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Quantitation of cotton fibre-quality variations arising from boll and plant growth environments

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Abstract

Crop growth simulation models used to manage cultural inputs and to improve yields of cotton, *Gossypium hirsutum* L., do not address fibre quality, a major determinant of cotton fibre price and end-use. Fibre maturation simulations require rapid, reproducible methods for fibre quality quantitation at the boll or locule level. Combination of fibre quality mapping by fruiting site with quality quantitation by an electron-optical particle sizer provided replicated, reproducible data suitable for use in predictive models and quantitative studies of fibre quality variations attributable to genotype and growth environment. The efficacy and potential of this unique fusion of agronomic and textile technologies were examined through comparisons of three 1992 fibre quality database subsets from the US Southeastern Coastal Plain and Mississippi Delta. Comparisons of 'Pee Dee 3' fibre quality, on a locule-by-locule basis at positions 1 and 2 on main-stem nodes 5 through 18, revealed that fibre length, cross-sectional area, and physical maturity varied among fruiting sites. Subsurface microirrigation applied during an early-season drought increased fibre yield by 40%, significantly increased fibre fineness, and decreased fibre maturity indicators. Fibre length variations were compared between ginning methods and among nine genotypes grown in the Coastal Plain. Irrigation-related reductions in physical fibre maturity, found in the Coastal Plain, were contrasted with chronological maturities of 'DPL5415' and 'DES119' fibre harvested 21, 28, 35, 42, or 56 days post-anthesis in the Mississippi Delta. Fibre-quality mapping with particle-sizing represents a powerful, new tool for constructing fibre development simulations essential for improving cotton fibre quality and processing outcome. © 1997 Elsevier Science B.V.

Keywords: *Gossypium hirsutum* L.; Cotton; Fibre; Quality quantitation; Length; Maturity; Growth environment; Microirrigation

1. Introduction

In most crop production systems, yield and financial return to the producer depend on the quantity and quality of marketable component harvested. In the US, price, marketability, and utility value of cotton fibre are decided by the cotton classing system (USDA, 1980) in which micronaire, length, short fibre content, and strength/elongation are measured by high volume instrument (HVI) testing (Deussen, 1992; Behery, 1993; Sasser, 1994). Fibre properties, which are important to processors but for which HVI testing

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provides no quantitation, include fibre fineness and maturity in either the physiological (duration of fibre growth after floral anthesis) or physical (degree of fibre/cell wall thickening) sense (Lord and Heap, 1988; Deussen, 1992; Behery, 1993; Pellow et al., 1994).

Recognition that the price received by cotton producers depends on fibre quality, as well as yield, has increased interest in fibre-growth models comparable to cotton plant-growth simulations such as GOSSYM/COMAX (Baker et al., 1983; Lemmon, 1986). GOSSYM/COMAX simulates growth of the cotton plant from data collected on an organ-by-organ basis and coupled with data on soil density, hydrological and fertility properties. Recently, GOSSYM/COMAX models have been augmented by using branch-by branch and boll-by-boll yield monitoring (mapping) designed to determine how a cotton crop responded to cultural and environmental factors affecting its development (Jenkins et al., 1990a,b; Kerby, 1994). However, the combination of plant-mapping techniques with HVI fibre quality measurements is not feasible since large and, consequently, blended fibre samples are required for HVI determinations. Standard US cotton classing office HVI assays (omitting multi-sampling and colour and trash content determinations) require 3.0–3.3 g of randomly collected, ginned fibres (Annual Book of ASTM Standards, 1988). Cotton bolls contain three to five locules, and mature fibre from an individual locule weighs approximately 0.5 g (Leffler, 1986; Jenkins et al., 1990b). Non-instrumental and microscopic fibre-quality small-samples assay techniques are primarily qualitative, expensive, and subject to significant sampling bias (Munro, 1987).

Textile testing instrumentation includes a fibre quality quantitation method that has no minimum sample-size limit. The Uster Advanced Fibre Information System (AFIS), an airflow electron-optical particle sizer, rapidly and reproducibly measures fibre lengths, diameters, cross-sectional areas, and circularities (degrees of wall thickening, θ) of fibre samples taken from a single seed or even a specific seed coat region (Behery, 1993; Bragg and Shofner, 1993; Wartelle et al., 1995). Distributions of the direct measurements are used in calculations of short fibre contents (SFC, %), immature fibre fractions (IFF, %), and fine fibre fractions (FFF, %), and μAFIS, which is analogous to micronaire, the usual measure of fibre maturity. The AFIS sample size can be set from 1 to 10 000 fibres. Unlike HVI testing, AFIS fibre-quality quantitations require no specific fibre pre-treatment or conditioning since AFIS does not quantify fibre strength, the fibre property most affected by incomplete moisture conditioning (Knowlton and Alldredge, 1994; Knowlton, 1996).

Plant mapping, by fruiting site, was combined with AFIS quantitation of locule fibre properties (length, cross-section, circularity, and μAFIS) to produce maps of fibre-quality variability between branch positions 1 and 2 and among main-stem branches of Pee Dee 3 plants grown as part of a subsurface microirrigation study in South Carolina, USA. This report demonstrates the usefulness and potential of fibre-quality mapping, combined with AFIS quantitation, by comparing fibre quality at different fruiting sites and contrasting the effects of boll and plant growth environment on length, cross-section, and maturity of cotton fibres drawn from three experimental designs carried out in two US cotton growing regions.

2. Materials and methods

Bolls were collected from a subsurface micro-irrigation study on Eunola loamy sand (Typic Kandiudult) near Florence, South Carolina, in 1992 (Camp et al., 1992). The experimental design for the complete micro-irrigation study was a randomized complete block in a split-plot arrangement with four replications. This paper is based on a subset of data from rainfed (RF) and in-row (IR) irrigation treatments. Micro-irrigation tubing was installed 0.30 m below the soil surface directly under each row. Each sub-plot was 15 m long and 8 m wide.

The cotton cultivar Pee Dee 3 (PD3) was planted on 14 May 1992 in rows spaced 0.96 m apart. Irrigation applications were managed using the GOSSYM/COMAX model and tensiometers. The model was operated three times a week to decide

the need for irrigation. Irrigation applications were 6 mm h^{-1}. Nitrogen was applied, 12 kg ha^{-1} broadcast and pre-plant and 112 kg ha^{-1} in the irrigation tubing (56 kg ha^{-1} in the first and second week after flowering). Pesticide applications were made at planting and as warranted for control of weeds and insects. All sympodial branch flowers at 0 days post anthesis (0 DPA) on plants in 1-m row lengths were tagged five times a week from 16 July to 31 August. Just prior to harvest, tag-bearing plants were removed from the field and individual boll positions were mapped according to flowering date and fruiting site. Two interior rows of each eight-row plot were harvested with a spindle picker on 12 November 1992. Cotton lint yield was calculated from lint percentages determined in the laboratory on a saw gin from subsamples collected from each plot at harvest.

In this study, node is that place on the mainstem where a fruiting branch (sympodium) or a vegetative branch (monopodium) arose. Node 0 is the cotyledonary node. Position is the order in which buds (potential bolls) are produced on a sympodium (Heitholt and Schmidt, 1994). Position 1 refers to the first potential boll on any or all sympodia. Fruiting site is a specific node-position combination.

