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Genetic Modification of Cotton Fiber Properties as Measured by Single- and High-Volume Instruments

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ABSTRACT

Improved cotton fiber properties for the textile industry depends largely on genetic progress. Progress towards better fiber quality could be enhanced if breeders knew whether choice of fiber property measurement instrument affects direct and correlated responses to selection. The objectives of our study were to (i) compare heritability of a fiber property measured by single-instrument (fibrograph, micronaire, stelometer), that measure one or a few related properties, with the same fiber property measured by the integrated high volume instrument (HVI), capable of measuring multiple fiber properties, and (ii) compare direct and correlated selection response of fiber strength measured by the stelometer single instrument with that measured by the HVI. Other fiber properties important to textile processing including neps, short fiber content, immature fiber content, and fineness were measured by the Advanced Fiber Information System (AFIS). Heritability and selection response were estimated in two populations derived from mating the excellent fiber quality germplasm lines PD-3-14 and PD 5363 with the lesser fiber quality germplasm LA 870222. Heritability of micronaire reading (by micronaire instrument) and length (2.5% span length by fibrograph measurement) by single-instrument was similar to that measured by HVI. Heritability of fiber strength was greater when measured with stelometer than HVI, but the subpopulations with highest fiber strength by stelometer or HVI measurement differed little for fiber strength when evaluated with either instrument. Heritability of short fiber content averaged about 0.2, fiber fineness about 0.5, and immature fiber content about 0.6, indicating the potential for genetic progress. Overall, early generation selection for fiber strength by HVI measurement resulted in desirable fiber profiles.

GENETIC IMPROVEMENT of fiber properties contributes to productivity gains in the textile industry (Meredith et al., 1991). Yarn and textile manufacturers have been driven by global competition in the 1990s to produce products more efficiently. Improved efficiency has been accomplished partly through increased machine output of knit and woven textiles, plus rotor and air-jet yarn manufacture (Deussen, 1992; Faerber, 1995). Associated with higher machine output and rotor and air-jet yarn manufacture, is demand for improved cotton fiber properties important to processing, particularly fiber strength. Stronger fiber can better withstand the forces associated with higher manufacturing speeds (Faerber, 1995), and it contributes to yarn tenacity (Meredith et al., 1991; May and Taylor, 1998). Besides fiber strength, neps, short fiber content, and fiber fineness are examples of additional fiber properties that affect processability and textile quality. Neps and short fiber content among other fiber properties can now be readily measured with the AFIS (Bradow et al., 1996; Meredith et al., 1996).

Fiber property measurement instruments can be classified into two general categories on the basis of their capability of measuring one or a few related properties, such as fiber length parameters (generally known as *single-instruments*), or whether they can measure a relatively complete profile of properties (HVI). Examples of single instruments include the stelometer (Hertel, 1953) and Pressley (Pressley, 1942) that only measure fiber strength and elongation, and the fibrograph that evaluates length parameters. In contrast, the HVI provides estimates of length, strength, and micronaire reading on the same fiber sample (Taylor, 1982). Compared with single-instrument testing, the HVI technology for evaluation of fiber properties is faster and costs less per measurement. The disadvantage of HVI for genetic modification of fiber properties may be reduced accuracy and ability to separate small differences (Green

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Abbreviations: AFIS, advanced fiber information system; HVI, high volume instrument.

and Culp, 1988; Cooper et al., 1988). Fiber property measurement by HVI has been beneficial to yarn manufacturers, especially when combined with bale selection software such as the Engineered Fiber Selection System (Chewning, 1994). Without recourse to heritability and selection response data, instrument choice to evaluate fiber properties in breeding programs may be based on cost and availability. Breeders need information on which instrument will result in the fastest genetic gain in fiber strength. Additionally, because there exist genetic correlations among fiber properties (Meredith, 1984), data are needed on how fiber properties important to textile performance such as length, fineness, neps, and short fiber content respond to selection for fiber strength measured by single- or HVI-instrument.

