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Breeding Methods for Improving Yield and Fiber Quality of Upland Cotton (*Gossypium hirsutum* L.)[1]

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ABSTRACT

In the introgression of *Gossypium arboreum* L. × *G. thurberi* Tod. fiber strength to medium staple Upland cotton (*G. hirsutum* L.), we have been most successful with the pedigree method of hybridization and selection. Hybridization is required for the recombination of genes for high lint yield and fiber strength or length, and selection is necessary to locate the desirable recombinants in segregating populations.

In 25 years of selection within breeding lines after the F_5 generation, only two highly desirable recombinants, Earlistaple-7 and Pee Dee 4381-54, have been found. Yield improvement in Earlistaple-7 is attributed to fusarium wilt resistance rather than to recombination of genes for lint yield and fiber quality. We cannot rule out the possibility of intercrossing or outcrossing in the isolated seed increase of Pee Dee 4381 from which Selection-54 was obtained.

Random intermating, backcrossing, and composite-crossing also were tried as methods to improve yield and fiber quality of Upland cotton. A valuable breeding line (Q) was developed by three cycles of backcrossing to three *G. hirsutum* parents (with selection only for high lint percentage) and a composite-cross of progenies from each of these backcross populations. No desirable recombinants were found with random intermating. Failure of this method was attributed to: 1) broad germplasm pools, 2) nonelimination of undesirable plants from the populations, and 3) study of small populations of 10,000 plants.

We believe that any breeding method that gives maximum combinations of genes for yield and fiber quality is desirable, and selection of promising recombinants in early generations is necessary to maintain populations of practical size.

Additional index words: Pedigree breeding, Backcrossing, Random intermating, Lint yield, Fiber strength, Fiber length.

SINCE 1950, dramatic changes have been made in harvesting and ginning Upland cotton (*Gossypium hirsutum* L.) and in the speed of processing fibers in the textile industry. These changes have demanded improved fiber quality, particularly increased fiber strength, in the general crop. Cotton production must be profitable for the grower and the fibers must be competitive for use by manufacturers. Cotton must also compete with synthetic fibers in the textile plants for ease and speed of processing and must meet the consumer demands for wearing comfort and durability.

Breeding high fiber strength cottons became a reality when Beasley (4) made the trispecies cross, *G. arboreum* L. × *G. thurberi* Tod. × *G. hirsutum* L. in 1938. He immediately backcrossed twice to the *G. hirsutum* parent, 'Coker 100.' Kerr (14) continued the introgression of *G. arboreum* × *G. thurberi* strength to Upland cotton with a modified backcrossing program. In 1943 and 1945, he backcrossed a BC_2F_3 selection of the trispecies hybrid to Cook 144-133 and a BC_2F_2 selection of this combination to 'Coker 100 WR.' We received pollen from the BC_4F_2 selection, TH 108 (growing at Raleigh, N. C.), in 1946 and seed of TH 108, TH 171, and other triple hybrid selections in 1947.

The cotton breeding program at the Pee Dee Experiment Station, Florence, S. C., was initiated in 1935 to 1) improve the yield and boll weevil (*Anthonomus grandis* Boheman) tolerance of Sea Island (*G. barbadense* L.), and 2) develop early-maturing, high-yielding, extra-long staple Upland cottons with Sea Island fiber properties. Thousands of crosses and selections were made each year and two extra-long staple cultivars, 'Sealand' and 'Earlistaple,' were developed. Sealand was selected from a 'Bleak Hall' (Sea Island type) × 'Coker Wilds' hybrid, which had been backcrossed four times (after selection) to the Coker Wilds parent (10). Earlistaple was selected from the cross of 'Tidewater Acala' × Coker Wilds (12). These cultivars were grown on less than 500 ha most years from 1947 through 1954 (9, 11); however, they proved to be excellent breeding stocks in the development of high fiber strength lines.