All tagged and mapped bolls (omitting monopodial branches) were shipped to the Southern Regional Research Center (SRRC), New Orleans, Louisiana, where boll and individual locule weights were determined. One boll from positions 1 and 2 of each node was randomly selected from each of the four blocks, and locules from the four boll sets were pooled so that ten intact, undiseased locules could be chosen from each fruiting site (weight per 10 locules ≥ 10 g for each fruiting site). When a fruiting site and block combination was represented by fewer than four bolls, that node-position was excluded from the three-way statistical comparisons of boll location and irrigation treatment effects. Locules were ginned separately in a reciprocating-knife roller gin, and the fibre from an individual locule constituted one AFIS sample and one replicate for statistical analysis.

The production model Uster AFIS-L&D (length and diameter) at SRRC is augmented with a prototype F&M (fineness and maturity) module (Zellweger Uster, Knoxville, TN[1]). AFIS samples are combed into individual fibres, and the individualized fibres are transported in a high-speed air stream perpendicular to a ribbon beam of light directed at an electron-optical sensor (Behery, 1993; Bragg and Shofner, 1993; Wartelle et al., 1995). The light blocked by an individual fibre is directly proportional to its mean optical diameter and time of flight in the sampling volume. The attenuated signal is analysed in measurements of fibre length by number, $L(n)$, and by weight, $L(w)$ in inches, and of fibre diameter by number, $D(n)$ in μm. As the fibres move with the air stream, part of the beam is scattered, reducing the amount of undeflected light and increasing the light at a specified scattering angle (40°). The 40° light-scattering signal is analysed in measurements of fibre cross-sectional area by number $A(n)$ and of fibre circularity (θ). Fibre circularity is related to $A(n)$ and fibre perimeter (P) according to the formula: $\theta = 4\pi A(n)/P^2$ where the units of $A(n)$ and P are μm^2 and μm, respectively. Short fibre contents (SFC) by weight and number are generated from the corresponding fibre length distributions and reported as the percentages of fibres under 12.7 mm (0.5 inches) in length. Immature fibre fractions (IFF) are derived from distributions of dimensionless θ, and IFF is the percentage of fibres with $\theta < 0.25$. Fine fibre fraction (FFF) is obtained from the distribution of $A(n)$ and represents the percentage of fibres with $A(n) < 60\ \mu m^2$. Mean AFIS sample size in this study was >9000 fibres per assay.

AFIS is calibrated with USDA Agricultural Marketing Service calibration cottons and through inter-laboratory testing. In this method-development study, cross-genotype and cross-maturity comparisons of SRRC AFIS data were obtained by contrasting PD3 fibre quality data with those from another field trial in South Carolina and with data from a separate chronological fibre matura-

[1] Trade names are necessary to report factually on available data. The USDA neither guarantees nor warrants the standard of the product or service, and the use of the name USDA implies no approval of the product or service to the exclusion of others that may be suitable.

tion study (Wartelle et al., 1995). The second South Carolina trial was also carried out in 1992 on a Norfolk loamy sand (Typic Kandiudult), and included 'Deltapine 20' (DPL20), 'Deltapine 50' (DPL50), 'Deltapine 5690' (DPL5690), 'Deltapine Acala 90' (DPL90), 'Coker 315' (CO315), 'Paymaster 145' (PM145), and F2 and F3 crosses of CO315 and PM145. Fibre from this study was saw-ginned prior to the AFIS analyses.

The chronological fibre maturity study was carried out at Mississippi State, MS, and used 'DES119' in 1992 and 'Deltapine 5415' (DPL5415) in 1993. DES119 bolls were harvested at 21, 28, 35, or 56 days post floral anthesis (DPA). DPL5415 bolls were harvested at 21, 35, 42 or 56 DPA. Bolls were freeze-dried for more than 48 h before separation into carpels, fibres, and seeds. The individual boll components were weighed and stored frozen for further analysis. Hand-separated fibres were used in AFIS analyses of chronological and physical fibre maturity (Wartelle et al., 1995; Bradow et al., 1996).

All fibre-quality data ($L(n)$, $A(n)$, θ, and μAFIS) were subjected to analyses of variance (Sokal and Rohlf, 1981; MSTAT-C, 1991). Angular transformation of data expressed as % (SFC, IFF, or FFF) did not improve goodness of fit with a normal distribution (Sokal and Rohlf, 1981), and those data sets were analysed without transformation. The effects of the irrigation treatment and fruiting site on each AFIS fibre-quality factor were examined as three-way factorial designs (two treatments × eight nodes × two positions), using data from those nodes from which four or more position 1 and 2 bolls were collected ($n=10$ locules). In the RF treatment, nodes 7–14 met this criterion. Insufficient position 2 bolls were collected from node 14 in the IR treatment, and node 15 data from the IR treatment were used in the factorial analyses of variance. Four or more position 1 bolls were collected from nodes 15–18 in both the RF and the IR treatments. Therefore, fibre quality data from nodes 7–18 were analysed for each AFIS fibre factor, using Tukey's Honestly Significant Difference procedure for means separation. Position 1 and 2 bolls from a given node and within an irrigation treatment were compared by Student's t-tests of data for each AFIS fibre quality factor.

3. Results and discussion

In 1992, weather conditions in South Carolina were not favourable for cotton production (Camp et al., 1992). Temperatures during the spring and early fall were cooler than normal, and a killing frost occurred on 20 October. Total 1992 rainfall (589 mm) was poorly distributed, 63% occurring late in the growing season (mid-August to October). All 1992 irrigation (90 mm in nine irrigation events) was applied prior to mid-August (Julian days <225). The effective duration of the irrigation treatment corresponded with floral anthesis in position 1 of nodes 5–15 of the RF treatment and of nodes 6–12 of the IR treatment. The IR treatment prolonged flowering and increased boll retention in nodes 8–10.

Irrigation affected both cotton yield and boll distribution. Cotton fibre yields were 518 kg ha^{-1} for the RF and 723 kg ha^{-1} for the IR treatment (Camp et al., 1992). Sympodial boll counts per metre of tagged row were 53.5 in the RF treatment and 61.3 in the IR treatment. Mean seed cotton weights of tagged bolls were 5.95 ± 1.69 and 5.05 ± 1.55 g in the RF and IR treatments, respectively. The RF treatment seeds were generally larger and heavier than those produced under irrigation (Bradow and Bauer, 1993; Bradow et al., 1994). Mean RF single-seed weight was 0.13 ± 0.05 g, compared to 0.11 ± 0.05 g for the IR treatment. Mean boll weights ranged from 7.03 g at node 11-position 2 of the RF treatment to 4.15 g from the node 7-position 1 in the IR treatment. Position 2 bolls contributed more to the yield from IR than from RF plants (Fig. 1). Position 1 bolls of the RF treatment contributed 73.6% of the seed cotton yield on the sympodial branches, and position 2 produced 22.9%. In the IR treatment, position 1 produced 61.6% of the total seed cotton on the sympodial branches, and positions 2 and 3 accounted for 25.9 and 9.2%, respectively. Only IR plants retained position 5 bolls. The IR treatment skewed the seed cotton weight distribution toward higher fruiting positions.

