Breeding Cotton With Enhanced Fiber Qualities Amidst Technologically Evolving Yarn and Textile Manufacturing Industries

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Introduction

The evolving fiber quality requirements of cotton yarn and textile industries combined with time required to develop new cultivars compels implementation of crop improvement strategies to meet the changing needs of fiber consumers. Yarn and textile manufacturing technologies have progressed the last 20 years to enhance productivity and reduce unit-manufacturing costs (Deussen, 1992; Felker, 2001). More cotton yarn is now produced with open-end spinning, than with older ring spinning technologies (Smith and Zhu, 1999; Felker, 2001), with potential for expansion of even more productive air-jet spinning (El-Mogahzy, 1998). This technological evolution of yarn manufacture has been driven by a burgeoning global economy in the production and trade of textiles, compelling manufacturers to reduce costs to remain solvent. The economic advantage of rotor and air-jet yarn manufacturing technologies lies in less human intervention and reduced pre-spinning fiber preparation combined with greater output per unit of time. The disadvantage of these higher-output manufacturing technologies is less tolerance for variation in fiber length and need for finer and stronger fiber (Deussen, 1992).

Ring, rotor, and air-jet yarn manufacturing technologies have their own specific fiber property preferences for conversion into yarn at a competitive price and quality for sale or subsequent construction of textiles (Deussen et al., 1995; Kechagia and Harig, 2000), yet fiber quality improvement is not targeted to the special needs of each spinning technology. Instead, seed companies that are the primary source of improved planting seed available to growers tailor fiber quality improvement towards priorities expressed in the cotton marketing system. Commercial breeders endeavor to maintain staple length, fiber strength, and micronaire within ranges that will not incur price discounts by the cotton marketing system, with little financial incentive to exceed the market's expectations. Public breeders may set different priorities, but their germplasm is often not directly accessible to growers as cultivars due to constraints of commercializing cultivars, but instead the improved germplasm is used by commercial seed developers in their breeding efforts. Also impacting the direction of breeding efforts is that fiber properties considered important in determining the value of cotton for marketing purposes are not always those yarn manufacturers would establish as a priority (El-Mogahzy, 1999). An example is fiber color grade. While it is true that fiber with the least desirable color grade representing discoloration from insect deposits and/or weathering in the field can negatively impact yarn manufacture, spinners also indicate that there is very little or no difference in the processing merits of fiber differentiated by small variation in the whiter color grades. Nonetheless, the grower is penalized for delivering fiber of such color grades to the marketplace. These sometimes-conflicting forces can constrain efforts to provide mills with improved fiber quality.

The key barrier to genetically enhancing the processing capabilities of cotton is inability to verify response to selection for fiber quality. Breeders develop germplasm with a suite of fiber traits normally measured by HVI (Taylor, 1982) or single instruments (Latimer et al., 1996; May and Jividen, 1999; Palmer et al., 1994), but generally lack the capability to validate the processing merits of the fiber from the improved germplasm (May and Taylor, 1998; Meredith, 1984). This disconnect between cultivar development and evaluation of the processing merits of fiber must be solved to maintain cotton's share of the textile market.

Variability of fiber properties should also be considered in defining fiber quality because variation in the fiber properties that permit yarn formation can confound efforts to produce yarns of uniform strength and quality (Lewis, 2001; Felker, 2001). For example, when fiber length is measured by staple length or more commonly upper-half mean length by high volume instrument it should be recognized that these are measures of the longest fibers in a sample (Steadman, 1997). In fact, the same fiber sample contains a range of lengths that prior to the development of the Advanced Fiber Information System (AFIS®) could not be effectively measured (Bragg and Shofner, 1993). Goals for fiber quality *improvement* should simultaneously consider enhancing magnitude and reducing variability in fiber properties (Hequet and Ethridge, 2002; May and Bednarz, 2002).

Meredith (2003) summarizes the intricacies involved in breeding to simultaneously enhance yield and fiber quality. It is often not presented in discussing approaches to breeding better quality fiber that indeed the properties of fiber conferring textile performance are also components of yield. The statistical analyses of Meredith (2003) demonstrate the positive association between micronaire and yield, and lower yields associated with longer fiber length and greater fiber strength. But, rare exceptions do exist with the desired combination of yield, length, strength, and micronaire to satisfy growers, merchants, and mills. The key to making this fiber available to mills lies in grower acceptance of such cultivars. Grower acceptance of cultivars is based on yield potential and then transgenically imparted insect and weed management traits. Hence, the need for cultivars with the requisite pest management traits, yield potential, and fiber quality to meet requirements of all sectors of the cotton industry.

