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# Heterosis and Combining Ability in Top and Diallel Crosses Among Primitive, Foreign, and Cultivated American Upland Cottons[1]

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HETEROSIS for yield and certain other characters has been reported in all of the cultivated species of cotton *(Gossypium hirsutum, G. barbadense, G. herbaceum,* and *G. arboreum).* Loden and Richmond (12) in 1951 reviewed the literature pertaining to heterosis in cotton. A few of the more notable presentations on this specific subject since that time are those of Jones and Loden (10), Turner (19, 20), Christidis (2), Fryxell et al. (6), Barnes and Staten (1), and Stroman (18). These writers reported on a wide range of hybrids, both inter- and intraspecific, with varying degrees of expression of heterosis for yield and other agronomic characters. As a basis for measurement, they used the mid-parent, the better parent, or a commercial variety.

Cotton lacks many of the attributes which adapt certain other economic crops to hybrid-seed production. Cotton plants produce perfect flowers which require a tedious (though simple) operation to effect their emasculation. The pollen is relatively heavy and sticky, and the flowers must depend on insects for the crossing that takes place. Although cross-fertilization ranging from 1 to 80% has been reported in cotton, the predominant situation in commercial production is self-fertilization. Cotton plants produce relatively few seeds per inflorescence. Thus far these traits have contributed enormously to the problem of producing adequate amounts of hybrid cotton seed at a commercially feasible cost.

In the face of such seemingly insuperable obstacles, researchers during this century have been somewhat hesitant to enter the quest for hybrid cotton. Selection of suitable parents and studies of combining ability were not pursued with great enthusiasm as these were thought to be rather fruitless tasks. Lately, however, certain scientific advances have given cotton workers a measure of encouragement. A chemical compound, sodium 2, 3-dichloroisobutyrate (Rohm and Haas FW-450), showed promise as a male gametocide, or a "tool" for increasing the percentage of hybrid seed produced under otherwise natural conditions (3). While this possibility is being investigated (13), an increasing amount of time is being spent on the search for genetic-cytoplasmic male-sterility. Two genetic male-sterile genes have been found and designated $ms_1$ and $ms_2$; the former is a gene conditioning partial male sterility (11), the latter is a gene conferring complete male sterility (14). Although the desired interaction of these genes with a fertility-restoring cytoplasm has not been found, workers over the Cotton Belt are continuing to screen many stocks for the cytoplasmic-genetic type of male sterility. The bumble bee is the most efficient pollinator of cotton, but studies elsewhere (8) have shown that the use of supplemental colonies of honey bees in hybrid production fields to effect adequate cross-fertilization may be feasible. Green[3] suggested that seedling marker genes might be employed to aid in rouging non-hybrid cotton plants or in selecting the hybrid plants to leave for a stand.

These developments in methodology emphasize that if hybrid-cotton production is to be a reality in the foreseeable future similar advances must be made in combining ability and parent selection. An amiable controversy is now in progress among cotton geneticists and agronomists on the relative position research on hybrid cotton should occupy with respect to other breeding efforts. The status of hybrid cotton in the research programs of these workers now varies from a high-priority endeavor to a low-level methodological niche. The research reported here was conceived with the objective of adding to present information more evidence on the expression of heterosis and the measurement of combining ability for yield and other agronomic and fiber characters among relatively widely related Upland stocks of cotton, *G. hirsutum.*

## MATERIALS AND METHODS

Five parental stocks were selected to use in a combining study based on a diallel crossing system. These were MU8b, a Cambodia type selected by Hutchinson in Central India in 1935; Texas 468, a *punctatum* collected in Mexico by Richmond and Manning in 1946; CB3150, a Russian Upland obtained through H. D. Loden; Texas 63, a *latifolium* collected in Mexico by Richmond and Manning in 1946; and 2-8-7-6, the $F_4$ of a cross between DPL-14 and Texas 324, a *palmeri* collected in Mexico by Ware and Manning in 1948. These stocks will be referred to in this paper by code letter (A through E, respectively) while their $F_1$ hybrids will be designated by appropriate letter combinations. In the selection of these parents, the principal criteria which influenced the choices were the following precepts: *(1)* degree of hybrid

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[3] Green, J. M. Possibilities for use of seedling markers for increasing the stand of hybrid plants. Second Cotton Improvement Conference. Biloxi, Miss. 1950. (Mimeo.)

vigor is positively correlated with genetic divergence and *(2)* good combining ability is most often found between (or among) good parents. Of course, certain other factors such as the ability to flower under the summer growing conditions at College Station, Texas, and absence of any known genetic or cytological anomalies influenced the selection of stocks. The 10 possible crosses among the 5 parents and their 10 reciprocals were made in 1960. In addition, self-pollinated seeds were produced on each of the 5 parental stocks, making a total of 25 diallel progenies, and each parent was topcrossed to Stoneville 3202, a commercial variety.