Because extra-long staple cottons could be produced more economically in other areas (6) and the demand had increased for improved fiber quality in the general cotton crop, previous breeding objectives were dropped and work was begun on the development of medium staple cottons with high fiber strength. When TH 108 and TH 171 were received in 1946 and 1947, they were crossed to the following *G. hirsutum* parents: 'Hopi-Acala,' Sealand, and Earlistaple (6). From these crosses four extra-long staple, high fiber strength lines, F = KPSE 330, J = KPE 363, A = KSE 313, and N = KPE 482, were selected. These lines were intercrossed and crossed to several commercial varieties from which three experimental lines, Pee Dee 0259 (1), Pee Dee 2165 (1), and Pee Dee 4381 (3), were developed. These lines produced lint yields that approached the yield of the commercial check variety 'Coker 201' with an increase in yarn strength of 10 to 20% when tested at Florence, S. C. (6).

The strong negative correlation between yield and quality (either fiber strength or length) was noted in early breeding studies. This could be attributed to either pleiotropy, linkage, or a combination of these factors. It is difficult to establish pleiotropic effects of genes or to measure extra energy required to produce stronger or longer fibers in a cotton boll; however, several investigators (15, 17) presented results implicating linkage as a contributing cause for the negative correlation between yield and fiber quality.

Recently Meredith and Bridge (15) questioned the commonly used pedigree system of hybridization and selection, which is used to breed quality cotton, and they suggested consideration of several alternative methods that might help to break linkages between

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lint yield and fiber strength and length. These methods were as follows: 1) random intermating as suggested by Hanson (8) and by Miller and Rawlings (17); 2) diallel selective matings as proposed by Jensen (13); 3) modified backcrossing; 4) bulk breeding followed by selection; and 5) the use of selection indices with the above methods.

The purposes of this paper are to show that 1) major improvement in lint yield and fiber quality of Upland cotton has been made by hybridizations and early generation selection under the pedigree system of breeding; 2) selection within established lines of the F_5 or more advanced generations has been ineffective in varietal improvement; and 3) some suggested breeding methods, such as backcrossing and random intermating, to improve lint yield and fiber quality were not superior to the pedigree system of hybridization and selection. We recognize that it is more difficult to present these breeders' findings in a long-term breeding project than to describe a limited, precisely designed experiment. Nevertheless, valuable lessons can be learned from our long experience with various breeding methods which are not available in precisely designed experiments.

MATERIALS AND METHODS

The pedigree breeding system of hybridization and selection has been used in the development of most Pee Dee lines and strains (6). Plant characteristics, such as bolls per plant, plant type, lint percentage, boll size, fiber properties, and yarn strength, were used as the basis for selecting or discarding F_2 and F_3 plants and F_4 progeny rows. In more advanced generations these characters as well as yield were measured in replicated performance trials.

Selection of superior plants in the F_6 or more advanced bulk generations has been the common practice in attempts to improve lint yield and fiber quality of outstanding lines developed in the Pee Dee breeding program. Depending on the availability within the planting, from 8 to 102 high-yielding plants were field selected from semi-isolated seed multiplication blocks (Table 1). Semi-isolation refers to a planting of closely related material in an isolated, 2.5-ha field. These plants were further selected on laboratory measures of lint percentage, boll size, seed index, fiber length, and fiber strength (6). Plants retained after evaluation in the selection process were screened in a similar manner in replicated progeny rows the following season. Superior rows were selected and tested for 2 or 3 years in replicated yield trials at Florence, S. C. The second cycle of selection was begun by selecting within strains or a bulk of strains evaluated in yield tests in the first selection cycle and repeating the process. Two cycles of selection in Earlistaple, Line F (KPSE 330), Pee Dee 2165, and Pee Dee 4381 were conducted from 1954 through 1971. The number of selections, progeny rows, and strains evaluated in tests for two cycles of selection are given in Table 1. Original selections of Earlistaple-7, Pee Dee 2165, and Pee Dee 4381 were included in appropriate yield trials.