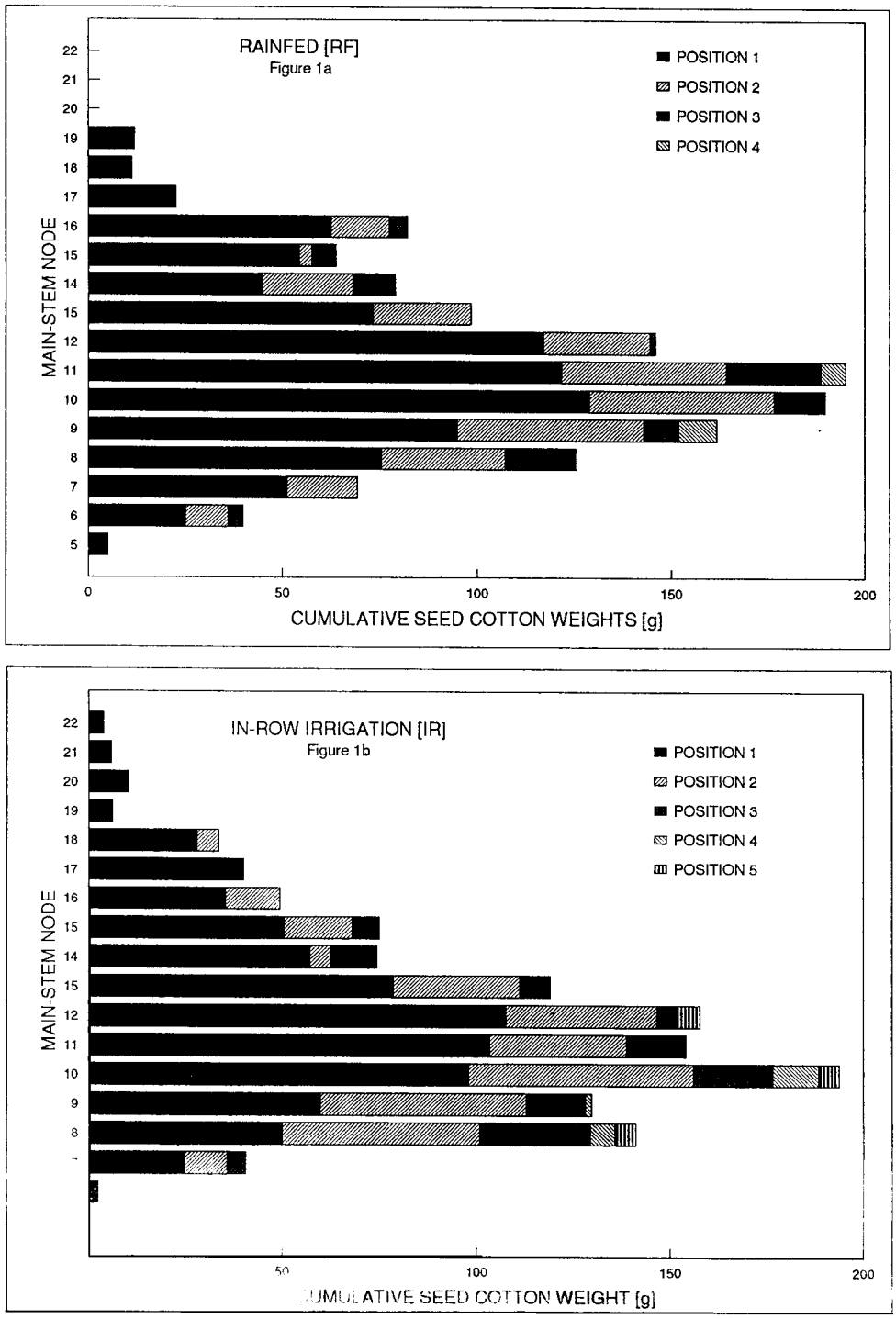


Fig. 1. Cumulative PD3 seed cotton weights by sympodial fruiting position in rainfed (a) and irrigated (b) treatments.

The RF treatment is considered the 'norm' for plant mapping (Kerby, 1994). The experimental design requirement that ten replicate locules be randomly selected for AFIS analyses from four or more bolls at each fruiting site focused data analyses on positions 1 and 2 of nodes 7–14 in the RF treatment. The IR plants produced no node 14-position 2 bolls, and the factorial design was completed by the substitution of position 1 and 2 bolls from node 15 of the IR treatment. The results of the factorial analyses of variance for $L(n)$, $A(n)$, θ, and μAFIS are shown in Table 1.

Length has long been considered the most important cotton fibre property (Bragg and Shofner, 1993). However, fibre length varies greatly within any sample (Munro, 1987; Behery, 1993). On a single seed, the longest fibres occur on the blunt (chalazal) end and the shortest are found near the pointed (micropylar) end of the seed. In this study, fruiting site and environmental conditions also contributed to fibre length variability (Table 1). In roller-ginned fibre from the RF treatment, $L(n)$ ranged from 16.8 to 22.9 mm in the fruiting-site distribution shown (Fig. 2(a)). On the lower nodes (node <9), position 2 fibres tended to be longer than position 1 fibres. The IR ginned fibre lengths (Fig. 2(b)) ranged from 13.2 to 23.9 mm in a less regular distribution of lengths than that observed in the RF data (Fig. 2(a)). The RF and IR $L(n)$ values differed significantly ($p \geq 0.01$) at node 9-position 1, node 9-position 2, node 12-position 1, node 13-position 1, and node 14/15-position 2. IR position 1 and 2 fibre lengths at nodes 13 and 15 were significantly different. AFIS fibre $L(n)$ distributions are biased toward shorter lengths because the fibre individualizer may introduce breakage similar to that attributed to carding during fibre processing (Bragg and Shofner, 1993). All AFIS data reported here were collected with the same instrument, under the same conditions of relative humidity and temperature, and with the same sampling methodology and, thus, should show the same degree of length-bias. The $L(n)$ values for RF and IR roller-ginned PD3 from the 1992 crop are compared in Table 2 with the $L(n)$ values for eight cotton genotypes grown, spindle-picked, and saw-ginned in Florence, South Carolina, in the same year. Saw-ginning consistently decreased AFIS fibre-lengths, compared to roller-ginning. Using AFIS to monitor the effects of ginning and other fibre processing steps has been suggested (Behery, 1993); and ginning, as well as boll and fibre collection, methods should be considered carefully when making comparisons of fibre length data obtained with AFIS and with other quantitation methods.