Genetic studies that have compared fiber properties measured by single- and HVI-instruments have focused mainly on fiber strength. Stelometer and HVI fiber strength were only moderately correlated in studies by Green and Culp (1988, 1990), leading to speculation that the two instruments may measure different genetic properties. Cooper et al. (1988) and Palmer et al. (1994) found in advanced generation lines that the HVI could not discern the same magnitude of variation in fiber strength as that measured by stelometer. In contrast, Latimer et al. (1996) estimated heritability of fiber properties measured with HVI- and single-instruments and concluded that selection on the basis of HVI-measured fiber properties was sufficient to make progress in improving cotton fiber quality.

The objectives of our study were to compare (i) heritability of fiber properties measured by single- and HVI-instruments, and (ii) direct and correlated selection response of fiber strength measured by stelometer and HVI-instruments.

MATERIALS AND METHODS

Population Development

We crossed the germplasm lines PD-3-14 (May et al., 1996) and PD 5363 (Green et al., 1991) with germplasm line LA 870222 (later released as cultivar Hartz 1244; Calhoun et al., 1997) in 1993 to produce F_1s. The F_1s were self-pollinated at the USDA-ARS winter nursery in Mexico, and F_2 populations were evaluated in 1994. Plot size for the F_2 trials was two 10.6 m long rows spaced 96 cm apart, with plant density of about 2 per 0.3 m^{-1}. About 100 plants were harvested individually from each F_2 population. The seedcotton from each plant was ginned separately on a laboratory model gin and fiber was submitted to Starlab, Knoxville, TN, for analysis. The $F_{2:3}$ seed from each plant in both populations was planted as a progeny row in 1995. Plot length and plant density were the same as in the F_2 trial, except that plots were single rows. Twenty-five bolls were picked from the progeny rows and the seedcotton was ginned as in the F_2 generation. Fiber from each row from both populations was submitted for fiber analysis as in the F_2 generation. To evaluate response to selection, replicated trials were conducted in the F_4 and F_5 generations in 1996 and 1997, respectively. The $F_{3:4}$ progeny of each line from both populations were evaluated in separate (each population in its own trial) randomized complete block designs with two replicates. At maturity, 75-boll samples were picked from each plot to yield sufficient lint for the desired fiber testing. The 75-boll samples were ginned as described for the F_2 trial. This $F_{4:5}$ seed was then planted in 1997 in trials similar to those conducted in 1996. For the F_2 to F_5 trials, the soil type was a Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Kandiudult). Cultural practices including plant density, row spacing, and chemical inputs were those recommended by the Clemson University Cooperative Extension Service (Lege et al., 1995).

Fiber Analysis

Fiber analysis was conducted on F_2 to F_5 progeny of each population. Single instrument testing consisted of the 2.5% span length (by fibrograph instrument), strength and elongation (by stelometer instrument), and micronaire reading (by micronaire instrument) as described by Green and Culp (1990). High volume instrument properties included upper-half-mean fiber length, strength, elongation, and micronaire reading (Green and Culp, 1990). Yarn tenacity of 27-tex, ring-spun yarn (Landstreet et al., 1962) was obtained from the F_4 and F_5 generation replicated trials. Yarn tenacity was measured only in the PD 5363/LA 870222 population because the expense of measurement (about $30 per sample) precluded obtaining these data on both populations. The single-instrument, HVI, and yarn tenacity measurements were obtained from Starlab, Knoxville, TN.

Fiber analysis by AFIS (Bragg and Shofner, 1993; Hossein et al., 1994) was conducted by the Cotton Incorporated Textile Services Laboratory, Raleigh, NC, on the F_4 and F_5 generations. Neps (No. g $lint^{-1}$), short fiber content (by weight and number of fibers of length <12.5 mm, expressed as a ratio of all fibers in the sample), fineness (millitex), and immature fiber content (g kg^{-1} of fibers with incomplete secondary wall thickening) were measured by AFIS.

Statistical Analysis

Heritability of fiber properties was estimated for F_2 plant and F_3 progeny row selection units as regression coefficients from parent-offspring regression. Heritability of fiber properties measured by AFIS was estimated on a bulk-F_4 row selection unit as the regression coefficient from parent-offspring regression. This estimate of heritability was based on means derived from the replicated F_4 and F_5 studies.

Analyses of variance within year and combined over years were conducted on fiber properties derived from the replicated studies in the F_4 and F_5 generation. Square-root transformations (p. 307, Gomez and Gomez, 1984) were applied to the AFIS-measured properties neps, short fiber content, and immature fiber content. Simple correlations among fiber properties were calculated from progeny means averaged over the F_4 and F_5 generations.