The objective of this paper is to examine the necessity of breeding cotton with fiber qualities to satisfy each spinning technology and to propose strategies to advance fiber quality to meet the evolving needs of fiber consumers.

Historical Success of Fiber Quality Improvement

Cotton breeding since ancient times successfully modified fiber from coarse textured and short length into one with properties capable of being spun into yarn on machine spinning frames (Brubaker et al., 1999). Highlighting the impact of certain successful modern breeding efforts affords a glimpse of the impact of sustained crop improvement as support for the long-term viability of fiber production and processing industries.

One of the more successful breeding efforts forming the foundation of a profitable industry in the production of cotton is the CSIRO Cotton Breeding Unit at Narrabri, N.S.W., Australia (Kay, 1998). Begun about 1972 in response to lack of locally adapted cultivars, this program has bred some of the most broadly adapted, high yielding, sought after fiber quality cultivars since scientific breeding efforts commenced in the early 20th century (Drew, 1998). The Siokra and Sicala series of cultivars produce excellent fiber quality with mill demand evidenced by an almost entirely export driven market since domestic conversion into yarn and textiles is not extensive (Schulze, 2002). Fiber from these cultivars has supplanted U.S. cotton once used preferentially by east-Asian rotor spinners because of its excellent performance on this yarn manufacturing technology. Currently, the CSIRO bred cultivars are being marketed globally through Cotton Seed International and in the U.S. through Bayer Cotton Seed International. The excellent fiber quality of the CSIRO cultivars can be viewed in state Official Cultivar Trials such as Georgia (http://www.griffin.peachnet.edu/caes/cotton/varieties/var2002.htm) and South Carolina (http://www.clemson.edu/peedeerec/cotton/JonesSCVarietyTrialsMAS.html).

The California and New Mexico Acala breeding programs are also renowned for their fiber quality and have similarly supported respective production industries, the fiber of which is considered premium quality by spinners (Cooper, 1992; Cooper, 1998; Staten, 1998). Additionally, the USDA-ARS cotton breeding programs in Mississippi and South Carolina have contributed numerous Upland germplasm lines with higher fiber strength, overall fiber quality, and high yield potential (Culp, 1998; Meredith, 1992).

The successful breeding programs cited above provide hope that cotton can be made to fit requirements of fiber consumers, extending its dominance as a textile fiber.

Prospects For Further Fiber Quality Improvement

Fiber quality can be defined in broad terms by linear density, length, and tensile properties that influence the success of yarn and textile manufacture (Kechagia and Harig, 2000). Fiber properties are at least moderately heritable, so long as adequate genetic variation was introduced into the population under selection, indicating that they will respond to selection (Table 1). While these properties appear rather simple, their definition can be much more complex. For example, fiber length is somewhat of a misnomer in the sense that a sample of fiber contains a range of lengths, reflecting effects of genes, environment, and fiber handling from field through the bale. The length of the longest fibers is still important to processors, but length variation of the remaining fibers in a sample is now of added concern because of its influence on open-end spinning. Fiber strength is another trait more complex than at first glance. Fiber strength is determined by breaking a bundle of fibers, but reflects the effects of a number of fiber properties such as individual fiber strength and number of fibers in the bundle (Taylor, 1986; Meredith, 1992). The reality is that selection for a composite property can result in alteration of related properties the breeder did not intend to modify.

Breeding cotton with improved fiber quality has traditionally focused on the requirements of ring spinning technologies (Meredith et al., 1991; May and Taylor, 1998). Selection for longer fiber as measured by HVI upper-half-mean length or longer 2.5% span length by fibrograph, combined with greater bundle fiber strength usually measured with Stelometer were the fiber properties receiving emphasis (Meredith, 1984). These selection criteria were adequate until open-end spinning became the dominant yarn manufacturing technology, placing emphasis on a different slate of fiber properties.