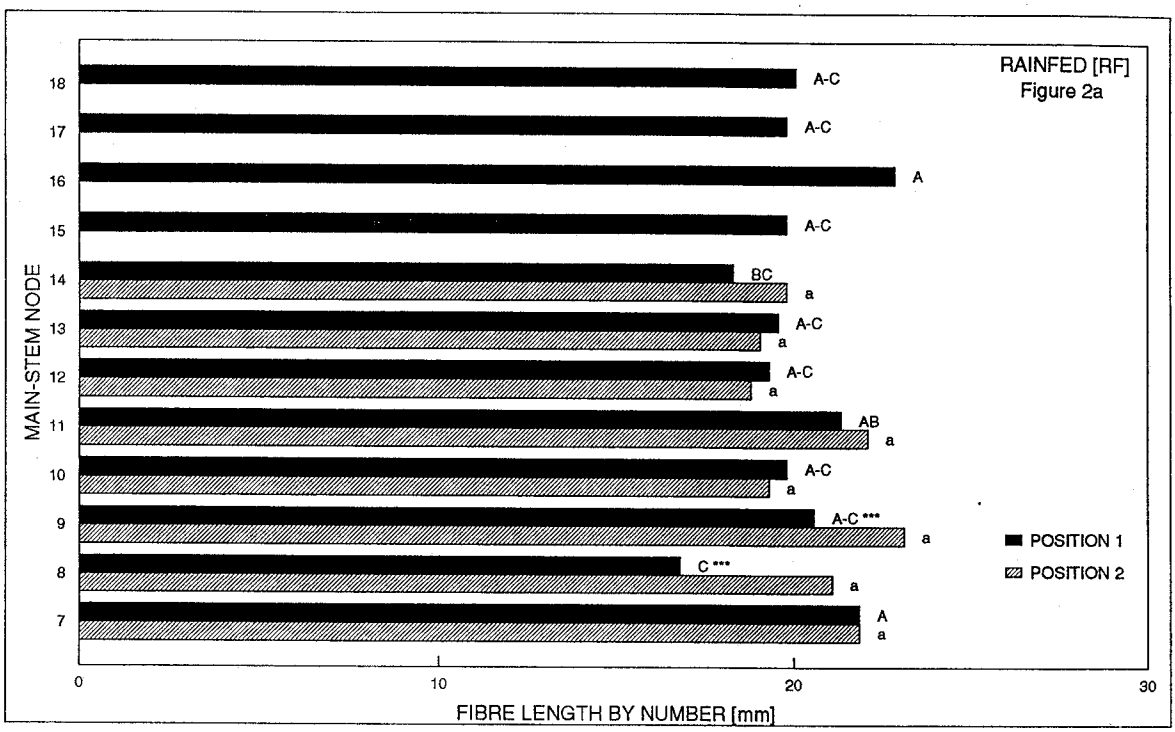
Table 1
Mean squares of analyses of variance of irrigation treatment, node and position number effects on length by number as $L(n)$; cross-sectional area as $A(n)$; circularity as θ; and μAFIS of PD3 fibre[a]

Source	dF	Mean square			
		$L(n)$	$A(n)$	θ	μAFIS
Irrigation (I)	1	0.068*	3880.69***	0.302***	44.524***
Node (N)	7	0.121***	954.25***	0.047***	8.089***
$N \times I$	7	0.192***	1384.64***	0.602***	13.174***
Position (P)	1	0.035	1719.72**	0.036**	5.334*
$I \times P$	1	0.026	1270.38*	0.011	3.115
$N \times P$	7	0.028*	1022.60***	0.023***	5.172***
$I \times N \times P$	7	0.067***	1751.41***	0.036***	9.158***
Error	96	0.013	220.18	0.005	0.847

[a]The symbols *, **, and *** indicate significance at the $p = 0.05$, 0.01, and 0.001 levels, respectively.

Fibre length variations by fruiting site in this study are characteristic of a biological fibre, and competition from synthetic fibres has increased the need for sound estimates of fibre length uniformity and short fibre content (SFC = percentage of fibres <12.7 mm). In short fibre content by number, SFC(n), data from the 1992 PD3 crop, the interaction between irrigation treatment, node, and position was significant ($p < 0.001$). The SFC(n) for RF fibre ranged from 36.7% at node 8-position 1 to 16.7% for position 2-node 9. The IR SFC(n) values ranged from 14.7% for node 13-position 1 to 6.5% for position 1-node 7. There were no patterns apparent in the differences between SFC(n) values from the RF and IR treatments or between values for position 1 and position 2.

Fibre diameter and perimeter are poor estimates of fibre fineness (Munro, 1987) because the shape of an individual cotton fibre is that of a *uniquely* collapsed and twisted end-tapered tube of variable thickness. Fineness is more commonly measured



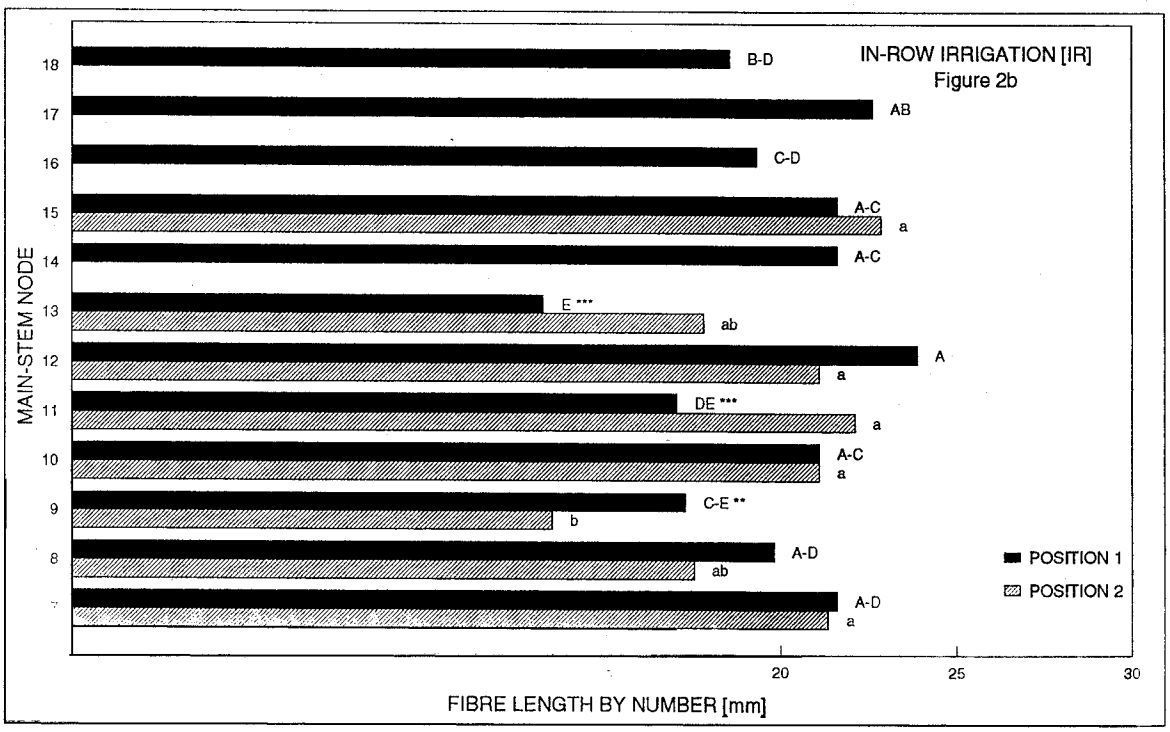


Fig. 2. Fibre lengths, $L(n)$, by sympodial fruiting position in rainfed (a) and irrigated (b) PD3 cotton. Means represented by bars associated with the same letters in the same case are not significantly different ($p=0.01$). *, **, *** indicate significant differences between positions 1 and 2 at associated node ($p=0.05$, 0.01, and 0.001, respectively).