The main phase of the experiment was conducted at the Agronomy Farm in 1961 employing the 25 diallel progenies, the 5 top-crosses, and 6 commercial checks—Acala 1517C ($Ch_1$), Acala 4-42 ($Ch_2$), Austin ($Ch_3$), Deltapine 15 ($Ch_4$), Empire WR ($Ch_5$), and Stoneville 3202 ($Ch_6$). Seeds were planted in 6-ounce paper cups in the greenhouse on April 4 and the resulting seedlings were transplanted to the field on April 21 in 30-foot by 40-inch rows with a plant spacing of 18 inches. During the growing season the plants received the insect-control treatment, supplemental irrigation, and other cultural treatments that were applied to the other stocks in the genetics and breeding nursery at the Agronomy Farm.

The statistical design was a 4-replicated 36-entry simple lattice. Because of the necessity of sacrificing a number of plants from each plot for determination of fruiting indices, each 3⅓- by 30-foot plot was divided into 2 equal parts, each containing 10 plants. This manipulation is not to be confused with a split-plot design, or analysis. The first 10 plants were used to measure or determine all characters other than the fruiting indices. Five of the second group of 10 plants (if that many thrifty plants were available) were randomly taken to furnish the fruiting data so as not to introduce border effects into the plots harvested for yield.

The following characters were measured:

*Seedling height* (mm.) at the age of 11 days—Four random plants in each plot were measured from the soil to the growing point.

*Days to anthesis of first flower*—Beginning with the date of planting in the greenhouse, days elapsing before anthesis of the first flower were determined for each plant.

*Plant height* (mm.)—During the peak of flowering each plant was measured from ground level to the base of the petiole of the oldest unexpanded leaf in the growing point. Only "normal" plants (those in which the main stem was still dominant) were measured.

*Fruiting efficiency*—The plots were inspected daily for boll maturation. When a freshly opened boll was found on a plant in the section of the plot set aside for the determination of fruiting indices, that plant was removed at ground level. All fruiting forms (including very young, obviously "set" bolls) were counted, removed from the plant, and weighed. The remaining aerial portions of the plant were then weighed. These data were used to calculate two indices:

a. *Relative fruitfulness,* the number of bolls per 100 grams (fresh weight) of aerial vegetative matter (4).
b. *Fruiting index,* the ratio of the fresh weight of fruiting parts to the fresh weight of vegetative parts (9).

*Earliness*—For this study, the measurement of earliness of maturity was the expression of lint cotton from the first 2 of 5 pickings as a percentage of the lint cotton from all 5 pickings. A stratified method of harvesting, following the method of Richmond and Radwan (15), was employed to detect the real differences in earliness.

*Total yield*—Pounds of lint per acre.

*Boll size*—Number of bolls per pound of seed cotton.

*Lint percent*—Ratio of lint cotton to seed cotton expressed as percentage.

*Seed index*—Weight (grams) of 100 seeds.

*Lint index*—Weight (grams) of lint per 100 seeds.

*Upper half mean*—(UHM) Upper half mean length of fibers longer than ¼ inch.

*$T_1$*—An index of fiber strength.

*$E_1$*—An index of fiber elongation.

*Micronaire*—An index of fiber fineness.

With the exception of the last four characters, lattice analyses were made on the sets of data for the characters listed above. Because of the necessity of reducing the quantity of fiber samples to a number that could be handled by the fiber laboratory, and at the same time provide samples from each of 4 pickings, corresponding plot samples from replications 1 and 2 and replications 3 and 4 were bulked. Therefore, it was necessary to analyze the data for upper half mean, $T_1$, $E_1$, and micronaire as a randomized block design with two replications. Duncan's multiple range test was used to determine the significance of heterotic effects, and also whether a given $F_1$ was significantly *greater* than the highest check variety or significantly *different* from its corresponding top cross $F_1$'s. (In this paper, a true heterotic effect is considered to be one in which the $F_1$ *significantly* exceeds the greater parent at the .05 level, for a particular character.) Among each set of means, each $F_1$ was first compared with the highest check for the character under test; and by the use of Duncan's test each was determined to be significantly different from, or the same as, the highest check. Each $F_1$ was then compared with each of its parents in order to detect valid cases of heterosis. Similarly, each $F_1$ was compared with each of its corresponding top crosses to determine differences.