Cotton fiber length is an elementary property that permits the maintenance of fiber in yarn. Therefore, fiber length manipulation is one key to enhancing the processing capabilities of cotton. Developments in fiber measurement technology and software allow certain fiber properties to be measured on every fiber in a sample in a reasonably rapid fashion. The Advanced Fiber Information System® can measure the length of all fibers in the sample on a number and weight basis, and in rapid fashion compared with manual methods such as Suter-Webb array. As such, agronomists and breeders can assess not only the length of the longest fibers, such as the analogous upper-half mean length by HVI, but also the entire length by weight distribution that can now be captured and manipulated electronically (Table 2). Since length of the longest fibers in a sample is a heritable trait (Meredith, 1984), it is likely that additional fiber length distribution traits are heritable and can be selected for as well (May, 2001). Based on the detailed length distributions provided by AFIS, a fiber quality improvement goal to enhance performance on open-end spinning may be to reduce short fiber content while maximizing the proportion of fibers greater than an inch (25.4mm; Table 3). Experiments are underway to determine if the overall fiber length distribution can be made more uniform and if so, effects on yarn quality and strength (May and Bednarz, 2002). Beginning with an F2 population, two cycles of selection for the combination of least short fiber content and most fibers by weight exceeding an inch have been conducted, as depicted in Table 3. Following a seed increase generation, the selected population will be compared with an unselected control population to determine response to selection, with the fiber prepared through a small-scale gin system capable of preparing fiber as commercial gins do.

Open-end yarn manufacture is influenced also by the weight of fibers per unit length of the sliver spun into yarn, thus affecting the number of fibers in the yarn cross-section (Cotton Incorporated, 2003). This requirement for a minimum number of fibers in the yarn cross section to avoid frequent ends-down necessitates finer fiber (e.g., fiber with lower millitex; Deussen, 1992), typically chosen by the mill on the basis of bale micronaire readings between about 3.9 and 4.3. It is beyond the scope of this paper to delve further, but micronaire reading reflects the effects of fiber shape and maturity. Measured as resistance to airflow of a plug of fibers, micronaire reading cannot be rendered into separate estimates of fineness and maturity, but micronaire readings around 4.0 are usually interpreted as fine fiber and not fiber that is immature. Thus, the breeder may not have the information to evaluate and select for fiber fineness if micronaire is the only data available.

Genetic engineering to enhance cotton's fiber properties and add properties to the fiber not otherwise extant was well underway in the 1990s (John and Keller, 1996; John, 1999). Technological feats were achieved with the expression of polyhydroxybutyrate, a form of biopolymer, in the fiber lumen of cotton. The introduction of biopolymer in the fiber lumen was envisioned as a means of increasing the heat retention of winter wear textile products (John and Keller, 1996). The transgenic fiber containing polyhydroxybutyrate retained more heat than the non-transformed control. A similar feat was achieved with the ca. 60% increase in fiber strength of transgenic cotton compared with the non-transformed parent, but the unstable expression of the higher strength doomed any commercial application (Table 4; May and Wofford, 2000). Ultimately, the expense of commercializing a transgenic crop product and inability to capture economic returns of the enhanced fiber in a fiber market skewed towards discounting undesirable properties, but not rewarding better quality, led to the demise of this research. Still, the higher fiber strength and introduction of a biopolymer achieved through transformation argues that these efforts not simply be abandoned because the marketing system does not currently provide a return on investment to the biotechnology provider.

Fiber perimeter (distance in microns around the outside of the fiber cell) by arealometer instrument is a measure of fineness and is a heritable trait (May, 1999). Typically as perimeter becomes smaller, the fiber weight per unit length decreases, and thus card sliver delivered to the rotor frame would have more fibers per unit area relative to that of sliver prepared from larger perimeter fiber. In 1996, a study was initiated to determine the effect on fiber and agronomic properties of divergent selection for fiber perimeter in a population derived from crossing the germplasm lines PD 5529 and ARK 132-22. This population was chosen because a related study indicated that heritability of fiber perimeter was reasonable at 0.57. After two cycles of divergent mass selection for fiber perimeter, the selection differential between the large and small perimeter populations averaged about 16 microns in 1997. A replicated trial was conducted in 1998 to evaluate response to selection. The direct response to selection for fiber perimeter was measured as about a six-micron difference in mean perimeter between the small and large perimeter populations (Table 5), somewhat less than the selection differential in 1997. No significant differences in yield or percent lint existed between the large and small perimeter populations. These findings conflict with reports of yield reductions as fiber is bred to be finer, but may reflect that perimeter was only moderately changed through selection in our study (Meredith, 1984). Selection for smaller fiber perimeter resulted in lower micronaire reading and higher fiber strength, greater ring-spun yarn tenacity (small-scale skein test), and fiber maturity. Generally, these beneficial correlated changes in fiber properties and yarn tenacity without reduction in lint yield, lend encouragement to the development of germplasm with finer fiber. However, we still cannot assess the rotor spinning capabilities of the smaller perimeter fiber without scaling up this experiment to have sufficient fiber to spin yarn for testing.

