Chapter 21

EFFECTS OF ENVIRONMENT ON FIBER QUALITY

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1. INTRODUCTION

"White as snow; strong as steel; fine as silk; long as wool, cheap as -- possible."
Traditional cotton buyers' fiber quality specifications

The physiological responses of *Gossypium* species to the environment have been defined and described at the crop, whole-plant, or organ levels elsewhere in this book. Indeed, the profound and diverse effects of growth environment on cotton physiology are mentioned or implied in the title of every chapter in *Physiology of Cotton.* Bulk fiber yields have been used as the benchmark for treatment success, and environment-related yield components have been discussed. Clearly, the relationships between sub-optimal weather or management practices and reduced yields are much better understood than are the effects of growth environment on the 'quality' of the cotton fiber produced in response to the growth environment. Nevertheless, it is the *quality*, not the quantity, of the fiber ginned from the cotton seed that determines the end-use and economic value of the cotton crop and, consequently, the profits returned to both the producers and processors.

2. WHAT IS FIBER QUALITY?

On a physiological basis, the fiber quality of any cotton genotype is a composite property determined by complex interactions among (1) the genetic potential of the genotype, (2) the environmental fluctuations experienced by the maternal plant from planting through harvest, and (3) the genetically controlled responses of the genotype to those environmental fluctuations. As do all metabolizing plant cells, a cotton fiber cell responds individually to fluctuations in the macro- and micro-environments so that the fibers on a single seed constitute a continuum of fiber lengths, shapes, cell-wall thicknesses, and maturities (Bradow *et al.*, 1996a, 1996b). Environmental variations within the plant canopy, among plants, and within and among fields assure that every bale of cotton contains a highly variable fiber population that encompasses broad ranges in fiber-quality properties. Thus, natural genetic and physiological variations in fiber cell shape, size, and maturity are modulated by fluctuations in the growth environment.

3. WHY IS FIBER QUALITY IMPORTANT?

Successful processing of cotton fiber depends on highly variable fiber physical attributes which have been shown to affect finished-product quality and manufacturing efficiency (Bradow *et al.*, 1996a). If blending levels and spinning and dyeing processes are to be optimized for specific end-uses, production managers of textile mills require effective description and measurement of these highly variable fiber-quality properties (Moore, 1996). In the United States, the components of the cotton fiber-quality composite are those properties reported for every bale by the classing offices of the USDA, Agricultural Marketing Service (AMS). Fiber physical properties reported by the USDA, AMS classing offices are: micronaire, length, length uniformity index, strength, and trash measured by the High Volume Instrument (HVI), the classer's color and leaf grades, preparation (degree of roughness of ginned lint), and extraneous matter.

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The naturally wide variations in fiber quality and differences in cotton end-use requirements introduce significant variability into the value of the fiber. Therefore, a system of premiums and discounts has been established with respect to a specified 'base' quality. In general, cotton fiber value increases as the fiber increases in whiteness, length, strength, and micronaire. However, discounts are made for both 'low mike' (micronaire <3.5) and 'high mike' (micronaire >4.9). Traditionally, ideal fiber-quality specifications have been summarized thus: "as white as snow, as strong as steel, as fine as silk, as long as wool, and as cheap as hell." Current fiber-classing technology allows the quantitation of such qualitative fiber properties, the improvement of standards for end-product quality, and the beginnings of a fiber-quality 'language' and system of measurements that can be meaningful to producers and processors alike.

4. FIBER-QUALITY PROPERTIES UNDER GENETIC CONTROL

4.1 Genetic Control and Environmental Variability

Ongoing changes in textile processing, particularly the new, improved spinning technologies, have led to increased emphasis on breeding for *both* improved yield *and* fiber quality (Meredith and Bridge, 1972; Green and Culp, 1990; Meredith, 1990; Patil and Singh, 1995). Studies of gene action and heterosis have suggested that, within Upland cotton genotypes, there is little non-additive gene action in fiber length, strength, and fineness (Meredith and Bridge, 1972). Large interactions between combined annual environments and fiber strength have suggested that environmental variability can prevent full realization of genotype fiber-quality potential (Green and Culp, 1990.) However, early (pre-1980) statistical comparisons of the relative genetic and environmental influences on fiber strength suggest that fiber strength is conditioned by a few major genes only (May, 1999).

4.2 Genetic Potential and Environment

In reference to either fiber yield or fiber properties, genotype potential is the fiber quantity or quality level attained under *optimal* environmental conditions. The variability of fiber properties at the crop level can be used to ascertain genotype potential. Sorting bulk seedcotton samples into weight categories revealed that as seed weight increased fiber length and maturity increased while short fiber percentage decreased (Davidonis *et al.*, 1999). When seedcotton weight categories were compared by dye uptake, it was found that non-dyeing fiber was associated with low seedcotton weights (Kerby *et al.*, 1993). This genotype optimum changes in response to environmental fluctuations and modulations, including the inevitable seasonal shifts in environmental factors such as temperature, day-length, and insolation. Such seasonal shifts in cotton metabolism and fiber properties have been seen in the higher growth rates of Upland and Pima bolls from July flowers, relative to the growth rates of bolls from August flowers on the same plants (Sassenrath-Cole and Hedin, 1996). The micronaire values and maturities of fibers from the July-flower bolls were also higher than those from the corresponding August-flower bolls (Bradow *et al.*, 1996b). Similar effects of environment on genotype potential have been quantified in fiber-quality plant maps of micronaire and maturity (Bradow *et al.*, 1996a).

In addition to modulations of genotype fiber properties at the crop and whole-plant levels, differences in fiber properties can be traced to variations in fiber properties on a single seed. Fiber-length array histograms from individual seeds have revealed that length variations occur in the micropylar, middle, and chalazal regions of seeds (Delanghe, 1986). Mean fiber lengths were shortest in the micropylar region of the seed in *G. hirsutum* L., *G. barbadense* L., and *G. arboreum* L. cultivars (Vincke *et al.*, 1985). The most mature fibers and those having the largest perimeters were also found in the micropylar region of the seed. The percentage of short fibers on a cotton seed after hand-ginning was extremely low; and it was concluded by Vincke and coauthors that, in baled cotton, short fibers with small perimeters did not originate in the micropylar region of the seed. Advanced Fiber Information System, Zellweger-Uster (AFIS) measurements of fiber from micropylar and chalazal regions of seeds revealed that the relative location of a seed within the boll was related to the magnitude of the differences in the properties of fibers from the micropylar and chalazal regions (Davidonis and Hinojosa, 1994). Motes (unfertilized ovules or aborted seeds) and seeds were examined 34 days post anthesis and showed micropylar and chalazal fiber property differences (Weis *et al.*, 1999).

There are also significant variations in other fiber properties that can be related to the seed position (apical, medial, or basal) within the boll (Porter, 1936; Iyengar, 1941). Degree of secondary wall thickening (quantified by AFIS as the fiber cell-wall maturity parameter, θ) is lowest in seeds at the apex (seed location 1) of the boll and highest in seeds at the pedicel or basal end (seed location 7) of the boll (Table 21-1). Fiber length and maturity also exhibit both seed and boll location effects. Porter (1936) examined fiber length in relation to seed position in the locule and found that seeds near the apical or basal end of the boll produced the shortest fibers. Fiber weight per unit length was greatest in seeds near the basal end of the boll (Iyengar, 1941). In Table21-1, the least mature fiber occurred closest to the boll apex, whatever the plant fruiting node number. Fiber from plant nodes 9, 10, and 11 higher in the plant canopy was consistently longer and more mature than fiber from node 7 or lower on the plant. Thus, the different micro-environments within the boll and within the plant canopy had significant effects on the properties of fiber produced within the same macro-environment, *i.e.*, on the same plant in the same field in the same crop year.

Table 21-1. Effect of seed location within the locule on Upland 'DPL51' cotton fiber properties quantified by AFIS. Seed nearest the pedicel (basal) end of the boll is designated as location 7. Each value is an average of three bolls containing no motes (underweight seeds). All data are from first-position bolls. Data from nodes 9, 10, and 11 were pooled to obtain a statistically valid population. Cotyledonary node = 0. (Davidonis, unpublished).

	Node	Seed location						
Fiber property	number	1	2	3	4	5	6	7
Length by weight, mm	7	24.6	25.1	25.6	25.4	25.1	24.6	24.9
Theta, θ		0.542	0.584	0.592	0.604	0.616	0.616	0.641
Immature fiber fraction (% with θ <0.250)		6.8	5.6	4.4	4.0	3.7	3.8	3.4
Length by weight, mm	9, 10,	26.2	26.7	26.7	26.7	26.9	26.9	26.4
Theta, θ	& 11	0.610	0.632	0.627	0.631	0.660	0.657	0.672
Immature fiber fraction (% with θ <0.250)		4.0	3.8	4.1	3.7	2.6	2.7	2.7

5. FIBER QUALITY, PLANT ARCHITECTURE AND SUBOPTIMAL GROWTH ENVIRONMENT

The effects of environment on cotton plant morphology and the correlations between plant architecture and yield are considered in other chapters in Parts II, III, and IV of this volume. In this chapter, linkages between canopy characteristics (both genotype and those induced by environmental factors) and fiber quality are considered on the basis that any modification of whole-plant morphology that significantly alters yield will also modify one or more fiber-quality properties in some way.

5.1 Canopy Architecture and Fiber Quality

Cotton canopy architecture, particularly plant height and branch formation, is modified by environmental factors such as temperature (Hanson *et al.*, 1956; Reddy *et al.*, 1990; Hodges *et al.*, 1993), growth-regulator application (Reddy *et al.*, 1990; Cadena and Cothren, 1996; Legé *et al.*, 1996), light intensity (Hanson *et al.*, 1956; Sassenrath-Cole, 1995), and herbivory (Terry, 1992; Rosenthal and Kotanen, 1994; Sadras, 1996c). Genotype canopy characteristics, such as solar tracking and leaf shape, and macro- and micro-environmental factors interact to modulate canopy light distribution which, in turn, alters photosynthetic activity within the canopy and the crop (Wells *et al.*, 1986; Reddy *et al.*, 1991; Sassenrath-Cole, 1995; Sassenrath-Cole and Heitholt, 1996). Thus, reduced photosynthetic rates and the modulation of other metabolic factors in association with lower light intensities resulted in lower micronaire, fiber strength, and yield (Pettigrew, 1996).

