowering groups that presumably escaped the adverse effects of N deficiency later in the season.

Similar to Reddy et al. (2004), lint weight boll^{-1} increased in cotton provided either 0% or 20% of control N, but lint yield was significantly less than control in 0% N treatment only. These results support evidence that decreased yield under N stress is related more to decreased boll number than boll weight (Wullschleger and Oosterhuis, 1990). The mechanism by which the crop partitions its C and N is complex (Boquet and Breitenbeck, 2000). Because N-stress limits several growth processes (Reddy et al., 1997; Gerik et al., 1998), increased lint weight boll^{-1} under stress likely resulted from better light distribution within the canopy due to reduced leaf area index (Wullschleger and Oosterhuis, 1990; Reddy et al., 2004).

In 1999, values for weighted-sum micronaire increased to about 5.1 (in the discount range) when plants were sufficient to low in N (20% N treatment) and to about 4.8 when plants were low to deficient in N (0% N treatment). This agrees with reports of increased micronaire as leaf N decreased due to limited availability of N either in nutrient solution (Reddy et al., 2004) or field soil (Bauer and Roof, 2004). An overall increase in assimilate supply would help to explain the increase in micronaire of flowering group one in N-deficient plants, particularly if canopy photosynthesis was favored by the warm conditions evident early in the season 1999 (Reddy et al., 1999; Bauer et al., 2000). A large (1.0 unit) increase in micronaire of flowering group one was also observed in both K-stress treatments in 1999. This response is inconsistent with field studies showing either no change (Minton and Ebelhar, 1991) or decrease (Pettigrew, 1999) in micronaire under low K fertility. It also disagrees with leaf K values that were generally below 10 g kg^{-1}, a level associated with decreased growth and photosynthesis (Kerby and Adams, 1985; Reddy and Zhao, 2005). Jones and Wells (1998) reported a positive correlation between micronaire and dry weight boll^{-1} across various sympodial-branch positions and plant populations in the field. Similarly, low micronaire was evident in control in 1999, particularly in flowering groups one and two, and was associated with low average lint weight boll^{-1}. Favorable N or water status appears to result in low micronaire due to shading of lower bolls and leaves, which may reduce the amount of carbohydrate available to mature bolls (Gerik et al., 1998; Pettigrew, 2001).

Similar to results of Reddy et al. (1999) with temperature and Reddy et al. (2004) with N nutrition, our results of significant year by N treatment interactions indicate fiber strength is influenced by environment. Nevertheless, the 0% N treatment in 1999 often led to significant reductions in fiber strength. Cotton was low or deficient in N following 23 July 1999, but was generally not N-deficient in 2000. Nutrient stress 20–40 days post-anthesis is expected to impact fiber strength development (Ramey, 1986; Bradow and Davidonis, 2000). Because fiber development became increasingly N-limited in 1999 as nutrient reserves were utilized, the 0% N treatment produced low strength fibers in flowering groups two, three, and four, that also supported a high percentage of the total lint yield. The 2.5% span length was influenced by both N stress and environment. Consistent with evidence that fiber length is associated positively with leaf N during boll maturation period (Reddy et al., 2004), N-deficient cotton in 1999 (leaf N < 25 g kg^{-1}; Gerik et al., 1998) had low fiber length in flowering group four. Similar to Reddy et al. (1999), the warm temperature conditions evident during the blooming period in 1999 were associated with significantly lower weighted-sum length of cotton in 1999 than 2000.

In contrast to N stress, the 0% K treatment from squaring-stage onward in 2000 led to significant reductions in lint weight boll^{-1}, which adversely impacted lint yield. The observed reductions in cotton yield and micronaire in K-deficient cotton in 2000 is consistent with reports that K deficiency causes premature termination of reproductive growth (Pettigrew, 2003), low boll weight (Kerby and Adams, 1985) and decreased translocation of sugars out of the leaf (Pettigrew, 1999). Recently, Reddy and Zhao (2005) reported the critical leaf K for cotton photosynthesis, biomass and stem growth was 12 g kg^{-1}, and for leaf area expansion the critical value was 17 g kg^{-1}. In that study, less biomass partitioning to bolls was due to increased fruit abscission under K stress. In the present study, leaf K of 5–10 g kg^{-1} observed in the 0% K treatment would have certainly depressed leaf growth and photosynthesis, and altered biomass partitioning to various plant components (Reddy and Zhao, 2005). Because fiber length, strength, and micronaire were not adversely affected until K deficiency was severe, there may be little concern that K deficiency will adversely impact fiber quality in commercial situations.

An apparent direct effect of K deficiency on lint quality was observed for micronaire (Table 5), with values sometimes at

or below the discount of 3.5 and not strictly related to fibers that developed in the most productive flowering groups. No other fiber property traits were consistently altered by K deficiency. Low micronaire cotton (<3.5) will have a thin cell wall with a smaller amount of cellulose in the fiber cell. Added K appears to increase metabolic processes related to secondary-wall thickening (Bradow and Davidonis, 2000). Pettigrew (1999, 2003) found plants grown at 0 kg K ha^{-1} produced lint with low micronaire, but values were not less than 3.8. Reductions in overall plant assimilate levels and partitioning to bolls would help explain the lower micronaire in some flowering groups in the present study.

Despite decades of research on crop N and K management (Kerby and Adams, 1985; Gerik et al., 1998), few studies have determined the consequences of limited nutrient availability on cotton fiber development in different fruiting zones (Bradow and Davidonis, 2000; Reddy et al., 2004). Our results indicated N stress indirectly influenced fiber quality, because N deficiency in cotton (leaf N < 25 g kg^{-1}; Gerik et al., 1998) and a relatively high boll load combined to produce low quality fiber. Nitrogen stress in 1999 produced cotton with low fiber strength and high micronaire. A lack of consistent (N stress) or significant (K stress) treatment difference in fiber length suggested that early stages of fiber development were indirectly affected by nutrient stress. Results also indicated that N and K stress in cotton will likely have opposite effects on fiber micronaire.

Acknowledgements

The authors would like to thank P.J. Bauer, J.M. Bradow, and W.T. Pettigrew for their helpful comments on the manuscript, and Mr. D. Brand, Mr. K. Gourley, and Mr. W. Ladner for their excellent technical assistance. This study was in part supported by The National Aeronautical and Space Administration-funded Remote Sensing Technology Center at Mississippi State University (NASA grant number NCC13-99001).

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