In addition to the two-mean comparisons, comparisons among certain *groups* of means or between a group of means and a single mean were considered to be valuable. However, such group comparisons tested in the usual manner, though of practical value, are technically unsatisfactory in that no probability statements can be made regarding them. For this reason, Scheffé's multiple *F* test (16) was used for these group comparisons. Scheffé's test is the *F* counterpart of Tukey's test based on allowances; it makes possible a statement of probability when making such comparisons, or *contrasts* as he calls them. Of the "infinite" number of contrasts, the meaningful ones are those which compare the parents with the checks, the parents with the $F_1$'s, the $F_1$'s with the checks, each array (i.e., the "A" array refers to AB, AC, AD, AE, and their reciprocals) with the checks, each array with the highest check, and each array with its corresponding top cross, (i.e., the "A" array vs. SA).

Estimates of combining ability effects were made by Griffing's Method 1 Model 1 (7) on certain agronomic characters. This procedure is similar to that employed by Sprague and Tatum (17), who also used a diallel cross (modified) in their original work, except that parents and reciprocals are included and a reciprocal effect may be estimated. The method of employing parents and reciprocal crosses in the analysis was chosen on the recommendation of Griffing (7) who stated that if appreciable inbreeding occurs, the parents should be included in the analysis.

Sampling for determination of the fiber characters was done in a nested manner, and the appropriate analyses were made. Significant groupings of means were made by Duncan's test. Scheffé's test was not used on these data, nor were they subjected to a combining-ability analysis.

## RESULTS

### Heterosis

When the data were analyzed, entry mean squares for each of the characters were found to be highly significant. Although none of the $F_1$ hybrids yielded significantly more than the best yielding check, $F_1$'s significantly exceeded the highest check for two other characters. In seedling height CE was significantly taller than $Ch_1$, the tallest check. In earliness, both CB and EC were significantly earlier than $Ch_6$, the earliest check. The top cross, SC, was also significantly earlier than the check.

Two cases of heterosis (as herein defined) were noted in yield. EA significantly exceeded both $E^2$ and $A^2$; DC significantly exceeded both $D^2$ and $C^2$. Five cases of heterosis were found in the fiber character upper half mean (UHM). The $F_1$ hybrids DB, DC, CD, DA, and AD all exceeded their longer linted parent in UHM. The means of the yield and UHM data may be seen in Table 1, along with significance relationships based on Duncan's test. The data for the other characters, which showed no significant heterosis, are not presented here in tabular form.

Among the multiple contrasts made by Scheffé's test, significant contrasts were apparent only for yield, boll size, lint percent, and lint index. However, for the contrasts in each of these characters except yield the check(s) proved to be greater than the $F_1$'s. The contrast which compared the B array with the checks in yield was significant and showed that, on the average, the B array performed better than the average of the checks. The contrast which compared the B array with the *highest* check was not significant, indicating that the B array did not significantly exceed the highest ranking check.

None of the contrasts comparing the arrays with their corresponding top crosses were significant for any character, indicating that, for this experiment, the top cross involving a given parent was in fair agreement with the general combining ability of that parent. On the other hand, a great many $F_1$'s differed significantly from their corresponding top crosses; at least certain differences were apparent for each character. As was to be expected the top crosses were not reliable estimators of specific combining ability.

## Combining-Ability Analysis

The variance associated with general combining ability (GCA) was highly significant for every character except fruiting index, for which it was significant at the .05 level. Significant specific combining ability (SCA) variance for four characters was noted. Of these, seedling height, boll size, and seed index were significant at the .05 level. However, when SCA effects of the hybrids and selfed parents were calculated and tested for significance with the proper standard errors, no differences were noted. On the other hand, yield was highly significant. No significant reciprocal differences were noted for any character.

Table 2 lists the estimated general combining ability (GCA) effects for each character and their significance relationships. The GCA effects of the parents for days to flower do not show significant differences, even though the GCA variance was significant at the .01 level. This is attributed to the fact that E and C approached a significant difference.