5.2 Boll Retention Patterns and Fiber Quality

Another obvious architectural linkage among environment and fiber yield and quality is seen in boll retention patterns. Environmental conditions that induce boll drop alter fiber quality of the remaining bolls by modifying assimilate and metabolic resource partitioning within the reduced boll population. Assimilate partitioning, source/sink relationships and related topics are covered in Chapters 5, 14, and 17. The connection between boll retention and micronaire distribution patterns can be seen in Figures 21-1 and 21-2. Irrigation method was the macro-environment treatment in this study of PD3 grown in South Carolina in 1992 (Bradow *et al.*, 1997a; 1997b). The irrigation treatments were natural rainfall or water added through micro-irrigation tubing laid in the root zone under each row (in-row) or laid between alternate rows (alternate-row). Both the in-row and alternate-row irrigation treatments delivered a season total of 90 mm additional water in nine irrigation events.

In comparison to both the rainfed and alternate-row treatments, the in-row irrigation treatment skewed boll retention toward the lower nodes (Fig. 21-1). Both micro-irrigation methods increased boll retention on the upper branches and this trend was more evident in the alternate-row treatment. Overall, the rainfed plants retained 15% fewer bolls than did the plants in the micro-irrigation treatments, and irrigation method modulated the resulting boll retention patterns. Alternate-row irrigation resulted in greater boll retention at nodes 15 and above, and the increase in rainfed boll number at node 14 was associated with increased rainfall associated with a hurricane system passing to the south of the field in 1992.

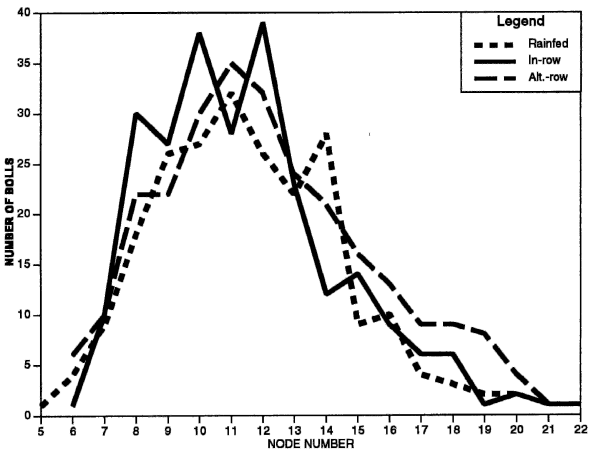

Figure 21-1. Boll retention patterns at harvest in rainfed, in-row, and alternate-row micro-irrigated PD3 cotton. Number of bolls = mean number of bolls at each node across branch positions from all plants in 1-m rows (with four replications; Bradow *et al.*, 1997b).

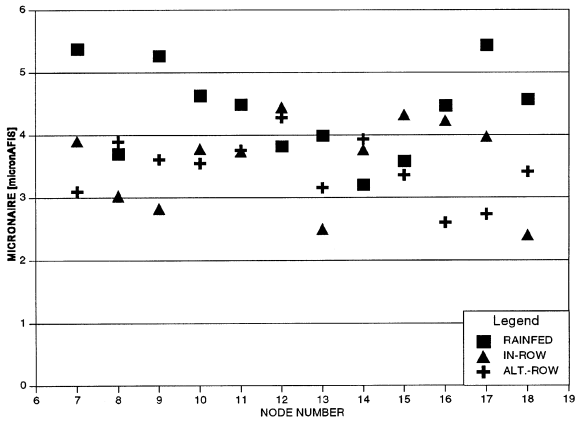

Figure 21-2. Node-by-node micronaire distributions from plant maps of PD3 Upland cotton irrigated by natural rainfall or in-row or alternate-row micro-irrigation (Bradow *et al.*, 1997a; 1997b).

The irrigation treatments did not significantly affect seed cotton yields or crop-average micronaire (Bradow *et al.*, 1997a; 1997b), but the macro-environment effects on the micronaire distribution patterns within the crop averages were apparent when micronaire was mapped according to node (Fig. 21-2). The rainfed micronaire distribution was bimodal with higher micronaire values occurring at the lower nodes within the main-crop (nodes 7 through 18) and a second high micronaire peak corresponding to the top of the main crop at nodes where only a single boll per plant persisted to harvest. Increased boll retention associated with in-row irrigation was correlated with marked decreases in micronaire. The low-micronaire bolls from nodes 13 and 14 were in peak fiber cell-wall deposition stage during a prolonged period of low insolation and increased rainfall associated with a hurricane in 1992.

Micronaire distributions in Figure 21-2 show the effects of both macro-environment and micro-environment on an economically important fiber property. Fluctuations in the environment increased fiber property variability and the frequency and proportion of fibers falling outside the fiber-quality range required by cotton processors, *i.e.*, 3.5 < micronaire > 4.9. Similar environment-related modulations of fiber maturity, cross-section, and length distributions have also been mapped within the whole-plant architectural framework (Bradow *et al.*, 1996a; Bradow *et al.*, 1997a; 1997b).

5.3 Seed Setting Efficiency and Fiber Quality

Marked variations in fiber properties were also found when within-boll architecture (or seed-setting efficiency) was considered as a subset of whole-plant architecture. The seed-setting efficiency, *i.e.*, the number of seeds produced compared to the number of ovules per ovary (Turner *et al.*, 1977; Davidonis *et al.*, 1996), is an indicator of the number of motes per boll where motes are developmentally arrested, non-viable seeds and their associated fiber (Verschaege, 1989; Davidonis *et al.*, 1996). Large numbers of long-fiber motes per boll reduced the degree of secondary wall thickening and, therefore, the relative maturity of fibers from the middle seeds in the same boll (Davidonis *et al.*, 1996).

6. FIBER LENGTH

Due to the inherent variability of cotton fiber, there is no absolute value for fiber length within a genotype or within a testing sample (Behery, 1993). Even on a single seed, fiber lengths vary significantly with longer fibers occurring at the chalazal end of the seed and shorter fibers being found at the micropylar end. Coefficients of fiber-length variation, which also vary significantly from sample to sample, are on the order of 40% for cotton.

Variations in fiber length attributable to genotype and fiber location on the seed are, of course, modulated by micro- and macro-environmental factors (Bradow *et al.*, 1997a; 1997b). Environmental changes around the time of floral anthesis may limit fiber initiation or retard the onset of fiber elongation. Sub-optimal environmental conditions during the fiber elongation phase may decrease the rate of elongation per day or shorten the duration of the elongation period so that the genotype fiber length potential is not fully realized (Hearn, 1976). In addition, the causative environmental fluctuation need not occur during the affected growth stage. Thus, the results of the physiological responses may become evident at a later stage in fiber development.

6.1 Measurement of Fiber Length

Fiber lengths on individual seeds can be determined while the fibers are still attached to the seed (Gipson and Joham, 1969; Munro, 1987) or, after ginning, by hand-stapling or photo-electrical measurement (Munro, 1987; Behery, 1993). Traditionally, staple lengths have been measured and reported to the nearest thirty-second of an inch or to the nearest millimeter. The four Upland staple classes are: Short (<21mm), Medium (22 to 25 mm), Medium-Long (26 to 28 mm), and Long (29 to 34 mm). Pima staple is classed as Long (29 to 34 mm) and Extra-long (>34 mm).

The term staple length was used by cotton buyers and processors long before satisfactory methods for measuring fiber properties had been developed. Consequently, staple length has never been formally defined in terms of any statistically valid length distribution (Munro, 1987; Behery, 1993). Historically, fiber length was measured using the Baer diagram or Suter-Webb array methods. Both methods are based on sorting fibers, within a defined sample, according to length and/or weight. Banks of parallel combs segregate fibers into length arrays or length groupings at one-eighth inch intervals. In Suter-Webb testing,

fibers in each length group are accurately weighed and the length-weight distribution is used in calculating various fiber length properties, including the mean length and upper quartile length by weight, *i.e.*, the fiber length exceeded by 25% of the fiber by weight in the test specimen.

Construction of Baer fiber-length diagrams must be done by hand and, consequently, is prohibitively labor- and time-intensive, particularly for classing-office use. Array construction with the Suter-Webb Duplex Cotton Fiber Sorter has been accepted as a standard test method for length and length distribution of cotton fibers (ASTM D 1440-90, 1994). The Suter-Webb array method physically sorts fibers of different lengths and serves as a benchmark to which other methods are compared. However, Test Method D 1440-90 is not commonly used for acceptance testing in commercial shipments. The Peyer Almeter AL-101, which reports fiber lengths by weight and by number (ASTM D 5332-92, 1994), is also used in the U.S., European, and Pacific Rim cotton industries (Bargeron, 1986; Behery, 1993).

Fiber length is directly related to yarn fineness, yarn strength, and spinning efficiency (Moore, 1996). Therefore, rapid, reproducible instrumental methods for fiber length measurement have been developed. Both length and length uniformity can be measured by the Fibrograph (ASTM D 1447-89, 1994). In Fibrograph testing, fibers are randomly caught on combs, and the beard formed by the captured fibers is scanned photoelectrically from base to tip (Behery, 1993). The amount of light passing through the beard is a measure of the number of fibers that extend various distances from the combs. Data are recorded as span length, *i.e.*, the distance spanned by a specific percentage of fibers in the test beard. Span lengths are usually reported as 2.5% and 50%, the 2.5% span length being the basis for machine settings at various stages during fiber processing. The uniformity ratio is the ratio between the two span lengths expressed as a percentage of the longer length. The Fibrograph provides a relatively rapid method for reproducibly measuring the length and length uniformity of fiber samples, and Fibrograph test data are used in research studies and in qualitative surveys such as checking commercial staple length classifications and assembling cotton bales into uniform lots.

Since 1980, USDA, AMS classing offices have relied increasingly on high volume instrumentation (HVI) for measuring fiber length and other fiber properties (Moore, 1996). The HVI length analyzer determines length parameters by photoelectrically scanning a test beard selected by a specimen loader and prepared by a comber/brusher attachment (Spinlab HVI, ASTM D 4605-86, 1994). (The Motion Control HVI, for which production ceased in 1995, pneumatically scanned the test beard [ASTM D 4604-86, 1994].) The fibers in the test beard are assumed to be uniform in cross-section so that the pressure drop across the beard is an estimate of the number of fibers in the airflow path. Scanning the pressure drop along the length of the beard provides a count of the fibers present at each point along the beard. These data are converted to represent the percentage of the total number of fibers present at each length value and other length parameters such as mean length, upper-half mean length, and length uniformity (Behery, 1993). This test method for determining cotton fiber length is considered acceptable for testing commercial shipments when the testing services use the same reference standard cotton samples (Moore, 1996).