Table 2
Comparison of mean $L(n)$, θ, and $A(n)$ values from rainfed and irrigated PD 3, and rainfed DPL20, DPL50, DPL90, DPL5690, PM145, CO315, and an F2 and F3 cross between CO135 and PM145, all grown in 1992 in Florence, South Carolina

Germplasm	$L(n)$ (mm)	$A(n)$ (μm^2)	θ	μAFIS
RF PD3	20.2±0.3	107.1±10.2	0.521±0.090	4.36±0.13
IR PD3	19.6±0.4	100.4±8.7	0.460±0.090	3.57±0.12
DPL20	16.8±0.4	116.3±5.6	0.490±0.025	4.51±0.81
DPL50	16.9±0.4	126.3±3.8	0.505±0.014	4.74±0.24
DPL90	17.2±0.4	119.0±5.1	0.528±0.019	4.76±0.32
DPL5690	17.3±0.5	120.9±4.1	0.539±0.020	4.88±0.34
PM145	17.3±0.5	118.1±3.2	0.526±0.017	4.69±0.25
CO315	17.0±0.3	117.4±3.3	0.520±0.021	4.62±0.28
F2	17.5±0.1	119.1±5.9	0.521±0.019	4.43±0.87
F3	17.3±0.1	121.6±4.8	0.523±0.017	4.79±0.26

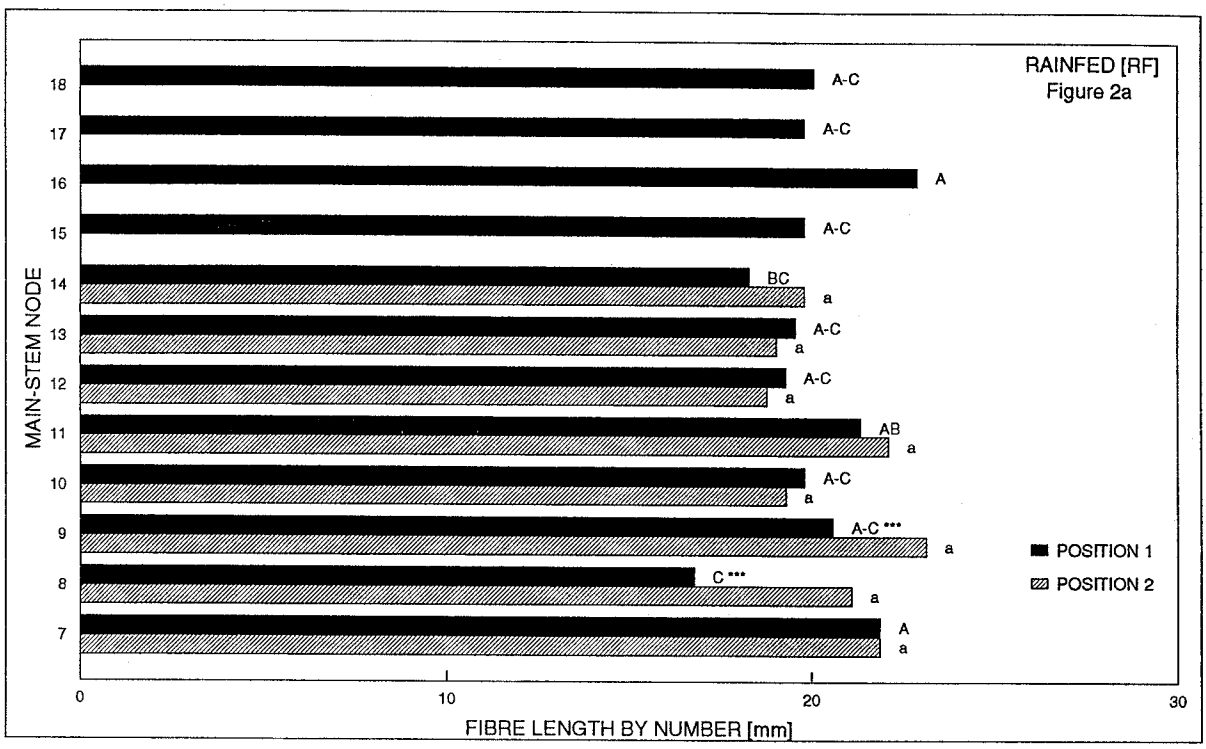
as the mean fibre weight per unit length after the tapered fibre ends are trimmed evenly. Traditional fibre fineness units are $\mu g\ in^{-1}$ or $\mu g\ cm^{-1}$, but those units are being replaced by linear density measured in $\mu g\ m^{-1}$ or millitex. AFIS quantifies the distribution of diameter by number, $D(n)$, and determines the mean diameter for a fibre sample of 1–10 000 fibres. In this study, neither irrigation treatment nor fruiting site affected fibre diameter. RF fibre diameters varied from 11.3 μm at node 7-position 2 to 14.3 μm at node 10-position 2. The IR diameters ranged from 6.5 μm at node 7-position 1 to 14.7 μm at node 13-position 1. The high variability in $D(n)$ was subsequently found to be correlated with fibre maturity variations related to growth temperatures and insolation levels (Wartelle et al., 1995; Bradow et al., 1996)

Both irrigation and fruiting site strongly affected fibre fineness measured as cross-sectional area, $A(n)$ (Table 1); and significant interactions occurred among irrigation treatment, node, and position. The RF $A(n)$ means ranged from 85.9 μm^{-2} at node 14-position 1 to 135.0 μm^{-2} at node 7-position 1 (Fig. 3(a)). RF-treatment position 1 $A(n)$ values decreased with increasing node number until that height on the main-stem at which only position 1 bolls were retained (node 15 and above). In contrast, both the maximum (121.7 μm^{-2} at node 15-position 1) and the minimum $A(n)$, 78.8 μm^{-2} at node 18-position 1, occurred near the top of IR plants (Fig. 3(b)).

The lower $A(n)$ values for both RF and IR PD3 in the genotype comparisons of Table 2 suggest that more fine fibres are collected during gentler roller-ginning than during saw-ginning. The RF-treatment FFF (percentage of $A(n)$ $<60\ \mu m^{-2}$) values ranged from 6.3% at node 7-position 1 to 33.8% at node 14-position 1, where the mean FFF was 17.9%. The IR-treatment FFF range was from 10.4% at node 15-position 1 to 41.1% at node 18-position 1 with a mean FFF of 20.3%. As suggested by comparison of Fig. 3(a) and Fig. 3(b), the differences between RF and IR treatment $A(n)$ values formed no consistent pattern. Significant differences between RF and IR $A(n)$ means occurred at node 7-position 1, node 9-position 1 and at both positions in the node 14/15 pairings, the highest nodes compared using Student's t-testing.

Fibre circularity, the degree of fibre cell wall thickening, is an indicator of maturity, and AFIS calculations translate θ distributions as IFF percentages (immature fibre fractions). According to the formula, $\theta = 4\pi A(n)/P^2$, where $\theta = 1$ for a perfect circle. The collapsed and twisted cross-sections of a cotton fibre, whatever the maturity, are more kidney-shaped than circular; and θ values for the 1992 South Carolina comparison genotypes were grouped around 0.500 (Table 2).