Responses to selection for fiber strength by stelometer and HVI measurements within populations were calculated as follows. Twenty F_2 plants within each population were identified on the basis of highest fiber strength measured by stelometer and HVI. The $F_{2:3}$ progeny of these 20 plants were similarly evaluated, and the top 10 were identified. These 10 lines then constituted the subpopulations within each population (e.g., PD-3-14/LA 870222 or PD 5363/LA 870222) identified as possessing highest fiber strength measured by stelometer or HVI. Direct and correlated responses to selection for fiber strength were calculated by comparing the mean of the subpopulations with the mean of all of the progeny within populations. These means were derived from averaging over the replicated F_4 and F_5 trials. The PD-3-14/LA 870222 and PD 5363/LA 870222 F_4 and F_5 populations were composed of 87 and 78 lines,

Table 1. Parent-offspring regression heritability of fiber properties determined by single- and high-volume instrument (HVI) tests in a PD-3-14/LA 870222 cotton population grown at Florence, SC, from 1994–1996.

	Selection unit							
	F_2 Plant			2.5%‡	F_3 Row			2.5%
Instrument	MIC†	Elongation	Strength	length	MIC	Elongation	Strength	length
Single	0	0.21**	0.30**	0.46**	0.03	0.20*	0.24**	0.21**
HVI	0	0	0.12	0.53**	0.03	0.03	0.08*	0.34**

*,** Significant at $P < 0.05$ and 0.01, respectively.
† MIC-micronaire reading.
‡ The HVI instrument measures upper mean length, which is analogous to the 2.5% length.

respectively, because some of the original 100 F_2 plants failed to produce enough lint for fiber analysis. Note also that we advanced all lines in each population through the F_5 generation for purposes of agronomic evaluation, not just representatives of the stelometer and HVI selected subpopulations.

RESULTS AND DISCUSSION

Low to moderate estimates of heritability for most fiber properties (Tables 1–3), reflected significant genetic variation (Table 4). Genotype × year (g × yr) interactions ($P < 0.05$) were noted only in the PD-3-14/LA 870222 population for upper half mean length and short fiber by number (data not shown). However, the genotype mean squares were large relative to the interaction mean squares. Thus, we did not consider g × yr interactions to be a serious bias in estimating heritability or response to selection. This observation is consistent with the findings of Meredith et al. (1996) and May and Taylor (1998), that genotype × environment interactions for breeder fiber samples are small relative to genetic variation.

Heritability estimates for micronaire reading and the length measurements (2.5% fiber span length, upper-half-mean) were similar between single- and HVI-instruments (Tables 1 and 2). Micronaire reading is one of several bale selection criteria yarn manufacturers employ to produce a certain size yarn and control variation in its quality (Deussen, 1992). Cotton bales with high and low micronaire reading have limited use by textile manufacturers (Hake et al., 1990), which is the basis for use of micronaire values in classing and marketing cotton. We found that heritability of micronaire reading was low, suggesting little progress from selection could be made. Other studies report reasonable heritability estimates for micronaire reading (May, 1998). Heritability estimates of the length measurements, 2.5% span length and upper-half-mean length, were similar, and of a magnitude to expect progress from selection. Although 2.5% span length and upper-half-mean length are not the same measure of fiber length distribution, both give information on the length of the longest fibers in a sample of cotton (Kerr, 1961). Yarn manufacturers make use of these length measurements to establish machine settings, such as the distance between draft rolls in the drawing process (Perkins et al., 1984). Modernization of yarn manufacturing technology to include open-end spinning necessitates less increase in the 2.5% span length or the upper-half-mean length, but instead demands more fiber length uniformity (Deussen, 1992). Current breeding goals for Upland cotton emphasize maintenance of existing gains in 2.5% span length and upper-half-mean length, while ameliorating the amount of short fibers.

Heritability of elongation in the PD-3-14/LA 870222 population was greater when measured by stelometer (Tables 1 and 2). Elongation has been touted as a fiber property that should be given higher priority by yarn manufacturers in assembling bale laydowns to control variation in yarn quality (Backe, 1996). Elongation has not been emphasized in breeding programs because it has an inconsistent genetic contribution to yarn tenacity (Green and Culp, 1990; Meredith et al., 1991; May and Taylor, 1998). Were elongation to receive attention from breeders, our data indicates that elongation measurements from the HVI-instrument in populations where heritability of fiber strength is low to moderate may not be as reliable as those determined with the stelometer.