All of the fiber length measurement methods discussed above require from three to five grams of ginned fiber and were developed for classing relatively large bulk samples of cotton fiber. For analyses of small fiber samples, *e.g.*, the single-seed or single-locule samples collected in plant-mapping and boll-mapping studies, fiber property measurements from an electron-optical particle sizer, the Zellweger-Uster AFIS (Advance Fiber Information System), have been found acceptably sensitive, rapid, and reproducible. The AFIS Length & Diameter module (Bragg and Shofner, 1993) generates values for mean fiber length by weight, mean fiber length by number, fiber length histograms, upper quartile length, and short fiber contents by weight and by number (the percentage of fibers shorter than 12.7 mm), and also mean fiber diameters by number (Behery, 1993). AFIS is a count-based system and values are given on number basis while values given on a weight basis are calculated.

Although short fiber content (SFC) is not currently reported as part of USDA, AMS classing office information, SFC is increasingly recognized as a fiber property comparable in importance to fiber fineness, strength, and length (Deussen, 1992; Behery, 1993). The importance of SFC in determining fiber processing success, yarn properties, and fabric performance has led to serious consideration being given to the establishment of SFC standards similar to the micronaire premium and discount system. Although fiber length is primarily a genotype trait, SFC is dependent upon genotype, growing conditions, harvesting, ginning, *and* processing methods.

If the strong genetic component of fiber length is to be separated from the environmental components introduced by excessive temperatures and water and nutrient deficiencies, it is essential that cotton breeders, and physiologists understand the underlying concepts and limitations of the various methods used in fiber-length and SFC measurement. Genetic improvement of fiber length is fruitless if the genotype response to the growth environment prevents full realization of the enhanced genetic potential. The effects of separate environmental factors on fiber length and SFC at harvest are discussed in subsections that follow.

6.2 Fiber Length and Temperature

Maximum cotton fiber lengths were reached when night temperatures were around 19 to 20°C, depending on the genotype (Gipson and Joham, 1968; Gipson and Ray, 1970b). Early fiber elongation was highly temperature-dependent; late fiber elongation was temperature-independent (Gipson and Joham, 1969; Xie *et al.*, 1993). Fiber length (upper half

mean length) was negatively correlated with the difference between maximum and minimum temperature (Hanson, 1956).

Field experiments on the Texas High Plains showed that a night temperature of 15°C caused a 4- to 5-day delay in lengthening of fibers, compared to a night temperature of 25°C (Gipson and Ray, 1968; 1969). Although the observed effects of cool night temperatures were not separated into delays in fiber initiation and early fiber elongation, field studies in India showed that fiber grown under 15°C conditions took three to five days longer to reach final fiber length than did control (24°C) fiber (Thaker *et al.*, 1989). Final fiber length was not significantly affected by temperature because reduced elongation rates were compensated by lengthening the elongation period by 8 to 24 days (Thaker *et al.*, 1989). Modifications of fiber length by growth temperatures have also been observed in planting-date studies in which later planting dates were associated with small increases in 2.5% and 50% span lengths (Aguillard *et al.*, 1980; Greef and Human, 1988). If the growing season is long enough and other inhibitory factors do not interfere with fiber development, early-season delays in fiber initiation and elongation can be counteracted by an extension of the elongation period (Bradow *et al.*, 1997b).

In addition to field studies, cotton ovule cultures have served as models for fiber growth and development (Meinert and Delmer, 1977; Haigler *et al.*, 1991; Xie *et al.*, 1993). Ovule cultures have been employed to differentiate the effects of cool temperatures on fiber initiation and early elongation. Ovules cultured under a 34°/15°C (12/12h) cycling temperature schedule showed delays in fiber initiation and early elongation. After fibers were 0.5 mm long, rates of elongation were similar in 34°C constant and 34/15°C cycling schedules (Xie *et al.*, 1993).

Variations in fiber length and the elongation period were also associated with relative heat-unit accumulations. Regression analyses showed that genotypes which produced longer fibers were more responsive to heat-unit accumulations than were genotypes that produced shorter fibers (Quisenberry and Kohel, 1975). However, genotype earliness was also a factor in the relationship between fiber length (or short fiber content by weight) and accumulated heat units (Bauer and Bradow, 1996; Bradow and Bauer, 1997b). Lower total cumulative heat units in 1992, compared to 1991, increased the short fiber content of the earliest genotype, 'DPL20' (Fig. 21-3). Higher total heat-unit accumulations in 1991 increased the short fiber content of the latest-maturing genotype, 'DPL5690'. Planting two weeks earlier than normal in the cooler spring of 1992 reduced the short fiber contents of 'DPL50' and 'DPL90'. The mean fiber length across genotypes and years was 21.6±0.4 mm, and the mean short fiber content by weight across genotypes and years was 13.8±2.7%.

Under well-watered conditions in closed-environment, sunlit growth chamber SPAR (Soil-Plant-Atmosphere-Research) units (Phene *et al.*, 1978) increased temperatures, decreased fiber length and short fiber percentage in ambient and elevated CO_2 environments (Reddy *et al.*, 1999).

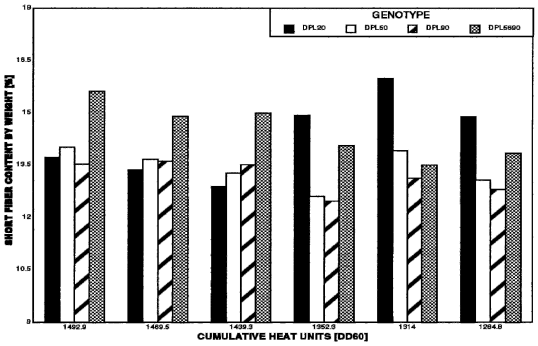

Figure 21-3. Relationships between Upland fiber short fiber contents by weight and total annual cumulative heat units (Degree Day 60) from a planting date study of 'DPL20', 'DPL50', 'DPL90', and 'DPL5690'. Planting and harvest dates were staggered so that the heat unit data on the x-axis above correspond, in descending order, to early planting date in 1991, normal planting date in 1991, late planting date in 1991, early planting date in 1992, normal planting date in 1992, and late planting in 1992 (Bauer and Bradow, 1996).

As temperature increased from 20° to 26°C fiber length frequency distributions were more uniform (Reddy *et al.*, 1999). Aware of the limitations imposed by growth chambers, Liakatas *et al.* (1998) varied day/night temperatures and found that the shortest fibers were observed under a 30/20°C regime and the longest in a 30/16°C regime. Length uniformity percentage was 42.5 for the 30/20°C regime and 54.3 for the 26/16.5°C regime (Liakatas *et al.*, 1998).

High temperatures promote the abscission of small bolls and abscission is more pronounced when the boll load is heaver (see Chapters 19 and 22) when cotton plants are grown in SPAR units boll retention decreased significantly at temperatures above 28°C (Reddy *et al.*, 1992c, 1995, 1999). As temperature increased the percentage of small, short-fiber motes increased (Reddy *et al.*, 1999). The low percentage of short fibers at higher temperatures may be related to increased assimilate availability to the fibers when there were fewer seeds per boll (see Chapter 14).

Boll shedding associated with high temperatures has also been attributed to pollen sterility (Powell, 1969; Fisher, 1973; 1975). Cotton pollen fertility was first linked with fiber length by Pressley (1937). However, subsequent research emphasis has been on the effects of pollen sterility on ovule abortion (Percy, 1986), particularly in interspecific crosses between *Gossypium hirsutum* and longer-fiber *G. barbadense* genotypes (Verschraege, 1989; Waller and Mamood, 1991) and in breeding programs directed at improving cotton heat tolerance and fertilization efficiency (Barrow, 1981; 1982; Rodriguez-Garay and Barrow, 1988; Gwyn and Stelly, 1989; Stelly *et al.*, 1990).

6.3 Fiber Length and Water

Cotton water relationships and irrigation have usually been studied with respect to yield (Hearn, 1976, 1995;

Ramey, 1986; Radin *et al.*, 1992). Grimes and Yamada (1982) concluded that fiber length was not affected unless the water deficit was great enough to lower the yield to 700 kg ha^{-1}. Fiber elongation was inhibited when the midday water potential was -2.5 to -2.8 mPa. The occurrence of moisture deficits during the early flowering period did not alter fiber length. However, when drought occurred later in the flowering period, fiber length was shorter (Marani and Amirav, 1971; Shimshi and Marani, 1971; Hearn, 1976).

Severe water deficits during the fiber elongation stage reduce fiber lengths (Hearn, 1995). Although water-deficit modulations of fiber length would appear to be linked simply and directly to the processes of cell expansion, the effects of water availability on duration and timing of flowering and boll set and upon fiber elongation result in complex physiological interactions between water deficits and fiber properties, including length. In the Coastal Plain of Texas, water deficits regularly occur during the mid- to late-flowering periods. When bolls containing zero to two small short-fiber motes were grown under rainfed and irrigated conditions in that region (Davidonis *et al.*, 1996), fiber lengths (both length by weight and length by number) were shorter in the mid-season population of rainfed bolls than in the mid- to late-season irrigated-bolls. The SFCs were the same for all irrigated bolls. In other studies, irrigation increased mean fiber length and upper-half mean length (Grimes *et al.*, 1969; Spooner *et al.*, 1958).

Drip irrigation and placement of the drip-irrigation tubing under or between the plant rows also modulated fiber length by weight (Bradow *et al.*, 1997a; 1997b). When the rainfed mean fiber length was 24.5±1.6 mm, the drip-irrigated fiber length by weight mean was 23.3±2.6 mm when the irrigation tubing was buried in the row under the plants and 23.5±2.6 mm when the tubing was buried between every other row. Fiber length distributions, according to fruiting site and within the locules, were also modified by irrigation method. The higher fiber length mean for the rainfed plants was related with the greater boll retention on nodes 13 and below (Fig. 21-1).

In India, moisture conservation practices [mulching] increased fiber length and yield (Singh and Bhan, 1993). However, under irrigated conditions, conservation tillage surface residues (Bauer *et al.*, 1995; Bauer and Busscher, 1996) did not affect any fiber property, including length.

6.4 Fiber Length and Light

Changes in the growth environment also alter canopy structure and the photon flux environment within the canopy. For example, loss of leaves and bolls resulting from unfavorable weather (wind, hail), disease, or herbivory and subsequent compensatory growth after loss of photosynthetic or reproductive organs can greatly affect both fiber yield and quality (Sadras, 1995). The light environment within the crop canopy is an important determinant of photosynthetic activity (Sassenrath-Cole, 1995) and, therefore, of the source-to-sink relationships that allocate photoassimilate within the canopy (Pettigrew, 1994; 1995). Eaton and Ergle (1954) observed that reduced light treatments increased fiber length. Shading during the first seven days after floral anthesis resulted in a 2% increase in the 2.5% span length of 'DES119', 'DPL5690', and 'Prema' genotypes (Pettigrew, 1995).