Two additional breeding methods were used to develop high-quality breeding lines. The first was a modified backcrossing method and the second a random intermating method. In the modified backcrossing program (Fig. 1), original crosses were made between an experimental *G. barbadense* strain (V) with high lint percentage (developed by J. G. Jenkins) × 'Auburn 56' (G) and 'Coker 100 Wilt' (M). Hybrid V × G was backcrossed to G three times and hybrid V × M was crossed to Earlistaple (E) and backcrossed twice to E. Selection was conducted only for high lint percentage during the backcrossing cycles. The two backcrosses were united in a composite cross (CC) in 1961. Selections 510-1 in the CC_{F_1} and 503-1 in the CC_{F_2} were made primarily on boll prolificy. Two unusual plants with light-green plant color, compact plant type, and unusual prolificy of small bolls were found in the CC_{F_4}. These two plants became the progenitors of breeding lines Q_1 and Q_2.

In 1956 a random intermating germplasm pool was established by bulking equal amounts of hybrid seed from crosses

Table 1. Number of selections, progeny rows, and strains evaluated in 2 or 3 years of yield testing under two cycles of selection to improve yield and fiber properties of four Pee Dee breeding lines at Florence, S. C.

Lines	First selection cycle: Number field selections	Progeny rows selected	Strains yield tested	Second selection cycle: Strains bulked or selected	Progeny rows tested	Strains yield tested
F (KPSE 330)	48	13	5	4	102	0
Earlistaple	102	31	6	1	70	13
Pee Dee 2165	35	27	8	8	39	15
Pee Dee 4381	8	7	7	7	60	4

made in 1955 between outstanding extra-long staple lines developed in the Pee Dee program (6) and most of the commercial varieties recommended for the Southeast. Two areas of about 0.1 ha each were planted in hills 30 cm apart in rows 100 cm wide. Each hill was thinned to one plant. Plants in one area were used as female parents (without selection) for only one pollination each. Plants in the second area were used as pollen parents. One flower from each plant (male plants used equaled female plants for pollination) was chosen (without selection) the afternoon before anthesis and bulked for pollen source. Over 2,000 crosses were made each year. The hybrid seed from these random intermatings were used to make a new germplasm pool and the process repeated each year from 1956 through 1959.

One open-pollinated boll from each hybrid female plant was harvested each year. The seed were bulked at ginning and used to plant an F_2 population of at least 10,000 plants spaced 30 cm apart in rows 100 cm wide. F_2 selections entered the regular F_3 nursery the following season for additional testing of lint yield and fiber quality. In addition, one open-pollinated boll from each of approximately 1,000 F_2 plants was harvested at random. Seed from these bolls were bulked and used to plant an F_3 population of approximately 10,000 plants spaced 30 cm apart in rows 100 cm wide for selection.

A second germplasm pool, consisting of crosses between medium staple Pee Dee lines with strong fibers and commercial varieties recommended for the Southeast, was established in 1966. This material was handled in a manner similar to that described for the 1956 germplasm pool with random intermating of plants in 1966, 1967, and 1968.

RESULTS AND DISCUSSION

Culp and Harrell (6) recently reported 25 years of progress in increasing the yield of Upland cotton while retaining a portion of the *G. arboreum* × *G. thurberi* fiber strength of Beasley's trispecies hybrid (4). Some 12 lines developed under the Pee Dee pedigree system of hybridization and selection showed a "stairstep" increase of 45 to 55% in yield and a decrease of 30 to 40% (40 to 50 units) in yarn strength. The lint yield and yarn strength measurements (Fig. 2) on