Fiber strength contributes to yarn tenacity (Meredith et al., 1991; May and Taylor, 1998) and durability of knit and woven textiles (Faerber, 1995). Improving fiber strength of U.S. cotton is essential to facilitate the competitive advantage of domestic yarn and textile manufacturers as they seek higher efficiency through open-end yarn production. Compared with ring spinning, open-end yarn manufacture produces a weaker yarn,

Table 2. Parent-offspring regression heritability of fiber properties determined by single- and high-volume instrument (HVI) tests in a PD 5363/LA 870222 cotton population grown at Florence, SC, from 1994–1996.

	Selection unit							
	F_2 Plant			2.5%‡	F_3 Row			2.5%
Instrument	MIC†	Elongation	Strength	length	MIC	Elongation	Strength	length
Single	0.05	0.17*	0.55**	0.41**	0.14*	0.16	0.34**	0.18*
HVI	0	0.17*	0.39**	0.49**	0.15*	0.18**	0.19**	0.22**

*,** Significant at $P < 0.05$ and 0.01, respectively.
† MIC-micronaire reading.
‡ The HVI instrument measures upper mean length, which is analogous to the 2.5% length.

Table 3. Parent-offspring regression heritability of fiber properties measured by the Advanced Fiber Information System in two cotton populations grown at Florence, SC, in 1996 and 1997.

Fiber property	Population	
	PD-3-14/LA 870222	PD 5363/LA 870222
Neps	0.05	0.08
Short fiber by weight	0.15*	0.17*
Short fiber by no.	0.15*	0.22*
Fineness	0.54*	0.44*
Immature fiber content	0.68*	0.52*

* Significant at $P < 0.05$.

resulting in less durable textile products (Faerber, 1995). Higher fiber strength can overcome these problems. An unresolved issue is whether selection for fiber strength by stelometer or HVI measurement will result in similar gains. Despite the higher heritability of fiber strength by stelometer measurement (Tables 1 and 2), we found little difference in mean strength between the subpopulations developed by selecting for strength with either instrument (Table 4). For example, in the PD 5363/LA 870222 population, selection for increased fiber strength by stelometer measurement resulted in a subpopulation with mean strength of 221 kN m kg^{-1} (by stelometer measurement) and 240 kN m kg^{-1} (by HVI measurement). Selection for best HVI fiber strength in the same population resulted in a subpopulation with mean strength of 218 kN m kg^{-1} (by stelometer measurement) and 240 kN m kg^{-1} (by HVI measurement). The similarity in fiber strength of the selected subpopulations would be expected if they shared the same lines; but, the subpopulations identified on the basis of highest fiber strength by stelometer or HVI measurement only shared five lines in the PD 5363/LA 870222 population and six lines in the PD-3-14/LA 870222 population. The HVI instrument has a reputation for producing strength measurements not highly correlated with stelometer (Cooper et al., 1988; Green and Culp, 1988). Fiber strength in those studies was evaluated mostly on germplasm that had experienced early generation selection for fiber strength by stelometer measurement, plus agronomic properties. If selection for fiber strength by stelometer or HVI instrument exploits different genetic properties, this could explain low correlations between the strength measurements when derived from advanced generation breeding lines. The correlation between fiber strength measured by HVI and stelometer in our study was about 0.7 ($P < 0.05$) in both populations (n = 87 and 78, PD-3-14/LA 870222 and PD 5363/LA 870222 populations, respectively). Overall, the similarity in gain for fiber strength may result because selection for fiber strength with either instrument about equally modified the individual fiber properties that contribute to strength (Meredith, 1992).

In addition to stronger fiber, yarn and textile manufacturers are asking for fiber with fewer neps, less short and immature fiber, and increased fineness. These fiber characteristics have become more important to manufacturers as they adopt open-end yarn spinning and higher output textile manufacture (Faerber, 1995). The genetic control of neps, and short and immature fiber has received little attention (May, 1998), partly because breeders could not readily obtain these measurements until the advent of the AFIS instrument. Thus, the heritability of these traits and their correlated responses to selection for fiber strength were of interest in our study.