Shading (or prolonged periods of cloudy weather) and seasonal shifts in day-length also modulate temperature, which interactively modifies fiber properties, including length. Although commercial cotton genotypes are considered 'day neutral' with respect to both flowering and fruiting (Lee, 1984), incorporation of day-length data in Upland and Pima fiber quality models based on accumulated heat units increased the coefficients of determination for the length predictors from 30 to 54% for the Upland model and from 44 to 57% for the Pima model (Bradow *et al.*, 1997a; Johnson *et al.*, 1997). Kasperbauer (1994) also found that light wavelengths reflected from red and green mulches increased fiber length although plants grown over those mulches received lower reflected photosynthetic flux than did plants grown above white mulches. The longest fibers were harvested from plants that received the higher far-red/red ratios.

6.5 Fiber Length and Mineral Nutrition

Studies of mineral nutrition of cotton and the related soil chemistry usually emphasize increased yield and fruiting efficiency (Waddle, 1984; Joham, 1986; Radin and Mauney, 1986; Radin *et al.*, 1991; Bisson *et al.*, 1995). More recently, the effects of nutrient stress on boll shedding have also been examined (Jackson and Gerik, 1990; Heitholt, 1994b), and several mineral-nutrition studies have been extended to include fiber quality (Cassman *et al.*, 1990; Minton and Ebelhar, 1991: Bauer *et al.*, 1993; Matocha *et al.*, 1994; Bauer and Busscher, 1996; Pettigrew *et al.*, 1996). These studies investigated the effects of either potassium or nitrogen on fiber properties, including span length.

Reports of fiber property trends are often contradictory because of combined influences of genotype, climate, and soil conditions. Added potassium (112 kg K ha^{-1} yr^{-1}) does not affect the 2.5% span length of 'DES119'and 'STV825' when genotype was a significant factor in determining both 2.5% and 50% span lengths (Minton and Ebelhar, 1991). Genotype was not a significant factor in Acala fiber length, but an additional 480 kg K ha^{-1} yr^{-1} increased mean fiber lengths of the two Acala genotypes, 'SJ2' and 'GC510' when the K X genotype interaction was significant (Cassman *et al.*, 1990). Foliar applications of KNO_3 did not affect either yield or fiber length in Corpus Christi TX (Matocha *et al.*, 1994). Soil-applied KNO_3 did increase yields in two years out of three, but no potassium effects on fiber length were observed. In a Mississippi Delta study of eight genotypes (Pettigrew *et al.*, 1996), added potassium (112 kg K ha^{-1}) increased the length uniformity ra-

tio and increased 50% span length, but not the 2.5% span length. The 2.5% span length was determined by genotype and the interaction, genotype X environment (crop year).

Added nitrogen and the nitrogen X genotype, nitrogen X potassium interactions had no effect on fiber span lengths or length uniformity (Pettigrew *et al.*, 1996). Environmental factors other than added nitrogen determined fiber span lengths in a South Carolina study of the effects of nitrogen and green manures on cotton fiber yield and quality (Bauer *et al.*, 1993). Nitrogen released from legume cover crops also had no effect on fiber span lengths (Bauer and Busscher, 1996).

6.6 Trends in Fiber Length

During the decade between 1985 and 1996, the U.S. Upland staple length trend has been toward greater fiber length (an increase of 1.8 mm per year) with two plateaus: an average length of 27.4 mm between 1985 and 1990 and an average length of 27.9 mm between 1991 and 1996 (Sasser and Shane, 1996). The apparent jump in staple length between the 1990 and 1991 crops has been attributed to the shift to 100% instrument testing of length in 1991. Annual fluctuations in fiber length were loosely correlated with variations in the growth environments. Weather extremes across the U.S. Cotton Belt in 1998 decreased average fiber length to 27.2 mm (Cotton Incorporated, 1999). In the twelve years during which length uniformity index data have been reported by USDA classing offices, length uniformity index has increased at a rate of approximately 0.1% per year but with the same kind of environment-related variability noted in the staple length trends during that period (Cotton Incorporated, 1999).

7. FIBER STRENGTH

The inherent breaking strengths of the individual cotton fibers are considered the most important factor in determining the strength of the yarn spun from those fibers (Munro, 1987; Patil and Singh, 1995; Moore, 1996). Recent developments in high-speed yarn spinning technology, specifically open-end rotor spinning systems, have shifted the fiber-quality requirements of the textile industry toward higher strength fiber that can compensate for the decrease in yarn strength associated with open-end rotor spinning techniques (Patil and Singh, 1995). Compared to conventional ring spinning, open-end rotor-spun yarn production capacity is five times higher and, consequently, more economical. Rotor-spun yarn is more even than the ring-spun, but the rotor-spun yarn is 15 to 20% weaker than ring-spun yarn of the same thickness. Thus, fiber strength, together with fiber fineness, is given highest priority by mills using open-end rotor and friction spinning systems. Length and length uniformity, followed by fiber strength and fineness, remain the most important fiber properties in determining ring-spun yarn strength (Patil and Singh, 1995; Moore, 1996).

7.1 Estimating Fiber Strength

Historically, two instruments have been used to measure fiber tensile strength, the Pressley apparatus and the stelometer (Munro, 1987; ASTM D 1445-90, 1994). In both of these flat-bundle methods, a bundle of fiber is combed parallel and secured between two clamps. Force is applied to separate the clamps and gradually increased until the fiber bundle breaks. Fiber tensile strength is calculated from the ratio of the breaking load to bundle mass. Due to the natural inhomogeneity within a population of cotton fibers, bundle fiber selection, bundle construction and, therefore, bundle mass measurements, are subject to considerable experimental error (Taylor, 1994).

Fiber strength varies along the length of a fiber, as does fiber fineness (perimeter, diameter, or cross-section; Hsieh *et al.*, 1995). Further, the inherent variability within and among cotton fibers assures that two fiber bundles *of the same weight* will not contain the same number of fibers and that the clamps of the strength testing apparatus will not grasp the fibers in the bundle at precisely equivalent positions along the lengths. Thus, a normalizing length-weight factor has been included in bundle strength calculations. In the textile literature, fiber strength is reported as 'breaking tenacity' or grams of breaking load per tex where tex is fiber linear density in grams per kilometer (Munro, 1987; Taylor, 1994). Both Pressley and stelometer breaking tenacities are reported as 1/8 in. gauge tests, the 1/8 in. (or 3.2 mm) referring to the distance between the two Pressley clamps. Flat-bundle measurements of fiber strength are considered satisfactory for acceptance testing and for research studies of the influence of genotype, environment, and processing on fiber (bundle) strength and elongation. The relationships between fiber strength and elongation and processing success have also been examined using flat-bundle strength testing methods (Dever *et al.*, 1988). However, modern cotton fiber testing requires that procedures be rapid, reproducible, automated, and without significant operator bias (ASTM D 4604-86, 1994; ASTM D 4605-86, 1994; Taylor, 1994). Consequently, the HVI systems used for length measurements in USDA, AMS classing offices are also used to measure the breaking strength of the same fiber bundles (beards) formed in the length measuring process.

Originally, HVI strength tests were calibrated with the 1/8 in. gauge Pressley measurement, but the bundle-strengths of reference cottons are now established by stelometer tests, which also provide bundle elongation data. Fiber bundle elongation is measured directly from the displacement of the jaws during the breaking process, and fiber bundle strength and elongation data are usually reported together (ASTM D 4604-86, 1994). HVI bundle-strength measurements are reported in grams-force tex^{-1} and range from 30 and above (Very Strong) to 20 or below (Very Weak). In agronomic papers, fiber strengths are reported as kN m kg^{-1} where one Newton equals 9.81 kg-force (Meredith *et al.*, 1996a).

The HVI bundle strength and elongation test methods are satisfactory for acceptance testing and research studies when 3.0 to 3.3 g of blended fiber is available and the relative humidity of the testing room is controlled. A 1% increase in relative humidity and the accompanying increase in fiber moisture content will increase the strength value by 0.2 to 0.3 g tex^{-1}, depending on the fiber genotype and maturity. Further, classing office HVI measurements of fiber strength do not adequately describe the variations of fiber strength along the length of the individual fibers or within the test bundle. Thus, predictions of yarn strength based on HVI bundle-strength data can be inadequate and misleading (Taylor, 1994; Suh *et al.*, 1996). The problem of fiber-strength variance is being addressed by improved HVI calibration methods (Taylor, 1994) and by computer simulations of bundle-break tests where the simulations are based on large single-fiber strength data bases of more than 20,000 single fiber load-elongation curves obtained with MANTIS® (Suh *et al.*, 1996).

7.2 Fiber Strength, Environment, and Genotype

Growth environment and genotype responses to the growth environment all play a part in determining fiber strength and strength variability (Sasser and Shane, 1996). Early studies showed fiber strength to be significantly and positively correlated with maximum or mean growth temperature, maximum minus minimum growth temperature and potential insolation (Hanson *et al.*, 1956). Increased strength was correlated with a decrease in precipitation. Minimum temperature did not affect fiber strength. All environmental variables were interrelated, and a close general association between strength and environment was interpreted as an indication that fiber strength is more responsive to the growth environment than is either fiber length or fineness. (See section 8 - *Fiber Maturity* in this chapter.) Other investigators reported that fiber strength was correlated with genotype only (MacKenzie and Van Schaik, 1963; Greef and Human, 1988; Green and Culp, 1990).

Square removal did not affect either fiber elongation (Pettigrew *et al.*, 1992) or fiber strength (Terry, 1992; Pettigrew *et al.*, 1992). Shading, leaf-pruning, and partial fruit removal decreased fiber strength (Pettigrew, 1995). Early defoliation, at 20% open bolls, increased fiber strength (and length), but the yield loss due to earlier defoliation offset any potential improvement in fiber quality (Snipes and Baskin, 1994).

7.3 Fiber Strength, Mineral Nutrition, and Conservation Tillage

Acala fiber strength and elongation were positively correlated with the rate of added potassium (Cassman *et al.*, 1990). In 'SJ2' and 'GC510' fiber strength data, there were no significant genotype effects or interactions between genotype and potassium addition rates. However, the genotype main effect was significant for fiber elongation. Addition of potassium increased 'DES119' and 'STV825' fiber strength significantly and had a non-significant, but positive, effect on fiber elongation (Minton and Ebelhar, 1991). There were also strong genotype differences in the fiber strength and elongation of these two Upland genotypes. Added potassium and nitrogen did not affect fiber strength, but added potassium increased fiber elongation (Pettigrew *et al.*, 1996). Genotype differences in fiber strength were judged to be far more important than the level of nitrogen fertilization (MacKenzie and van Schaik, 1963). Supplemental boron had no effect on Upland fiber properties, including strength (Heitholt, 1994b).