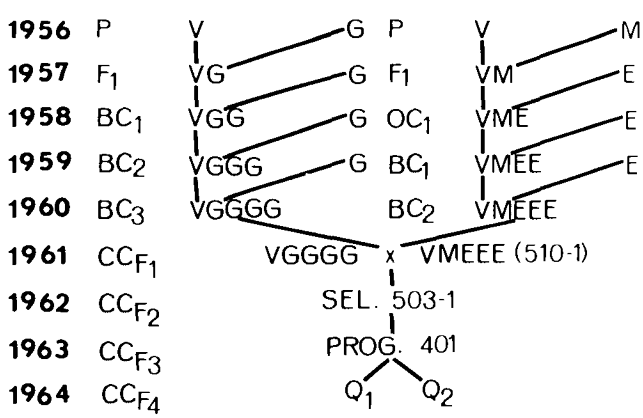

Fig. 1. Pedigree of the Q lines derived by backcrossing and composite crossing. E = Earlistaple, G = Auburn 56, M = Coker 100 Wilt, V = Experimental *G. barbadense* strain with high lint percentage (developed by J. G. Jenkins), P = parents, BC = backcross, OC = outcross, and CC = composite cross.

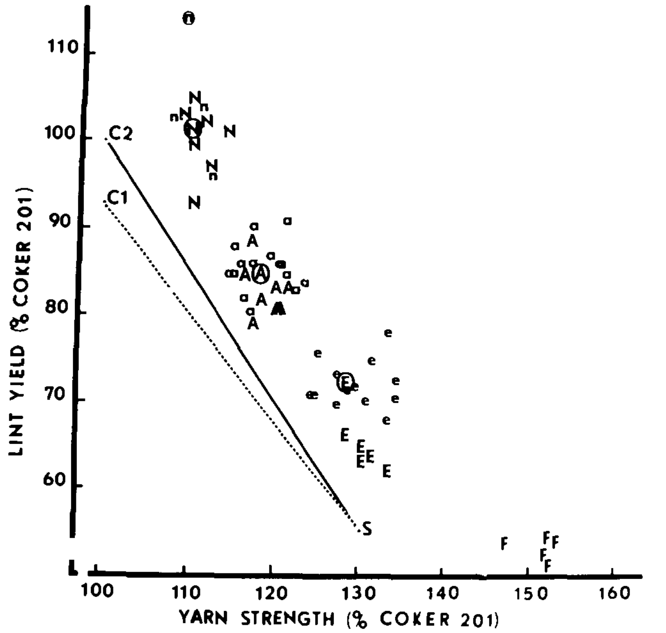

Fig. 2. Lint yield and yarn strength (expressed as a percentage of Coker 201) of strains from three Pee Dee lines in the first and second cycles of selection on the Pee Dee Experiment Station, Florence, S. C., from 1954 through 1971. F = line F (KPSE 330); E = first cycle selections of Earlistaple; (E) = Earlistaple-7; e = second cycle selections of Earlistaple-7; A and a = first and second cycles selections of Pee Dee 2165, respectively; (A) = original selection of Pee Dee 2165; N and n = first and second cycle selections of Pee Dee 4381, respectively; (N) = original selection of Pee Dee 4381; (n) = Pee Dee 4381-54; C1 = Coker 100 A; C2 = Coker 201; and S = Sealand 542.

the four families of lines in this study illustrate graphically our success in improving yield while sacrificing some fiber quality with the pedigree breeding method. Nevertheless, the most recently developed lines, when tested at Florence, S. C., approach the yields of Southeastern commercial varieties with a 10 to 20% increase in yarn strength.

After the new experimental lines were tested in the F_5 generation, an effort was made to improve them by selection within each line. This involved several lines most years from 1942, but yield and quality improvements were minimal in progeny rows or first cycle yield tests and the studies were discontinued. Two cycles of selection and testing were completed on lines F, Earlistaple, Pee Dee 2165, and Pee Dee 4381. Major improvements occurred with Earlistaple-7 and Pee Dee 4381-54 (Fig. 2), but no progress was measured for Pee Dee 2165 or line F. The increase in yield without a reduction in fiber quality of Earlistaple-7 is attributed to its resistance to *Fusarium oxysporum f. vasinfectum* rather than to a recombination of favorable genes for yield and fiber quality. Pee Dee 4381-54 may be the result of a recombination of genes for yield and quality obtained by selection; however, we cannot eliminate intercrossing and the possibility of outcrossing in the semi-isolated seed increase field. We are inclined to believe that either intercrossing of plants within the line or outcrossing between quality lines occurred because plant type of Pee Dee 4381-54 is different from that of the original Pee Dee 4381 line. Similar changes were observed in selections for higher yields and fiber quality in line F. Lint yields were slightly improved over those of the original selections, but yarn strength was reduced by approximately 30 units, which suggests outcrossing to low-quality cotton.