Neps are cotton fibers tangled into a knot (Pearson, 1944), that reduce yarn quality and cause dye defects in textile products. Their genetic control has not been extensively studied, except that cultivar variation was deemed more important in explaining variation in neps than was the main effect of location and the variety × location interaction (Pearson, 1944; Meredith et al., 1996). We did not find genetic variation for neps, nor that this trait was heritable in the two cotton populations. To reduce neps, the traits that contribute to them, such as small perimeter fiber, motes, and seed coat fragments may need to be addressed.

Short fiber content (fibers <12.7 mm in length) is important to yarn manufacturers because it is a source of fiber waste, and it contributes to weaker yarns (Behery, 1993). We found significant genotypic variation for short fiber content measured by weight and number of fibers,

Table 4. Response of fiber properties to selection for fiber strength by stelometer and HVI measurements in two cotton populations grown in 1996 and 1997 at Florence, SC.

Fiber property	Population							
	PD-3-14/LA 870222				PD 5363/LA 870222			
	Stelometer	HVI	Mean	Range	Stelometer	HVI	Mean	Range
Micronaire reading	4.4	4.5	4.3	4.1–4.8*	4.2	4.3	4.3	3.8–4.7**
Elongation (%)	7.5	7.3	7.3	6.8–8.1*	7.7	7.7	7.5	6.5–8.4*
Stel. strength (kN m kg^{-1})	217	215	211	192–230**	221	218	211	193–230**
2.5% span length (mm)	30.2	30.2	30.4	28.8–31.2**	30.0	30.1	30.0	29.1–31.0**
HVI-micronaire reading	4.3	4.3	4.2	3.9–4.7**	4.2	4.3	4.2	3.8–4.7**
HVI-elongation (%)	9.9	9.9	9.8	9.4–10.3*	9.9	10.0	9.9	9.4–10.3**
HVI-strength (kN m kg^{-1})	238	237	232	222–224*	240	240	235	221–248**
HVI-upper half mean (mm)	29.0	29.0	29.2	27.4–30.4**	29.2	29.3	29.3	27.9–30.6**
Neps (no. g^{-1})	122	125	133	99–170ns	134	130	137	101–182ns
Short fiber by wt (g kg^{-1})	54	54	60	44–81*	57	55	59	43–73*
Short fiber by no. (g kg^{-1})	164	163	178	139–221*	169	167	176	137–205*
Fineness (millitex)	170	170	168	160–178**	168	171	170	161–181**
Immature fiber (g kg^{-1})	53	53	57	44–68**	61	56	58	45–75**

*,** Significant genotypic variation at $P < 0.05$ and 0.01, respectively.
Stelometer and HVI indicate the mean (averaged over the F_4 and F_5 generations) of a fiber property for a subpopulation (n = 10) identified by selection in the F_2 and F_3 generations for fiber strength with the indicated instrument. Mean represents the average over the F_4 and F_5 generations for a fiber property for the entire population (n = 87 and 78, PD-3-14/LA 870222 and PD 5363/LA 870222 populations, respectively).

but that heritability was low (Table 3). A problem in evaluating short fiber content from early generation breeding material is that the expression of short fiber may not be fully realized. Sources of short fibers include those that do not lengthen past about 13 mm because of genotype and environment (Richmond and Fulton, 1936; Kerr, 1961), and those that break from harvesting and ginning operations (Mangialardi, 1991). The greatest contributor to short fiber content may be lint cleaning in the commercial ginning operation that is performed to achieve a certain bale grade. Our fiber and that of breeders, in general, from early generations is derived from hand picked boll samples ginned on a laboratory model gin that is not fitted with a lint cleaner. Therefore, when we evaluate short fiber content from fiber not subjected to commercial ginning, we may primarily be measuring the genetic basis of fibers that fail to lengthen past 13 mm, rather than those that break. Despite these limitations, there is a genetic basis for the short fiber we measured. Progress in alleviating short fiber can be expected, albeit slow because of low heritability. Compared with the population mean, the subpopulations identified on the basis of selection for HVI strength had slightly less short fiber content by number and weight in the PD 5363/LA 870222 population (Table 4). Despite the small differences in short fiber, we found a reduction in short fiber content of a similar magnitude is still of economic significance to yarn manufacturers that consume thousands of cotton bales in a year (Deussen, 1992). We can only speculate why selection for fiber strength by HVI measurement would result in less short fiber. A possible explanation might be found in the idiosyncratic methods by which the two classes of instrument obtain strength. Although both instruments measure the force required to break a bundle of fibers, variation exists in sample preparation and mass measurement that may cause each instrument to differentially act upon the fiber properties that contribute to fiber strength (Taylor, 1982; Meredith, 1992).