Should Fiber Properties Be Modified For Each Spinning Technology ?

The difficulty in answering this question lies in the logistics of executing studies to address such a complex issue. This research requires the development of a set of germplasm with an array of fiber properties thought to influence ring, rotor, and air-jet yarn strength and quality followed by production of adequate quantities of seed-cotton from replicated trials over a number of environments and management regimes to then be ginned similar to that of commercial ginning, then by spinning into yarns representative of those produced on each spinning technology. Yarn quality and strength would then be subjected to a rigorous statistical analysis to compare response to selection. It then becomes clear why cotton is not directly bred for processing quality. Instead, breeders select for fiber properties thought to be important determinants of yarn strength and quality, often termed indirect selection, with yarn quality and strength not assessed until the candidate cultivar stage, if at all.

Meredith et al. (1991) report one of the few studies addressing the need to breed cotton specifically for open-end and ring spinning technologies. Their experiments included 16 genetic lines produced in Mississippi and South Carolina replicated trials from which the seed-cotton was ginned through a small-scale gin, with one-lint cleaner, and otherwise processed into fiber similar to picker-type cotton ginned through a commercial gin. The resulting fiber was spun into various yarn counts on ring and rotor spinning frames. The 16 entries consisted of commercial cultivars and germplasm lines, each selected for high yield potential and a slate of fiber properties. Two yarn counts, 12 and 27 tex, were ring spun and 27 and 42 tex yarns were rotor spun. Fiber was also subjected to a battery of tests with Arealometer, HVI, and Shirley Fineness and Maturity Tester (FMT) among other instruments. Meredith et al. (1991) concluded that fiber strength and the interaction of 2.5% span length, fiber strength, and fineness by FMT were nearly equally important in explaining variation in yarn tenacity for each yarn count and spinning system. The authors concluded that breeding cotton with a fiber package for each spinning system would thus not be necessary.

Juxtaposed against these findings, the global marketplace is sending messages that portions of recent cotton crops are not meeting the needs of yarn manufacturers. Merchants indicate they are having increasing difficulty in marketing fiber from recent crops (Quinn, 2003) and processors report problems in converting fiber into yarn (Felker et al., 2001). Particularly problematic are bales characterized by short staple length (ca. 25 mm or less), high micronaire (5.0 and above), and elevated short fiber content, defined as fibers one-half inch (12.7 mm) or less in length (Felker et al., 2001). Given the dominance of open-end spinning, the answer seems to be for cotton breeders to tailor selection goals to the needs of open-end spinners.

Summary

The properties of cotton fiber subject to modification to promote yarn manufacture and high-output textile production are mostly heritable and readily enhanced through breeding. Fiber quality of cotton can be altered to enhance its performance on high output manufacturing technologies. The challenge lies in developing cultivars that also have the yield potential and pest management traits to enable profitable fiber production and to make the seed available to growers. It is clear that the quality of the fiber supply must change to meet processor requirements or cotton's share of the fiber market may drastically decline in the near future.

Much education and research effort has addressed fiber quality enhancement to meet needs of manufacturers, but most such efforts have focused on only portions of the fiber supply chain such as agronomic trials evaluating HVI fiber quality or post-harvest studies of the impact of fiber properties in the bale on yarn and textile production. Once the fiber is agglomerated in the bale, further enhancement of fiber quality can only be achieved by reduction of the problematic fibers such as short fibers. The University of Georgia is implementing a strategy involving cotton production through processing where experiments control factors influencing the magnitude and variability of fiber properties including agronomic, environmental, genetic, and management treatments and their interaction. A small-scale gin capable of substantially replicating fiber preparation from seed-cotton similar to that experienced in commercial ginning is a pivotal tool in this plan and is nearing completion. Fiber from these studies will be spun into yarn and fabric produced thereof and subjected to the requisite battery of tests to validate success in enhancing the processing capabilities of cotton. Seed of promising breeds is envisioned to be provided to growers through technology transfer agreements with biotechnology companies. It is hoped that this integrated approach to fiber quality and yield enhancement can meet the 21st century requirements of an evolving cotton industry.