Irrigation greatly affected PD3 θ values, as did fruiting site (Table 1). The maximum θ observed was 0.671 at RF node 7-position 1 (Fig. 4(a)). The lowest RF θ, 0.404, was at node 14-position 1, and RF θ values were higher at the higher nodes where fruiting sites were limited to position 1. The IR map of θ values was quite different from the



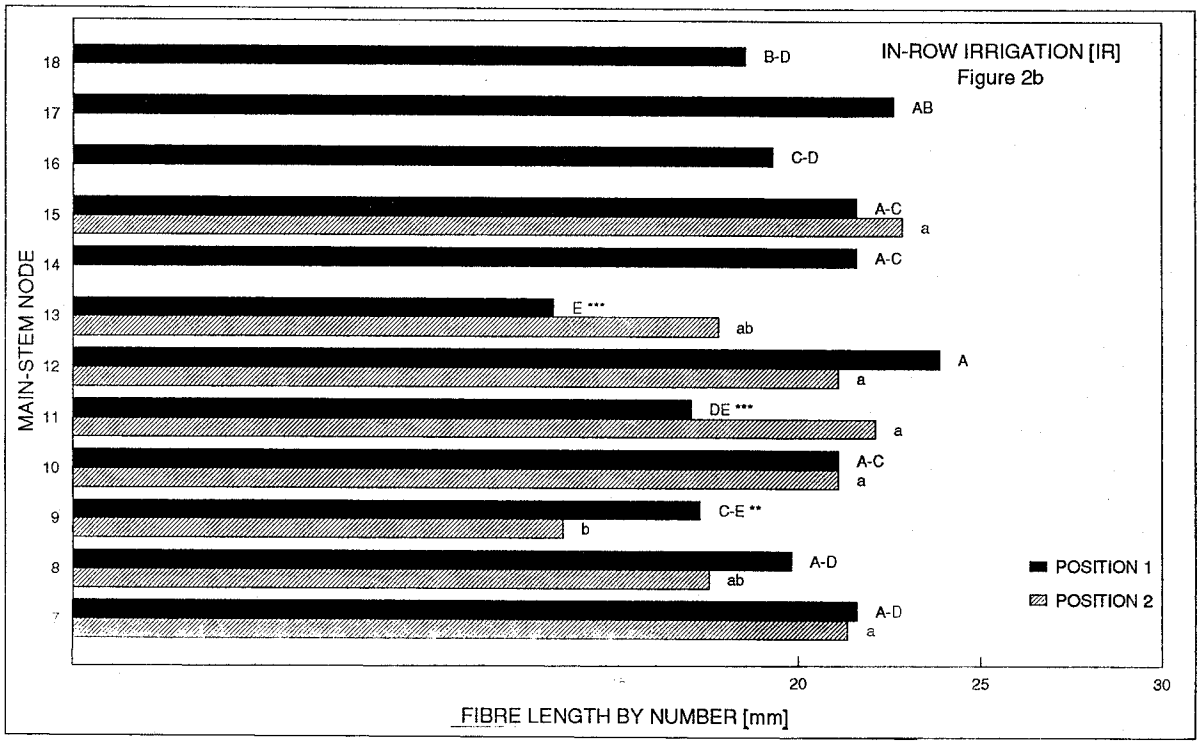
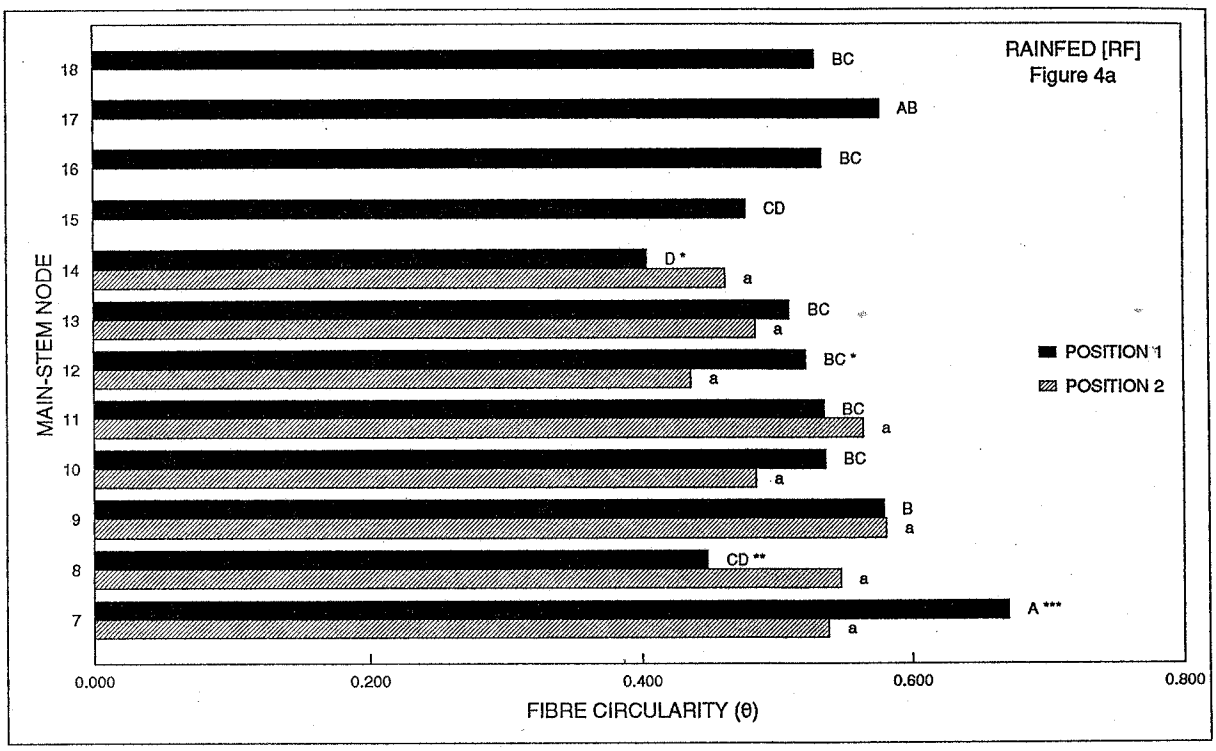


Fig. 3. Fibre cross-sectional areas, $A(n)$, by sympodial fruiting position in rainfed (a) and irrigated (b) PD3 cotton. Means represented by bars associated with the same letters in the same case are not significantly different ($p=0.01$). *, **, *** indicate significant differences between positions 1 and 2 at associated node ($p=0.05$, 0.01, and 0.001, respectively).