For the thousands of selections made to improve yield and at least retain fiber quality in numerous Pee Dee lines, two lines have shown major improvement that might be attributed to selection within lines. We agree with Feaster and Turcotte (7) in their work with 'Pima' cotton that greatest varietal improvement was realized from hybridization to produce recombinations and from selection to locate them in early segregating generations.

Feaster and Turcotte (7) suggested that crossing among varieties and strains followed by selection will probably be the most satisfactory breeding method for varietal improvement. This has been the most fruitful and widely used breeding method during the past 38 years at the Pee Dee Experiment Station (6). In a recent review Meredith and Bridge (15) suggested several alternative methods that might be helpful in overcoming the yield-quality barrier in cotton improvement. We agree with them that any breeding method that increases hybridizations and recombinations is desirable; however, the removal of undesirable plants or selection of the most desirable plants in early generations may be equally important in the varietal improvement process.

Our two attempts to produce desirable recombinants by random intermating were disappointing. Although approximately 10,000 segregates were studied each year in F_2 and F_3 populations, the frequency of high yielding plants with either long or strong fibers was low. None of the F_2 or F_3 selections (less than 50 per year) exhibited both high lint yield and fiber quality in advanced generations when compared with check varieties and experimental lines developed with the pedigree method. We might have been successful if we had used a narrow germplasm pool of highly selected parents and had selected desirable plants in much larger populations. This would make breeding by random intermating a questionable improvement over the pedigree system of hybridization and selection.

Feaster and Turcotte (7) and Culp and Harrell (5, 6) have presented evidence that lint yield and fiber strength and length are essentially fixed by selection in early generations following hybridization. Therefore, the value of bulk breeding or other methods devoid of early generation selection may be questionable. Recombination of genes should be at essentially the same rate whether a plant is selected and self-pollinated or left in a bulk where self-pollination generally occurs. Selecting desirable plants in early generations, particularly for fiber properties, is much more practical than to evaluate them in large populations of predominantly undesirable material. In the Pee Dee program 10,000 to 25,000 plants are evaluated in the F_2 and F_3 generations. Several hundred selections may be made, and we consider ourselves fortunate if one outstanding breeding line is developed in such a study. Without selection in the F_2 and F_3 generations, much larger populations would be required to find desirable recombinants.

Modified backcrossing has played a major role in the introgression of length and strength to Upland cotton. Several varieties and breeding lines, such as

Table 2. Lint yield, ginning and boll data, and fiber and yarn properties of Q lines with check varieties and experimental lines.

Entry	Lint yield	Lint	Boll size	Seed index	Span length 50%	Span length 2.5%	Micronaire	T_1	Yarn strength†
	kg/ha	%	g	g/100	inches	inches	units	gf/tex	units
Pee Dee 4381	1,501 a*	38.0 a	6.68 b	11.9 cd	0.56 b	1.15 b	4.02 a	19.29 c	138 b
Coker 201	1,457 ab	38.6 a	7.21 a	12.2 bc	0.55 ab	1.14 ab	4.53 cd	18.37 b	128 a
Pee Dee 2165	1,427 ab	39.8 a	7.20 a	14.0 a	0.58 b	1.22 c	4.66 d	22.35 e	154 c
Auburn 56	1,323 b	35.9 b	7.09 ab	12.7 b	0.52 a	1.10 a	4.36 bc	16.88 a	127 a
Q_1 (64-461)	1,105 c	38.4 a	6.30 c	11.0 e	0.56 b	1.17 b	4.21 ab	19.53 cd	137 b
Q_2 (64-467)	1,084 c	38.8 a	6.30 c	11.5 de	0.55 ab	1.15 b	4.17 ab	20.97 d	140 b

* Measurements followed by the same letters are not significantly different at the .05 level of probability. † Skein strength of 27 tex yarn.