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Table 1. Heritability† of fiber properties important to yarn and textile processing (summarized in May, 1999).

Fiber property	Mean	Range
Fiber length	0.62	0.1-1.0
Fiber strength	0.59	0.1-0.9
Micronaire	0.48	0.08-0.87
Fiber fineness	0.52	0.07-0.68

†Heritability (0-1.0) is that portion of a trait expected to be expressed in the progeny of the selected population. Breeders use this statistic to discern if traits can be modified.

Fiber length measures – upper half mean length or 2.5% span length from fibrograph

Fiber strength measures – by Pressley or Stelometer instruments

Fiber fineness – fiber perimeter or fiber specific surface by Arealometer instrument

Table 2. Example of fiber length by weight distribution available from the Advanced Fiber Information System. Bold percentages indicate the short fiber content defined as those with length less than one-half inch (12.7 mm), while the italicized percentages define the longest fibers by weight.

% Fibers by weight	Length category	% Fibers by weight	Length category
0.1	0.0625	*6.0*	1.3125
0.2	0.125	*3.1*	1.375
0.2	0.1875	*1.4*	1.4375
0.3	0.25	*0.6*	1.5
0.3	0.3125	*0.3*	1.5625
0.4	0.375	*0.2*	1.625
0.6	0.4375	*0.2*	1.6875
0.8	0.5	*0.2*	1.75
1.0	0.5625	*0.2*	1.8125
1.7	0.625	*0.2*	1.875
2.3	0.6875	*0.2*	1.9375
2.7	0.75	*0.1*	2
4.0	0.8125	*0.1*	2.0625
5.2	0.875	*0.1*	2.125
7.9	0.9375	*0.1*	2.1875
10.1	1	*0.2*	2.25
13.3	1.0625	*0.2*	2.3125
12.5	1.125	*0.2*	2.375
12.3	1.1875	*0.1*	2.4375
10.3	1.25	*0.1*	2.5

Data courtesy of Cotton Incorporated Textile Services Laboratory.

Table 3. Characterization of fiber length by weight distribution by AFIS of a candidate germplasm, demonstrating traits undergoing testing to determine their response to selection.

% Fibers by weight	Length Category (in)	
3	<=0.5	3% SFC
25	>0.5-0.94	
10.1	1	59%>1"
13.3	1.0625	
12.5	1.125	
12.3	1.1875	
10.3	1.25	
6	1.3125	
3.1	1.375	
1.4	1.4375	

Table 4. Fiber strength of R4 progeny derived from three transgenic R3 parents engineered for enhanced fiber strength (May et al., 2000).

R3 Plant #1	R3 Plant #2	R3 Plant #3	'Deltapine 50' Control
--------------kN m kg^{-1}--------------			
277 ± 3.3	277 ± 3.0	274 ± 3.3	171±11
N=22	N=10	N=18	N=20

Stelometer fiber strength±standard error. N=no. plants measured for fiber strength. The R4 progeny tested for expression of a marker gene to infer presence of transgene imparting higher fiber strength. The cultivar Deltapine 50 was the original transformed parent.

Table 5. Fiber and agronomic properties of large and small fiber perimeter germplasm developed from two cycles of divergent mass selection for fiber perimeter evaluated at Florence, SC in 1998.

Entry	Lint Yield	Micronaire	Fiber Strength	2.5% length	Maturity	Perimeter
	--kg/ha--	--Units--	--g/tex--	--cm--	--%--	--Microns--
PD 5529	1484	3.9	20.9	29.9	83	45
ARK 132-22	1341	4.8	19.2	28.7	85	49
Large Perimeter	1099	4.3	19.5	27.7	76	52
Small Perimeter	1066	3.9	21.4	27.7	82	46
Comparisons						
Parents	ns	ns	ns	*	ns	*
Parents vs. Selects	**	**	ns	*	*	ns
Large vs. Small	ns	**	*	ns	*	*

Micronaire, fiber strength, and 2.5% fiber span length measured by single instruments. Fiber maturity and perimeter measured by Arealometer. Fiber measurements conducted by Starlab, Inc., Knoxville, TN.