Immature fiber results from incomplete secondary cell wall development (Bradow et al., 1996). Secondary wall development has been shown to be under genetic control (Kohel et al., 1974), but it has not been a breeding priority. Immature fibers do not completely dye, and thus contribute to color variation in textile products. We found the heritability of immature fiber content to be moderately high (Table 3), combined with nonsignificant g × yr interactions (data not shown). Except for the stelometer selected subpopulation (PD 5363/LA 870222 population), selection for higher fiber strength resulted in less immature fiber (Table 4). The increased immature fiber in that stelometer selected subpopulation might be related to finer fiber, that can result from incomplete secondary wall development. Among all entries in the PD 5363/LA 870222 population (n = 78), the correlation between fineness and immature fiber content was −0.83 ($P < 0.05$); and selection for fiber strength by stelometer measurement resulted in a correlated finer fiber (Table 4). These data suggest that increased fineness (e.g., small fineness values by AFIS measurement) was generally immature fiber. Overall, the moderate heritability of immature fiber content suggests that breeding can result in progress.

Yarn tenacity results from the individual and combined effects of raw fiber characteristics such as length, strength, and fineness (Meredith et al., 1991). As yarn tenacity is an expensive trait to measure, breeders must rely on indirect selection of related fiber properties to make progress in improving yarn tenacity (May and Taylor, 1998). Fiber strength is generally one of the selection criteria breeders use to improve yarn tenacity. Therefore, comparison of gain in yarn tenacity from selection for fiber strength by stelometer- and HVI-measurement is another method of assessing the utility of single- and HVI-instruments. Our data indicate little difference in yarn tenacity between the subpopulations with highest fiber strength by stelometer (141 kN m kg^{-1}; n = 10) and HVI (139 kN m kg^{-1}; n = 10) measurement (PD 5363/LA 870222 population mean 136 kN m kg^{-1}; n = 78). Indeed, the line with highest yarn tenacity (145 kN m kg^{-1}) was a member of the HVI fiber strength selected subpopulation, although this subpopulation did contain four lines with low yarn tenacity that would not have been identified on the basis of selection for fiber strength by stelometer measurement. Among all 78 lines in this population, the correlation between HVI fiber strength and yarn tenacity was 0.75, while the similar correlation with stelometer fiber strength was 0.71.

The correlated responses of fiber characteristics, such as fineness and short and immature fiber content, to selection for fiber strength by stelometer or HVI measurement, provides insight into breeding strategies that should result in fiber profiles that better meet the needs of yarn and textile manufacturers. Our data indicate that selection for fiber strength by HVI measurement can result in similar or slightly better overall fiber profiles than selection for fiber strength by stelometer measurement. Fiber property measurement by HVI instrument is cheaper (about half the cost of single-instrument testing), which would allow a breeder to roughly double the size of their selected populations. Because yield and fiber strength are generally negatively correlated (Culp, 1992), larger populations are an advantage to identify rare segregates with increased yield and fiber strength.

CONCLUSIONS

We found that selection for fiber strength by stelometer and HVI measurement resulted in similar strength gains, but that correlated responses of other properties that affect textile performance can differ. Selection for fiber strength by HVI measurement resulted in similar fiber profiles as that achieved by selection for fiber strength by stelometer measurement in one population. Superior fiber profiles, characterized by less short and immature fiber, were realized from selection for fiber strength by HVI measurement in a second population. The reduced cost of fiber property measurement by HVI instrument would allow evaluation of larger populations. Fiber properties measured by the AFIS (short fiber content, immature fiber content, and fineness) were found to be heritable and thus,

amenable to selection. A further challenge is to integrate a strategy for fiber improvement with one that allows for simultaneous yield gains.

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