Use of cover crops and tillage method had no effect on fiber strength, but significant differences in elongation were associated with winter cover type (rye) and/or tillage method (Bauer and Busscher, 1996). The influence of green manures on fiber strength tended to be small and inconsistent from year to year (Bauer *et al.*, 1993), but the authors reported that cotton planted in rye and fallow plots tended to reach cutout earlier and was ready for harvest before the other plots in the study. Linkages among maturation rate, planting date, and fiber strength were also reported when later planting resulted in increased fiber strength (Aguillard *et al.*, 1980; Greef and Human, 1988; Heitholt, 1993b). During 'Acala SJ2' fiber maturation, single-fiber breaking force and fiber linear densities increased markedly and in parallel at approximately 35 days post floral anthesis in the greenhouse (Hsieh *et al.*, 1995). No boll-position effects on single-fiber strength were observed above the fourth fruiting branch.

7.4 Trends in Fiber Strength

The 1996 Upland crop average fiber strength was 28.4 g tex^{-1}, and U.S. cotton fiber strength has increased 0.25 g tex^{-1} every year since 1980 when HVI strength data based became available and new calibration cottons were used (Cotton, Inc. 1999). The 1997 Upland crop average fiber strength was 28.4 g tex^{-1} and due to extreme weather conditions in 1998 the average fell to 28.0 g tex^{-1}. Most of the increases in fiber strength have been credited to the introduction of improved genotypes such as 'Prema' (strength >33 g tex^{-1}) in California (Patil and Singh, 1995). Differences in genotype grown, growth environment, and fiber fineness resulted in a range of fiber strength averages from 26.4 g tex^{-1} at the Corpus Christi, Texas, classing office to 32.6 g tex-1 at the Visalia, California office (Sasser and Shane, 1996). Since rotor spinning systems demand 1/8 in. fiber-bundle strengths of 28 to 30 g tex^{-1} or more, the demand for cotton genotypes that yield high strength fiber in a variety of growth environments remains strong.

8. FIBER MATURITY ([FIBER FINENESS, FIBER WALL THICKENING, AND MICRONAIRE)

Of the various fiber properties reported by USDA, AMS classing offices for use by the textile industry, fiber maturity is probably least well defined and understood. The term, fiber 'maturity', as used in cotton marketing and processing, is *not* an estimate of time elapsed between floral anthesis and fiber harvest (Lord and Heap, 1988). However, 'chronological' maturity can be a useful concept in studies that follow fiber development over time (Ramey, 1982; Bradow *et al.*, 1996b). On a physiological or physical basis, fiber maturity is generally accepted to mean degree (amount) of fiber cell-wall thickening relative to the diameter or fineness of the fiber (Perkins *et al.*, 1984: Munro, 1987).

8.1 Definitions and Related Estimates of Fiber Maturity

Classically, the mature fiber is one in which two times the cell wall thickness equals or exceeds the diameter of the fiber cell lumen, the space enclosed by the fiber cell walls (Ramey, 1982). However, this simple definition of fiber maturity is confounded by the cross-section of a cotton fiber never being a perfect circle and by fiber diameter being a genotype characteristic (Ramey, 1982; Lord and Heap, 1988; Matic-Leigh and Cauthen, 1994). Furthermore, fiber diameter varies along the length of the fiber, as does cell wall thickness. Thus, attempting to differentiate between naturally thin-walled or genetically fine fibers and truly immature fibers on a wall-thickness basis seriously complicates maturity comparisons among and within genotypes. For example, mean fiber diameters of Upland genotypes range from 21 to 29 μm, and diameters of genetically finer Pima fibers range from 17 to 20 μm (Ramey, 1982). On a locule-average basis and across fruiting sites within a single crop, PD3 Upland cotton fiber diameters (sample mean diameters by number determined by AFIS-L&D) ranged from 1.2 to 18.7 μm with a crop mean of 12.4±2.1 μm (Bradow and Bauer, unpublished). Within a single fiber sample examined by image-analysis, cell-wall thicknesses ranged from 3.4 μm to 4.9 μm when lumen diameters ranged from 2.4 μm to 5.2 μm (Matic-Leigh and Cauthen, 1994). Based on the (2 X cell-wall thickness > lumen diameter) formula for fiber 'maturity', 90% of the 40 fibers in that sample were mature, assuming there was no fiber-selection bias in the measurements.

8.2 Estimating Fiber Fineness

Fiber 'fineness' has long been recognized as an important factor in yarn strength and uniformity, properties which largely depend upon the average number of fibers in the yarn cross-section. Spinning finer fibers results in more uniform and stronger yarns (Ramey, 1982). However, direct determinations of 'biological' fineness in terms of fiber or lumen diameter and cell-wall thickness are precluded by the high expense in both time and labor, the non-circular cross-sections of dried cotton fiber, and the high degrees of variation in fiber fineness (Ramey, 1982; Munro, 1987). Advances in image analysis have improved determinations of fiber biological fineness and maturity (Matic-Leigh and Cauthen, 1994), but fiber image analyses remain too slow and sample-size limited for inclusion in the HVI classing process.

Initially, the textile industry adopted 'gravimetric' fiber fineness or linear density as an indicator of fiber spinning properties, which depend on fiber fineness and maturity combined (ASTM D 1769-77, 1977; Ramey, 1982). The gravimetric fineness testing method was discontinued in 1989, but the textile linear density unit of 'tex' persists. Tex is measured in grams per kilometer of fiber or yarn, and fiber fineness is usually expressed as millitex or micrograms per meter (Ramey, 1982; Munro, 1987). Direct measurements of fiber fineness, either biological or gravimetric, were subsequently replaced by indirect fineness measurements based on the resistance to air flow of a bundle of fibers.

The first indirect test method approved by ASTM for fiber maturity, linear density, and maturity index was the causticaire method in which the resistance of a plug of cotton to air flow was measured before and after a cell-wall swelling treatment with an 18% (4.5 M) solution of sodium hydroxide (ASTM D 2480-82, 1991). The ratio between the rate of air flow through an untreated and then treated fiber plug was taken as an indication of the degree of fiber wall development or maturity. The airflow reading for the treated sample was squared and corrected for maturity to serve as an indirect estimate of linear density. Causticaire method results were highly variable among laboratories, and the method was never recommended for acceptance testing before it was discontinued in 1992.

The arealometer was the first dual-compression airflow instrument developed for estimating both fiber fineness and fiber maturity from airflow rates through untreated raw cotton (ASTM D 1449-58, 1976; Lord and Heap, 1988). The arealometer measures the specific surface area of loose cotton fibers, *i.e.*, the external area of fibers per unit volume (approximately 200 mg each in four to five replicate samples). Empirical formulae were developed for calculating the approximate maturity ratio and the average perimeters, wall thicknesses, and weights per inch from the specific area data. The precision and accuracy of arealometer determinations are sensitive to sample preparation variations, repeated sample handling, and previous mechanical treatment of the fibers, *e.g.*, blending and opening conditions. The arealometer was never approved for acceptance testing, and the ASTM method was withdrawn in 1977 without replacement.

The variations in cotton fiber biological fineness and relative maturity described earlier cause the porous fi-

ber plugs used in air-compression measurements of those properties to respond differently to compression and, consequently, to air flow (Lord and Heap, 1988). The IIC-Shirley Fineness/Maturity Test (Shirley FMT), a dual-compression instrument, was developed to compensate for this plug variation effect (ASTM D 3818-92, 1994). Air is drawn through a 4-g fiber plug at a rate of 4.0 L min^{-1}, and the initial pressure drop measured. The sample is then compressed to a higher density, and the pressure drop is measured at a flow rate of 1.0 L min^{-1}. Fineness in millitex and a maturity index in percentage points are calculated according to empirically based formulae given in the ASTM method (ASTM D 3818-92, 1994; Ramey, 1982). The FMT is considered suitable for research, but not for acceptance testing, due to low precision and accuracy. Instead, micronaire has become the standard estimate of both fineness and maturity in the USDA, AMS classing offices.

8.3 Micronaire, an Indirect Estimate of Fiber Fineness and Maturity

Micronaire is the most commonly used instrumental cotton fiber property test (Lord and Heap, 1988; Moore, 1996). Micronaire is an indirect measure of the air permeability of a test specimen of known mass in a container of fixed dimensions. Initially, air permeability of the sample was thought to depend on the fiber linear density, and the empirically derived curvilinear micronaire scale was set in gravimetric fineness units of fiber weight per inch (Ramey, 1982; Lord and Heap, 1988). However, basic fluid-flow theory sets air permeability as inversely dependent on the square of the fiber surface area; and linear density units were subsequently dropped from the micronaire scale so that micronaire or 'mike' is now treated as a dimensionless fiber property.

Under standardized testing and calibration conditions, the micronaire test method incorporated in the HVI systems (ASTM D 4604-86, 1994; ASTM D 4605-86, 1994) is considered satisfactory for acceptance testing, if users of the test results consider micronaire readings as estimates of *both* fiber fineness and maturity. The micronaire test in the HVI system is relatively insensitive to sample preparation and *small* variations in relative humidity and temperature during testing, and standardized preconditioning is required at the USDA, AMS classing offices. For micronaire determinations in the HVI system, the minimum sample size is currently 10 g (ASTM D 4604-86, 1994; ASTM D 4605-86, 1994).

In the U.S., the 'acceptable' Upland micronaire range for which no price penalty is assessed is 3.5 to 4.9 with a premium range of 3.7 to 4.2. Empirical relationships between micronaire and cotton fiber processing properties have been developed, and bale micronaire readings are used by mills in bale selection and blending (Chewning, 1995; El Mogahzy and Gowayed, 1995a; 1995b).

The fineness factor of micronaire is considered more important in spinning, and fiber maturity is thought to have more effect on dyeability. However, the finer the fiber, the higher the number of reflective surfaces per unit area and, consequently, the higher the luster of the dyed fabric (Ramey, 1982). Immature fibers have thinner walls and are finer than mature fibers of the same variety. However, lower micronaire fibers stretch, tangle, and break more easily and do not impart the greater yarn strength and uniformity expected of finer fibers. The complex interactions among fiber fineness, fiber maturity, fiber spinning properties, and fiber dye-uptake characteristics are very difficult to interpret or predict and can result in confusion and frustration for breeders and physiologists who engage in research designed to improve fiber quality (Cooper *et al.*, 1996; Palmer *et al.*, 1996a, 1996b; Pellow *et al.*, 1996).