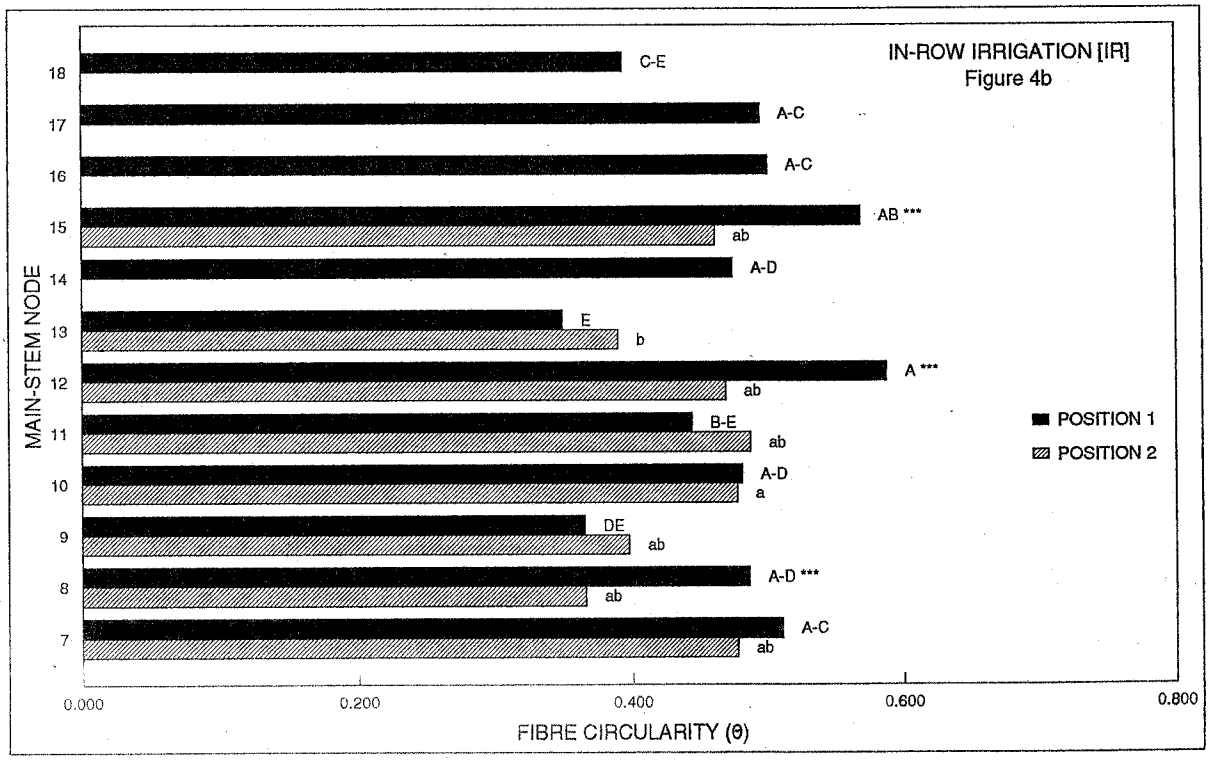


Fig. 4. Fibre circularity (θ) by sympodial fruiting position in rainfed (a) and irrigated (b) PD3 cotton. Means represented by bars associated with the same letters in the same case are not significantly different ($p=0.01$). *, **, *** indicate significant differences between positions 1 and 2 at associated node ($p=0.05$, 0.01, and 0.001, respectively).

corresponding map of the RF plants (Fig. 4(b)). The IR θ maximum (0.588) and minimum (0.349) occurred at positions 1 of node 12 and 13. Ginning method had no apparent effect on θ values (Table 2), but the IR θ mean, 0.406, was the lowest in the genotype comparison range. The genotypes included in Table 2 as comparisons to PD3 were not irrigated.

Physiologically, θ is directly related to secondary fibre cell wall thickness since a fibre with a well-developed cellulosic secondary wall will collapse less during maturation and drying and vary less from the circular unity approached by an isolated fibre cell in vitro (Wartelle et al., 1995). When the RF and IR PD3 θ values are compared to those obtained in a separate chronological fibre maturity study of DPL5415 and DES119 harvested at 21, 28, 35, 42, or 56 DPA, the minimum RF and IR PD3 θ values were lower than those of DES119 and DPL5415 harvested at 35 DPA (Table 3). The RF and IR PD3 θ means were lower than those of DPL5415 at 42 DPA and DES119 at 56 DPA.

Examination of the θ distributions or IFF (percentage of sample with $\theta<0.25$) revealed that the RF and IR PD3 mean IFF percentages approximated the IFF values of DES119 and DPL5415 at 35 DPA. The DES 119 bolls were tagged on 23 July and the DPL5415 on 28 July in central Mississippi. The Mississippi bolls are the developmental and positional equivalents of node 10-position 1 of IR PD 3 for which θ was 0.482 and IFF was 19.6%, and of node 8/9-position 2 in RF PD3 for which θ means were 0.547 and 0.580 and the IFF percentages were 9.7 and 8.6, respectively. The irrigation treatment first level effect was significant ($p<0.001$) for both IFF and θ. IR PD3 maturity, either measured as θ or calculated as IFF, was significantly less than that of RF PD3 at every fruiting site, except node 8-position 1, node 10-position 1, node 10-position 2, node 11-position 1, and nodes 14/15-position 2.

When measuring fibre fineness and maturity, textile technologists rely on micronaire testing which estimates fibre surface area (Munro, 1987) and is the most widespread instrumental cotton fibre test in use (Lord and Heap, 1988). The test depends on the principle that the resistance to the flow of air through a bundle of fibres varies directly as the square of the fibre surface area which, in turn, varies inversely as the product of M, maturity, and H, thickness. Empirical calibrations of micronaire instruments give rise to the relation $M\times H=3.86X^2+18.16X+13$ where X is the cotton fibre micronaire value. Higher fibre maturity and increased fibre thickness may operate independently to give higher micronaire values.

Table 3
Fibre maturity indicators, θ, with the corresponding immature fiber fraction (IFF), $A(n)$, and μAFIS of RF and IR PD3 cotton and of DPL5415 and DES119 harvested at 21, 28, 35, 42, or 56 DPA

Genotype	Fibre maturity parameter			
	θ	IFF (%)	$A(n)$ (μm^2)	μAFIS
RF PD3 (min.)	0.404±0.070	26.20	85.9±13.2	2.670±0.88
RF PD3 (mean)	0.521±0.090	12.95	108.7±7.2	4.363±1.27
RF PD3 (max.)	0.671±0.030	4.49	135.0±5.2	6.521±0.44
IR PD3 (min.)	0.349±0.060	36.15	78.8±7.0	2.184±0.83
IR PD3 (mean)	0.460±0.090	16.94	100.5±8.7	3.574±1.2
IR PD3 (max.)	0.588±0.030	7.91	121.7±6.3	5.214±1.04
DPL5415 (21 DPA)	0.269±0.010	48.10	75.1±2.0	1.005±0.14
DPL5415 (35 DPA)	0.461±0.010	13.53	120.2±2.0	4.075±0.14
DPL5415 (42 DPA)	0.651±0.010	5.95	146.0±6.0	6.741±0.17
DPL5415 (56 DPA)	0.605±0.010	6.31	139.0±4.6	6.080±0.10
DES119 (21 DPA)	0.214±0.010	67.54	89.3±0.8	0.496±0.10
DES119 (28 DPA)	0.290±0.020	40.29	81.3±2.6	1.370±0.32
DES119 (35 DPA)	0.438±0.030	14.23	118.8±3.4	3.824±0.41
DES119 (56 DPA)	0.565±0.070	7.67	127.1±6.5	5.364±1.15