Sealand (10), TH 149 (2), and lines F, J, A, and N (6), are the result of selective backcrossing. In 1952, when the decision was made to intercross quality lines in the Pee Dee program (6), backcrossing became less important because the frequency of desirable recombinants was much greater in the intercrossing program. This remained true until 1961 when it became necessary to outcross for desirable plant characteristics not found in Pee Dee lines. We used a modified backcrossing program similar to that proposed by Meredith and Bridge (15) to transfer high lint percentage of a *G. barbadense* line to *G. hirsutum*. Several backcrosses were undertaken, but only those with Auburn 56, Coker 100 Wilt, and Earlistaple proved to be useful (Fig. 1). We selected for only high lint percentage in the donor parent. After three cycles of backcrossing, no outstanding plant was found, but the decision to make a composite-cross of the two backcrosses was a wise one. Selection 510-1 in the CC_{F1} and selection 503-1 in the CC_{F2} produced an unusually large number of small bolls. Two distinct strains, designated as Q_1 and Q_2, were obtained in the CC_{F4} after three generations of selection.

Although the Q lines produced low lint yields and small bolls and seeds, these lines had a distinctive light-green color, high lint percentage, and excellent fiber properties (Table 2). Line Q_1 has proved valuable as a breeding line. It combines well with most varieties (16) and especially with some Pee Dee lines. In the cross between Q_1 and PD 3249 (Fig. 3), the F_1 was intermediate in quality but produced an increased lint yield of 36% over the highest yielding parent and 16% over the commercial check variety Coker 201 when tested at Florence, S. C. for 2 years.

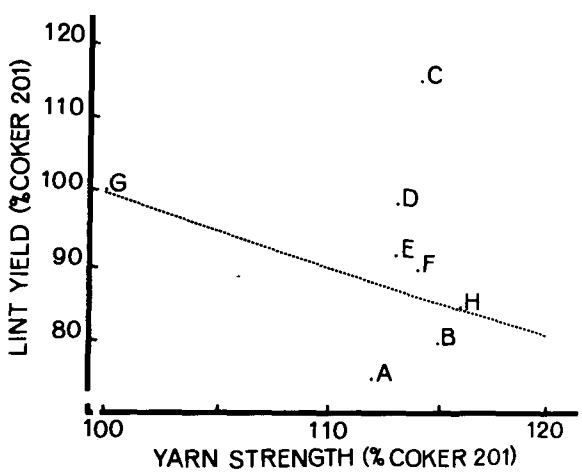

Fig. 3. Lint yield and yarn strength (expressed as a percentage of Coker 201) of parents, hybrid, and selections tested at Florence, S. C., in 1970 and 1971. A = Q_1; B = PD 3249; C = F_1 (Q_1 × PD 3249); D = PD 8529; E = PD 8515; F = PD 8540; G = Coker 201; and H = Pee Dee 2165.

Three selections of equal quality from this cross produced significantly higher yields than the two parents and approached the yield of Coker 201.

We have demonstrated success in overcoming the yield-quality barrier in cotton breeding with 1) the pedigree method of hybridization and selection and 2) modified selective backcrossing. No progress was made with random intermating; however, our germplasm pools were wide and populations of only 10,000 plants were studied. We strongly agree with other workers (5, 7, 15, 17) that any system that increases hybridizations that give recombinants is desirable but suggest careful choice of parents and early generation selection of desirable progenies. Anyone undertaking bulk breeding for several generations should be prepared to evaluate very large populations of segregating plants to recover desirable recombinants of yield and fiber strength or length.

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