8.4 The Fiber Fineness/Maturity Complex

Various methodologies and instruments have been used to separate the causes and the effects of cotton fiber 'fineness' and 'maturity'. In addition to the previously discussed microscopic and image-analysis assays of fiber 'biological' fineness and estimates of fiber linear density, near-infrared transmission spectroscopy (NITS) has been used to describe a linear relationship between fiber fineness and the amount of light scattered (Montalvo *et al.*, 1989). The distribution of cotton fiber fineness as diameter by number can also be determined rapidly and reproducibly by the AFIS Length and Diameter (L&D) module (Bragg and Wessinger, 1993; Yankey and Jones, 1993).

The AFIS Fineness and Maturity (F&M) module uses scattered light to measure single-fiber cross-sectional areas (Bradow *et al.*, 1996a; Williams and Yankey, 1996). Algorithms have been developed for calculating the Fine Fiber Fraction (% of fibers for which the cross-sectional area by number is less than 60 μm^2), perimeter, and a micronaire analog, micronAFIS from fiber data collected by the AFIS-F&M. Newer AFIS instruments combine the L&D and F&M modules as the Length and Maturity (L&M) module that generates fineness data in millitex (Williams and Yankey, 1996). Near infra-red reflectance spectroscopy (NIRS) has also been used to examine fiber cross-sectional area, *e.g.*, fineness (Montalvo, 1991a; 1991b; 1991c).

8.5 Fiber Maturity and Dye Testing

Fiber fineness is most closely associated with spinning characteristics and the properties of the resulting yarn (Ramey, 1982). Fiber maturity affects the color of the fiber, both before and after dye application (Lord and Heap, 1988; Smith, 1991). Indeed, the anisotropic nature of the fibrillar cell walls of cotton fibers suggested the use of plane-polarized light microscopy for assessing cell wall developmental maturity (Lord and Heap, 1988). However, sorting fibers into maturity classes of thin-walled (violet-indigo),

immature (blue), and thicker walled/more mature (yellow) is slow, strongly biased by differential color sensitivity of the classer, and insufficiently sensitive to the difference between mature fibers of small perimeter and immature fibers of large perimeter. Differential dye tests for assessing fiber maturity, including the Goldthwaite red-green dye test, have been found to be similarly biased and further confounded by differences in sample fiber fineness and affinity for the dyes used (Milnera, 1987; Lord and Heap, 1988). The Goldthwaite red-green dye test, in which redness is associated with maturity and an increasingly greenish coloration connotes decreasing fiber maturity, is still used (Pellow *et al.*, 1996). However, the results are qualitative and highly subjective since most dyed samples appear as a mat of mixed red and green fibers with the green coloration being strongly associated with boll suture lines in dyed intact, mature bolls. In dye uptake tests using a single dye, fibers appressed to boll sutures were also dye-resistant and, by inference, immature (Bradow *et al.*, 1996c).

8.6 Fiber Maturity and Circularity

As an estimate of fiber maturity, direct measurement of average cell wall thickness in traverse fiber sections is subject to numerous and serious biases, *e.g.*, insufficient sample size and non-circularity of cotton fibers (Lord and Heap, 1988; Matic-Leigh and Cauthen, 1994). Consequently, degree of thickening [θ] was defined as a measure of fiber maturity based on fiber cross-section and perimeter (Lord and Heap, 1988).

Degree of thickening is the cross-sectional area of the fiber wall divided by the area of a circle of the same perimeter. Thus, completely circular fibers of any perimeter have θ values equal to one. Mature, thick-walled fibers (56 DPA) collapsed into cross-sections shaped like kidney-beans with θ means approximating 0.576 for Upland genotypes and 0.546 for Pima (Bradow *et al.*, 1996b). Immature, thin-walled fibers (21 DPA) collapsed into flattened elliptical shapes with Upland θ means of 0.237 and Pima θ means of 0.221. Fruiting site and seed location within the locule also modulated fiber circularity and the degree of wall thickening (Table 21-1). In microscopic determinations of formalin-treated, air-dried *G. hirsutum* 'Gujaret 67' fibers, the 35 DPA circularity was 0.215 and the circularity at 63 DPA was 0.685 (Petkar *et al.*, 1986). In the same report, *G. barbadense* 'ERB4530' fiber circularity was 0.180 at 35 DPA and 0.567 at 56 DPA.

Degree of thickening can be directly quantified by image analysis (Matic-Leigh and Cauthen, 1994) or by AFIS (Bradow *et al.*, 1996a; Williams and Yankey, 1996). The AFIS-F&M also provides Immature Fiber Fraction (% of fibers with $\theta < 0.25$; Bradow *et al.*, 1996a), and the AFIS-L&M reports Immature Fiber Content (defined as for Immature Fiber Fraction from the AFIS-F&M) and Immaturity ratio, which is the ratio of fibers with $\theta > 0.5$ divided by the number of fibers with $\theta < 0.25$ (Williams and Yankey, 1996). In contrast to micronaire-based methods in which the fiber sample is held stationary in a porous plug when 'maturity' is measured at some arbitrary point on the long axis, the AFIS, in either configuration, estimates θ and cross-sectional area along the entire length of the fiber as up to 10,000 fibers per sample flow between the light source and the detector. The scattering of light in the near-infrared (NIR or near-infrared reflectance) is also used to quantify fiber maturity (Gordon, 1995; Thomassson *et al.*, 1995). A VIS/NIR diode-array HVI system is also in development (Buco *et al.*, 1995; 1996; Montalvo *et al.*, 1996).

8.7 Trends in Fiber Maturity (Micronaire)

In the U.S., the trend in Upland micronaire since 1985 has been a slight, but irregular, increase toward the 1995 crop average of 4.35 and the 1998 crop average of 4.47 (Cotton Inc., 1999). In 1995, the Upland cotton micronaire values in all western states were equal to or lower than the corresponding micronaire values from 1994 (Sasser and Shane, 1996). In every state east of Texas and Oklahoma, 1995 micronaire averages were lower than in 1994. This pattern was attributed to environmental influences on cotton micronaire. In 1998 micronaire averages from all classing offices were higher than the 1997 micronaire averages for those classing offices (Cotton Inc., 1999). Many areas of the U.S. Cotton Belt were plagued by hot, dry weather in 1998 (Wrona *et al.*, 1999).

8.8 Fiber Maturity and Environment

Whatever the method, direct or indirect, that is used for estimating fiber maturity, the fiber property being assayed remains the thickness of the cell wall. The primary cell wall and cuticle together (*ca*. 0.1 μm) make up approximately 2.4% of the total wall thickness (*ca*. 4.1 μm of a cotton fiber at harvest; Ramey, 1982; Ryser, 1985; Matic-Leigh and Cauthen, 1994). The remaining 98% of a fiber cell is the cellulosic secondary wall which is deposited during fiber maturation. Therefore, any environmental factor that affects photosynthetic carbon fixation and cellulose synthesis will also modulate cotton fiber wall thickening and, consequently, fiber maturation (Sassenrath-Cole and Hedin, 1996; Bradow *et al.*, 1996b; Murray, 1996; Murray and Brown, 1996; 1997). Please refer to Chapters 12, 14, and 19 for reviews of cotton carbon metabolism and assimilate partitioning.

8.9 Fiber Maturity and Temperature and Planting Date

The dilution, on a weight basis, of the chemically complex primary cell wall by secondary wall cellulose has been

followed with x-ray fluorescence spectroscopy. This technique determines the decreases in relative weight ratios, over time, of calcium associated with the pectin-rich primary wall (Wartelle *et al.*, 1995; Bradow *et al.*, 1996a; 1996b; 1997b). Growth-environment differences between the two years of the studies cited significantly altered the maturation rates, quantified as rate of calcium weight dilution, of both Upland and Pima genotypes. The rates of secondary wall deposition in both Upland and Pima genotypes were closely correlated with growth temperature, *i.e.*, heat-unit accumulation (Johnson *et al.*, 1997; Bradow *et al.*, 1996b).

When temperature regimes were evaluated in SPAR units that differed by 2°C below or above the ambient temperature, it was found that as temperature increased theta, cross-sectional area and micronafis (micronaire) increased with increasing temperature (Reddy *et al.*, 1999). Under growth chamber conditions micronaire values were highest in a 30/20°C day/night temperature regime (Liakatas *et al.*, 1998). In temperature regimes in which the mean 24 h temperature was 22°C alteration in the maximum and minimum temperatures led to the conclusion that in a high maximum-low minimum regime (35-11°C), the high maximum effect overshadowed the effect of the low mean thus acting as a higher mean temperature (Liakatas *et al.*, 1998).

An early study on the effects of suboptimal temperatures on fiber development used 'micronaire fineness' to quantify the effects of heat-unit deficits (Hessler *et al.*, 1959). Temperature deficiencies (degree-hours per week below 21.1°C) in mid- or late-season reduced micronaire means so that late-season micronaire was in the penalty range, *i.e.*, below 3.5. Cell-wall thickness was not measured in this study, but cool night temperatures (15 to 28°C) modulated cellulose synthesis and secondary cell wall deposition (Haigler *et al.*, 1991; 1994; 1996).

Increases in micronaire over time were documented in maturing fibers by Hessler and coauthors (1959), and micronaire (micronAFIS) was also found to increase linearly with time for Upland and Pima genotypes (Bradow *et al.*, 1996a; 1996b). The rates of micronaire increase were correlated with heat-unit accumulation (Johnson *et al.*, 1997; Bradow *et al.*, 1997b). Rates of increase in fiber cross-sectional area were less linear than the corresponding micronaire rates, and rates of Upland and Pima fiber cell-wall thickening [quantified as θ by AFIS] were linear and without significant genotype effect (Bradow *et al.*, 1996b).