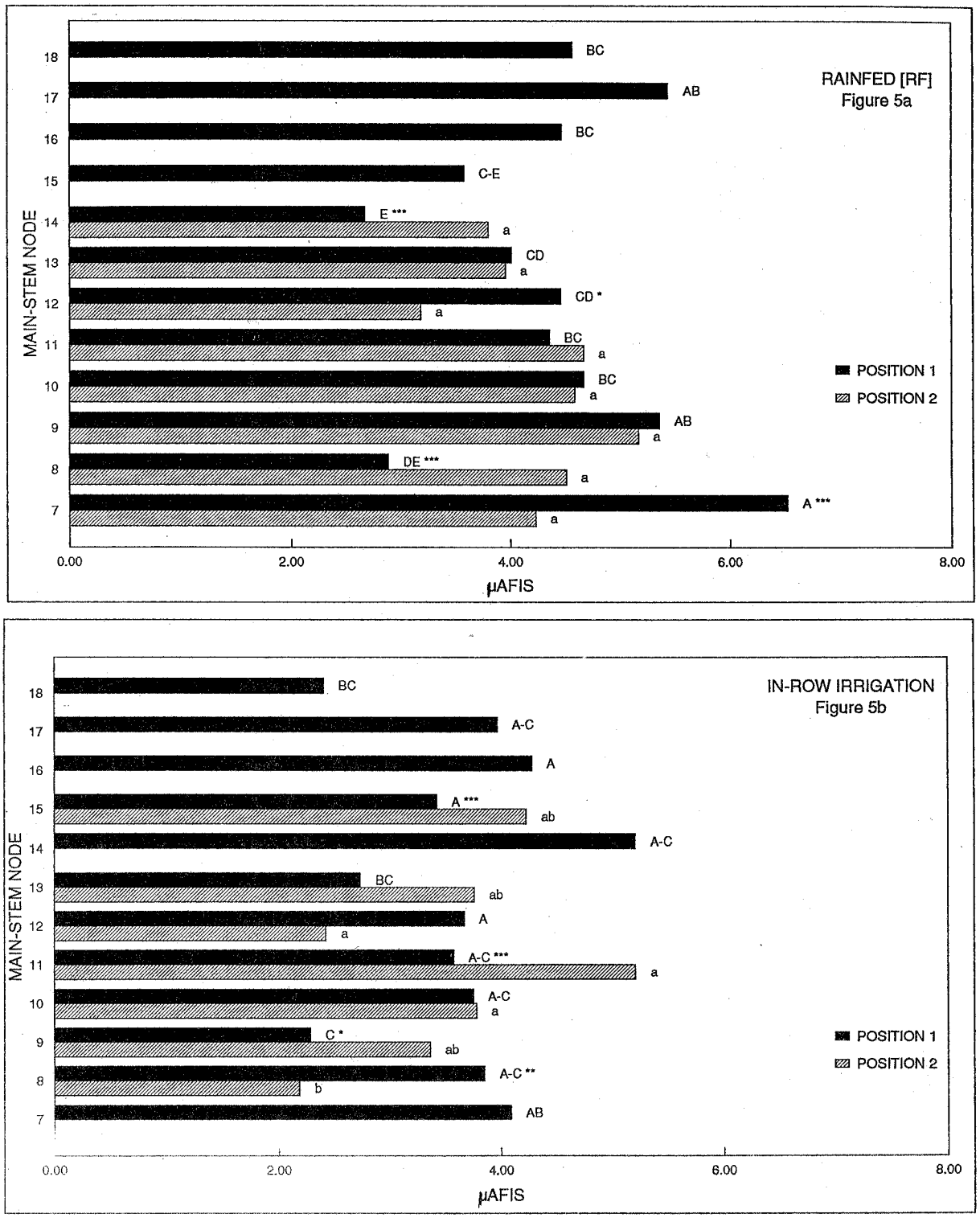


Fig. 5. Fibre µAFIS (micronaire analog) by sympodial fruiting position in rainfed (a) and irrigated (b) PD3 cotton. Means represented by bars associated with the same letters in the same case are not significantly different ($p=0.01$). *, **, *** indicate significant differences between positions 1 and 2 at associated node ($p=0.05$, 0.01, and 0.001, respectively).

Lower micronaire values arise from more immature cotton or more intrinsic fibre-fineness characteristics, e.g., those of Pima (*Gossypium barbadense*). Calculated values of μAFIS are analogous, but not identical, to micronaire. The slopes of least-squares fits of μAFIS and HVI micronaire values over 120 calibration samples were the same. The μAFIS regression line intercept was 0.3 units higher.

Irrigation treatment and both fruiting site components affected PD3 μAFIS (Table 1). The irrigation treatment effect can be seen in the low mean μAFIS of IR PD3 in Table 2 and by the closeness of RF and IR PD3 μAFIS values to the μAFIS values of DES119 at 35 DPA and of DPL415 at 35 DPA in Table 3. The distribution of μAFIS values by fruiting site can be seen in Fig. 5. The minimum RF PD3 μAFIS, 2.67, occurred at node 14-position 1, the maximum, 6.52, at node 7-position 1. In IR PD3, the minimum μAFIS, 2.18, was at node 8-position 2 and the maximum, 5.21, at node 11-position 2. The RF and IR treatment μAFIS values did not differ significantly ($p<0.01$) at node 8-position 1, node 10-position 1, node 2-position 10, node 11-position 1, and node 12-position 1. The mean RF μAFIS, which would be analogous to the crop micronaire value, falls in the 'average' micronaire range, and the mean IR μAFIS is in the 'low' micronaire range. DPL5415 μAFIS values at 42 and 56 DPA in Table 3 are in the 'very high' (>5.0) or discount micronaire range. Bulk micronaire measurements from a commercial laboratory were 4.225 for RF and 3.825 for IR fibres spindle-picked and saw-ginned before evaluation.

The distributions of μAFIS in Fig. 5 indicate that the bulk crop micronaire might be manipulated through cultural practices, e.g., timing of irrigation events or harvest aid applications. However, decreased micronaire is clearly associated with lower fibre maturity. Immature fibres have relatively thin secondary cell walls that contain less cellulose than the cell walls of more mature fibres. If the micronaire of the bulk crop is lowered by an increased proportion of immature fibre, the desired spinning properties may be present, but the number of dye defects in the yarn and fabric will increase significantly (Smith, 1991). Processors can compensate for fibre variation arising from genotype differences and yarn production methods, but the dye defects associated with fibre maturity, i.e., shading, streaking, and white specks, cannot be avoided or minimized without knowledge of the maturity characteristics of the fibres used to produce the yarn or fabric to be dyed or printed. Fibre quality data reported here indicate that attempts by cotton producers to meet industry requests for stronger and thinner cotton fibre may result in increased dye defects and reduced yields. This fibre quality-fibre yield conundrum can be solved only through careful comparisons and combinations of quantitative measurements and methods available separately to agronomists and fibre technologists. The development of an AFIS-based fibre quality module for plant growth simulations like GOSSYM-COMAX would be one step towards building the predictive models of fibre quality needed by both the producers and the processors of cotton fibre.

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