Environmental modulation of fiber maturity [micronaire] by temperature has most often been identified in planting and flowering date studies (Aguillard *et al.*, 1980; Greef and Human, 1988; Porter *et al.*, 1996; Bradow *et al.*, 1997b). Micronaire of four Upland genotypes decreased as the planting date advanced from early April to early June in Louisiana (Aguillard *et al.*, 1980). The effects of planting date on micronaire, FMT fiber maturity ratio, and fiber fineness (in millitex) were highly significant in a South African study (Greef and Human, 1988). Although genotype differences were detected among the three years of the study, delayed planting generally resulted in lower micronaire. The effect of late planting was repeated in the FMT maturity ratio and fiber fineness data. Consistent with earlier reports (Bilbro and Ray, 1973; Cathey and Meredith, 1988), delaying planting until mid-June from an early-May planting norm decreased micronaire of Upland genotypes grown in coastal South Carolina (Porter *et al.*, 1996). Planting date significantly modified θ, Immature Fiber Fraction, cross-sectional area, and micronaire (micronAFIS) of four Upland genotypes, which were also grown in South Carolina (Bradow *et al.*, 1997b). In general, micronaire decreased with later planting, but early planting also reduced micronaire of 'DPL5690', a long-season genotype, in a year in which temperatures were suboptimal in the early part of the season. Harvest dates in this study were also staggered so that the length of the growing season was held constant within each year. Therefore, season-length should not have been an important factor in the relationships found between planting date and fiber maturity. However, micronaire was reduced by early defoliation in a Mississippi study (Snipes and Baskin, 1994).

8.10 Fiber Maturity and Source-Sink Manipulation

Variations in fiber maturity were linked with source-sink modulations related to flowering date (Bradow *et al.*, 1997b), fruiting site (Pettigrew, 1995; Davidonis *et al.*, 1996; Bradow *et al.*, 1997a; Murray and Brown, 1997), or seed position within the boll (Bradow *et al.*, 1996a; Davidonis *et al.*, 1996). However, manipulation of source-sink relationships by early-season square (floral bud) removal had no consistently significant effect on Upland cotton micronaire (Pettigrew *et al.*, 1992). Early-season square removal also did not affect fiber perimeter or wall thickness (measured by arealometer). Partial defruiting increased micronaire and had no consistent effect on Upland fiber perimeter in bolls from August flowers (Pettigrew, 1995). Based on an increase in micronaire detected under natural fruiting load, fibers in August-bloom bolls of the Upland genotype, 'DPL5415', matured more rapidly than did fibers from July-flower bolls of that genotype (Bradow *et al.*, 1996b; 1997b). Other investigators found that loss of flowers four weeks or more after flowering had commenced led to increased micronaire, but loss of flowers earlier in the season had no effect (Jones *et al.*, 1996). The effects of intra-boll source/sink dynamics on fiber maturity (θ, Immature Fiber Fraction and micronaire/micronAFIS) have also been quantified (Davidonis *et al.*, 1996).

8.11 Fiber Maturity and Water

Generous water availability can delay fiber maturation (cellulose deposition) by stimulating competition for assimilates between early-season bolls and vegetative

growth (Hearn, 1995). Adequate water can also increase the maturity of fibers from mid-season flowers by supporting photosynthetic carbon fixation. In a year when rainfall was insufficient, initiating irrigation when the first bolls set were 20 days old increased micronaire, but irrigation initiation at first bloom had no effect (Spooner *et al.*, 1958). Irrigation and water-conservation effects on fiber fineness (millitex) were inconsistent between years, but both added water and mulching tended increase fiber fineness (Singh and Bhan, 1993). Aberrations in cell-wall synthesis correlated with drought stress have been detected and characterized by glycoconjugate analysis (Murray, 1996).

Adequate water supply in a growing season allowed maturation of more bolls at upper and outer fruiting positions, but the mote counts in those 'extra' bolls tended to be higher and the fibers within those bolls tended to be less mature (Hearn, 1995; Davidonis *et al.*, 1996). Rainfall during the blooming period and the associated reduction in insolation levels resulted in reduced fiber maturity (Bradow *et al.*, 1997b). Irrigation method also modified micronaire levels and distributions among fruiting sites. Early-season drought resulted in more mature fiber with higher micronaire from bolls in branch positions one and two on the lower fruiting branches of rainfed plants. However, reduced insolation and heavy rain reduced micronaire and increased Immature Fiber Fractions in bolls from flowers that opened during the prolonged rain incident. Soil water deficit and excess both may reduce micronaire if the water stress is severe or prolonged (Marani and Amirav, 1971; Ramey, 1986).

8.12 Fiber Maturity and Mineral Nutrition

Genotype differences, rather than added nitrogen, were responsible for micronaire treatment effects in an early study (MacKenzie and van Schaik, 1963). Green manures and added nitrogen had little consistent effect on fiber maturity, including micronaire (Bauer *et al.*, 1993; Bauer and Busscher, 1996). Nitrogen also did not affect fiber maturity index, micronaire, or perimeter of eight genotypes of differing relative earliness and regional adaptation. However, added potassium (112 kg ha^{-1}) significantly increased micronaire, fiber maturity index, and perimeter (Pettigrew *et al.*, 1996). That same level of added potassium did not affect micronaire in another study, but nematicide application did increase micronaire, probably through enhanced root growth (Minton and Ebelhar, 1991). Added potassium increased micronaire of two Acala genotypes, an effect the authors attributed to a potassium requirement for metabolic processes related to fiber secondary wall thickening (Cassman *et al.*, 1990). Genotype differences were noted in the relationship between micronaire and potassium availability. In a five-year study in which the fields were harvested twice, micronaire decreased with increasing nitrogen application rate (101 to 202 kg ha^{-1}; Ebelhar *et al.*, 1996). The decrease in micronaire was linear with increasing nitrogen for the first harvest only.

8.13 Fiber Maturity and Genetic Improvement

Micronaire or maturity data now appear in most cotton improvement reports (Green and Culp, 1990; Meredith, 1990; May and Green, 1994; Tang *et al.*, 1996). In a five-parent half diallel mating design, environment had no effect on HVI micronaire (Green and Culp, 1990). However, a significant genotype effect was found and associated with differences between parents and the F_1 generation and differences among the F_1 generation. The micronaire means for the parents were not significantly different although HVI micronaire means were significantly different for the F_1 generation as a group. HVI was judged to be insufficiently sensitive for detection of the small differences in fiber maturity resulting from the crosses. In another study, F_2 hybrids had finer fiber (lower micronaire) than the parents, but the improvements were deemed too small to be of value (Meredith, 1990). Unlike the effects of environment on the genetic components of other fiber properties, variance in micronaire due to the genotype X environment interaction can reach levels expected for genetic variance in length and strength (Meredith and Bridge, 1972; May and Green, 1994). Significant interactions were found between genetic additive variance and environmental variability for micronaire, strength, and span length in a study of 64 F_2 hybrids (Tang *et al.*, 1996).

The strong environmental components in micronaire and fiber maturity limit the use of these fiber properties as guides in studies of genotype differences in responses to growth environment. Based on micronaire, fiber maturity, cell-wall thickness, fiber perimeter, or fiber fineness data, row spacing had either no or minimal effect on okra-leaf or normal leaf genotypes (Heitholt, 1993b). Early planting reduced micronaire, wall-thickness, and fiber fineness of the okra-leaf genotype in one year of that study. In another study of leaf pubescence, nectaried *vs.* no nectaries, and leaf shape, interactions with environment were significant but of much smaller magnitude than the interactions among traits (Meredith *et al.*, 1996a).

Micronaire means for Bt transgenic lines were higher than the micronaire means of Coker 312 and MD51ne when those genotypes were grown in Arizona (Wilson *et al.*, 1994). In two years out of three, micronaire means of all genotypes, including the controls, exceeded 4.9. This apparent 'environmental' effect on micronaire may have been caused by a change in fiber testing methods in the one year for which micronaire were below the upper penalty limit. Genotype differences in bulk micronaire may be emphasized or minimized, depending on measurement method used (Meredith *et al.*, 1996b; Palmer *et al.,* 1996b; Pellow *et al.*, 1996).

9. GRADE

In U.S. cotton classing, non-mandatory 'grade' standards were first established in 1909, but compulsory

Upland grade standards were not set until 1915 (Perkins *et al.*, 1984). Official Pima standards were first set in 1918. Grade is a composite assessment of three factors – *color*, *leaf*, and *preparation* (USDA, 1980; Munro; 1987; Moore, 1996). Color and trash (leaf residue) can be quantified instrumentally, but traditional, manual cotton grade classification is still provided by USDA, AMS, in addition to the instrumental HVI trash and color values. Thus, cotton grade reports are still made in terms of traditional color and leaf grades, *e.g.*, light spotted, tinged, strict low middling.

The color grade that is provided by USDA-AMS Cotton Classing Offices is determined by the classer on the basis of official AMS color grade standards (Edmisten, 1997b). Color refers to the 'whiteness' or 'yellowness' of the fiber. The numerical codes for American Upland color grades are found in Table 21-2. These are the Color Grade codes that appear in the USDA-AMS Cotton Division Universal Classification Data reports provided by the USDA-AMS Classing Offices for each bale. A special condition code of '96' is assigned to mixtures of Upland and Pima. Similarly '97' indicates ''fiber damaged' color grade and '98' indicates 'water damaged' fiber.

9.1 Preparation

There is no instrumental measure of preparation, *i.e.*, the degree of roughness/smoothness of the ginned lint. Methods of harvesting, handling, and ginning cotton produce differences in roughness that are apparent in manual inspection, but no clear correlations have been found between degree of preparation and spinning success. The frequency of tangled knots or mats of fiber (neps) may be higher in 'high prep' ginned cotton, and the growth and processing environments can also modulate nep frequency (Perkins *et al.*, 1984). However, abnormal preparation occurs in less than 0.5% of the U.S. crop during harvesting and ginning (Moore, 1996).

9.2 Trash or Leaf Grade

Even under ideal field conditions, cotton lint becomes contaminated with leaf residues and other trash (Perkins *et al.*, 1984). Although most foreign matter is removed by the cleaning and drying processes during ginning, total trash extraction is impractical and can lower the quality of ginned fiber. In HVI cotton classing, trash in raw cotton is measured by a video scanner (Trash Meter), and the trash data are reported in terms of the total trash area and trash particle counts (ASTM D 4604, 1994; ASTM D 4605, 1994). These trash content data may be used for acceptance testing. In 1993, 'classer's grade' was split into color grade and leaf grade (Cotton Inc., 1999). Cotton fibers with the smallest amount of foreign matter, other factors being equal, have the highest value.

Table 21-2. Color Grade of American Upland Cotton (from Edmisten, 1997b).

	White	Light spotted	Spotted	Tinged	Yellow stained
Good Middling	11[z]	12	13	--	--
Strict Middling	21[z]	22	23[z]	24	25
Middling	31[z]	32	33[z]	34[z]	35
Strict Low Middling	41[z]	42	43[z]	44[z]	--
Low Middling	51[z]	52	53[z]	54[z]	--
Strict Good Ordinary	61[z]	62	63[z]	--	--
Good Ordinary	71[z]	--	--	--	--
Below Ordinary	81	82	83	84	85

[z] Physical Standards. All others are descriptive.

'Leaf' includes dried, broken plant foliage particles and can be divided into two general groups: large leaf and 'pin' or 'pepper' trash (Perkins *et al.*, 1984; Moore, 1996). The pepper trash is more expensive and difficult to remove and significantly lowers the value of the cotton to the manufacturer. Trash also includes stems, burs, bark, whole seeds, seed fragments, motes (undeveloped seeds), grass, sand, oil, and dust, all of which are found in ginned cotton. Growth environment obviously affects the amount of windborne contaminants trapped in the fibers, and environmental factors that affect pollination and seed development determine the frequency of undersized seeds and motes (Davidonis *et al.,* 1995; Davidonis *et al.*, 1996). Reductions in the frequencies of motes and small-leaf trash have also been correlated with semi-smooth and super-okra leaf traits (Novick *et al.*, 1991). Environment (year), harvest system, genotype, and second order interactions between those factors all had significant effects on leaf grade (Williford *et al.*, 1986). Delayed harvests resulted in lower grade fiber.

9.3 Fiber Color

Raw fiber stock color measurements are used in controlling the color of manufactured gray, bleached, or dyed yarns and fabrics (Nickerson and Newton, 1958). Of the three components of cotton grade, fiber color is most directly linked to growth environment. Color measurements are also related to overall fiber quality so that bright (reflective), creamy-white fibers are more mature and of higher quality than the dull, gray or yellowish fibers associated with field-weathering and generally low fiber quality (Perkins *et al.*, 1984). Although Upland cotton fiber is naturally white to creamy-white, pre-harvest exposure to weathering and microbial action can cause fiber to darken and to lose 'brightness' (Perkins *et al.*, 1984; Allen *et al.*, 1995). Premature termination of fiber maturation by frost or drought characteristically increases the saturation of the yellow fiber-color component. Other conditions, including insect damage and foreign matter contamination also modify fiber color (Moore, 1996).

The ultimate 'acceptance test' for fiber color, and also for finished yarns and fabrics is the human eye. Therefore, instrumental color measurements must be highly correlated with visual judgment. In the HVI

classing system, color is quantified as the degree of reflectance (Rd) and yellowness (+b), two of the three tristimulus color scales of the Nickerson-Hunter colorimeter (Nickerson, 1950; Nickerson and Newton, 1958; ASTM D 2253-88, 1994; Thomasson and Taylor, 1995).

Munsell Color Space can be represented quantitatively as three mutually perpendicular unit vectors in which Rd (reflectance, ±L) is represented perpendicularly on the +white/-black Z-axis, and the chromaticity coordinates, ±a (+red/-green X-axis) and ±b (+yellow/-blue Y-axis) are represented in the horizontal plane. The USDA has established an official color grade diagram that relates Rd on the vertical axis and +b on the horizontal axis to the traditional color grades of cotton (Perkins *et al.*, 1984). The USDA Rd reflectance scale range is from +40 (darker) to +85 (lighter/brighter). The +b scale is from +4 to +18 with the higher +b indicating an increasing degree of yellow saturation. The third tristimulus Color Space scale, +a, indicates the degree of red saturation and is not reported in HVI color measurements.

Colorimeter measurements and the USDA color diagram have been empirically correlated with manual classer's color grades. Thus, a fiber sample with Rd = +70.7 and +b = 9.7 would fall in the light-spotted, strict low middling grade. HVI classing information also supplies a number code in which the first number refers to color, *i.e.*, white, light spotted, *etc.* and the second number refers to grade, *i.e.*, good middling, strict low middling, *etc*. The code for the fiber sample above would be 42-1 with the number after the hyphen describing more precisely the intersection of the Rd and +b vectors on the USDA color grade diagram. Samples of the of the USDA color chart can be found on page 456 of the Perkins *et al.* (1984) reference and on page 587 of the ASTM D 2253-88 (1994) method. Colorimeter data can also be used to quantify dye uptake success (Bradow *et al.*, 1996c).

Fiber maturity has been associated with dye variability in finished yarn and fabric (Smith, 1991; Bradow *et al.*, 1996c; Bradow and Bauer, 1997a; Bradow *et al.,* 1997b), but the color grades of raw fibers have seldom been linked to environmental factors or agronomic practices. In one year only of a three-year study, increased nitrogen fertilization and application of mepiquat chloride were associated with decreased Rd, which represented an undesirable graying of the raw fiber (Boman and Westerman, 1994). There was also an undesirable linear increase in +b (yellowing) with increasing nitrogen level, but mepiquat chloride did not affect fiber yellow saturation (Boman and Westerman, 1994; Ebelhar *et al.*, 1996). Environment (year), planting date, and genotype all significantly affected fiber Rd and +b in a South Carolina study (Porter *et al.*, 1996). Late planting (mid-June) had the most consistently negative effect on both Rd and +b. In undyed knit fabric, fiber reflectance (+L, brightness) was positively correlated with increasing cumulative heat units (Bradow and Bauer, 1997a). Undyed-fiber yellow chromaticity, +b, was negatively related to increasing heat-unit accumulation. Removal of trash from the lint increased reflectance (Rd) but did not affect +b (Thomasson, 1993; Nawar, 1995).

9.4 Trends in Cotton Grade

Since 1985, there has been a significant increase in the number of U.S. bales classed in the 'white' grade and a corresponding decrease in the number of bales in the light spotted grade (Sasser and Shane, 1996). Since 1988, approximately 78% of the U.S. bales have been in the white grade, but there continues to be considerable variation among classing offices (Cotton Inc., 1999). In 1997, light spotted bale frequencies were above 35% in Georgia while Alabama, Louisiana, Arkansas and Missouri had ligh-spotted bale frequencies below 35% (Cotton Inc., 1999).

Although not yet included in the USDA, AMS cotton fiber classing system, cotton stickiness is becoming an increasingly important problem (Perkins, 1991; Brushwood and Perkins, 1996). Two major causes of cotton stickiness are insect honeydew from whiteflies and aphids and abnormally high levels of natural plant sugars. Insect honeydew contamination is randomly deposited on the lint in heavy droplets and has a devastating, production-halting effect on fiber processing. The cost of clearing processing equipment halted by sticky cotton is so high that buyers have included "honeydew free" clauses in purchase contracts and have refused cotton from regions known to have insect-control problems. Rapid methods for instrumental detection of honeydew are under development for classing offices and mills (Frydrych *et al.*, 1995; Perkins and Brushwood, 1995; Ethridge and Hequet, 1999). Elevated levels of natural plant sugars have been associated with premature crop termination from frost or drought.

10. RESEARCH NEEDS

Like all agricultural commodities, the value of cotton fiber responds to fluctuations in market supply-and- demand forces (Moore, 1996). Further, pressure toward specific improvements in cotton fiber quality, *e.g.*, the higher fiber strength needed for modern high-speed spinning, has intensified as a result of technological advances in textile production and increasingly stringent quality standards for finished cotton products. Changing fiber-quality requirements and increasing economic competition on the domestic and international levels has led to fiber quality becoming as important a factor in the value of cotton fiber as fiber yield (Ethridge, 1996; Hudson *et al.*, 1996). Indeed, it is the *quality*, not the quantity, of the fiber ginned from the cotton seed that decides the end use and economic value of a cotton crop and, consequently, the profits returned to the producer and processor.

Wide differences in cotton fiber quality and shifts in the demand for particular fiber properties based on end-use processing requirements have resulted in the annual creation of a price schedule of premiums and discounts for grade, staple length, micronaire, and strength (Deussen and Faerber, 1995; Ethridge, 1996). The price schedule was made pos-

sible by the development of rapid, quantitative methods for measuring those fiber properties considered most important in textile production (Chewning, 1995; Deussen and Faerber, 1995; Frye, 1995). Thus, with the arrival of fiber-quality quantitation by HVI, predictive models for ginning, bale-mix selection and fiber processing success were developed for textile mills (Chewning, 1995). Price analysis systems based on HVI fiber-quality data also became feasible (Deussen and Faerber, 1995; Ethridge, 1996; Hudson *et al.*, 1996). Quantitation, predictive modeling, and statistical analyses of previously qualitative fiber properties are now both practical and common in textile processing and marketing.

Field-production and breeding researchers, however, have failed to take full advantage of the fiber-quality quantitation methods developed for the textile industry. Most field and genetic improvement studies still focus upon *yield improvement* with little attention paid to fiber quality beyond obtaining bulk fiber length, strength, and micronaire averages for each treatment (*e.g.*, May and Green, 1994 Meredith *et al.*, 1996a, Porter *et al.*, 1996). Indeed, cotton crop simulation and mapping models of the effects of growth environment on cotton have been limited, almost entirely, to yield prediction and cultural-input management (*e.g.*, Boone *et al.*, 1995; Lemmon *et al.*, 1996; Wanjura *et al.*, 1996b; Chapter 38; Chapter 39). Some progress has been made in familiarizing breeders with AFIS data and their value in the late stages of cultivar development (Calhoun *et al.*, 1997).

Along the time line from cotton field to finished fabric, most field-production studies and the resulting quantitative fiber-quality databases terminate at the bale level. Fiber processing studies normally begin with selection of bales from the mill warehouse (Chewning, 1995). Although the experimental designs of field studies always include collection and analysis of environmental (weather) data, fiber processing studies begin to consider growth-environment factors *after* some significant processing defect cannot be attributed to post-harvest events. Very few integrated studies have attempted to follow fiber production and utilization from floral anthesis to finished yarn or fabric (*e.g.*, Bradow *et al.*, 1996c; Meredith *et al.*, 1996b; Palmer *et al.*, 1996a; 1996b; Pellow *et al.*, 1996). Physiological studies and textile processing models suggest that bulk fiber-property means at the bale, module, or crop level do not describe fiber quality with sufficient precision. Bulk fiber-property means do not adequately describe the variations in the fiber population response to environmental factors during the growing season. Such composite descriptors cannot accurately predict how highly variable fiber populations would perform during processing. Meaningful descriptions of the effects of environment on cotton fiber quality await high-resolution examinations of the variabilities, induced and natural, in fiber-quality means. Only then can the genetic and environmental sources of fiber-quality variability be quantified and modulated to produce the high quality cotton fiber demanded by the modern textile industry and, ultimately, the consumer. Only through increased understanding of the physiological responses to the environment that determine cotton fiber quality can real progress be made toward producing high yields of cotton fiber that is as white as snow, as strong as steel, as fine as silk, as long as wool, *and* as uniform as genotype response to the environment will allow.

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