The GCA effects for a particular character sum to zero and are estimates of the relative general combining ability of the parents for the character in question. A few of the pertinent differences might be pointed out. Parent B had the lowest combining ability for relative fruitfulness (number of bolls per 100 grams vegetative parts). It was significantly lower than E, C, and D. It was also significantly lower in combining ability for fruiting index than C and D. In GCA for yield, B was significantly greater than all other parents; E and A were significantly greater than D and C, although not significantly different from each other; and D and C were not significantly different. For boll size, B was greater than any other parent (magnitude of expression of boll size is inversely proportional to actual boll size), and D, C, and A were greater than E. B also rated highest for lint percent, seed index, and lint index. In earliness, C showed the best general combining ability.

The estimated specific combining ability effects for yield of each cross and self among the parents and the significance relationships are shown in Table 3. The standard

Table 1—Significance relationships among mean yields and upper half mean fiber lengths of the parents, hybrids, and commercial check varieties.

| Entry | Yield: Pounds per acre | Yield: Statistical significance* | Entry | Upper half mean: Inches | Upper half mean: Statistical significance* |
|---|---|---|---|---|---|
| SB | 1019 | a | $Ch_1$ | 1.15 | a |
| BA | 985 | ab | DB | 1.14 | a |
| DB | 981 | ab | EB | 1.11 | b |
| AB | 953 | abc | SB | 1.11 | b |
| EA | 938 | abcd | $B^2$ | 1.10 | bc |
| $Ch_2$ | 927 | abcde | BE | 1.10 | bc |
| BD | 924 | abcde | BD | 1.10 | bc |
| BE | 921 | abcde | $Ch_2$ | 1.09 | bcd |
| EB | 917 | abcde | BC | 1.08 | cde |
| $B^2$ | 914 | abcde | AB | 1.08 | cde |
| BC | 903 | abcdef | BA | 1.08 | cde |
| SE | 879 | bcdefg | CB | 1.08 | cde |
| CB | 855 | bcdefgh | ED | 1.08 | cde |
| SA | 850 | bcdefgh | $Ch_4$ | 1.07 | def |
| CE | 830 | cdefghi | AE | 1.07 | def |
| AE | 806 | defghij | $Ch_5$ | 1.07 | def |
| ED | 790 | efghijk | DC | 1.06 | efg |
| SC | 790 | efghijk | $Ch_3$ | 1.06 | efg |
| AD | 770 | fghijk | EA | 1.06 | efg |
| SD | 761 | ghijkl | EC | 1.06 | efg |
| $Ch_6$ | 758 | ghijkl | $E^2$ | 1.06 | efg |
| AC | 757 | ghijkl | CD | 1.06 | efg |
| DE | 747 | ghijkl | CE | 1.05 | fgh |
| DC | 741 | ghijkl | DE | 1.05 | fgh |
| $Ch_3$ | 725 | hijkl | DA | 1.05 | fgh |
| CA | 723 | hijkl | SD | 1.04 | ghi |
| $E^2$ | 722 | hijkl | SE | 1.03 | hij |
| $Ch_4$ | 714 | hijkl | AD | 1.03 | hij |
| DA | 695 | ijklm | SA | 1.03 | hij |
| EC | 678 | jklmn | SC | 1.02 | ijk |
| $A^2$ | 668 | klmn | AC | 1.01 | jk |
| $Ch_5$ | 667 | klmn | CA | 1.00 | kl |
| CD | 656 | klmn | $A^2$ | 1.00 | kl |
| $Ch_1$ | 624 | lmn | $D^2$ | 1.00 | kl |
| $D^2$ | 568 | mn | $Ch_6$ | 1.00 | kl |
| $C^2$ | 561 | n | $C^2$ | 0.98 | l |

* Measured by Duncan's test. Means belonging to the same subgroup (same letter) are not significantly different.

Table 3—Specific combining ability effects for yield of the 5 parents used in the diallel crossing scheme, calculated from $S_1$ progenies and $F_1$ hybrids.

| Combination $S_1$ or $F_1$ | SCA effect | Statistical significance* | Combination $S_1$ or $F_1$ | SCA effect | Statistical significance* |
|---|---|---|---|---|---|
| BD | 76.74 | a | AD | - 9.19 | bc |
| AE | 69.91 | ab | BE | - 19.92 | cd |
| AB | 49.24 | abc | CC | - 93.92 | de |
| CD | 28.88 | abc | EE | -101.62 | de |
| BC | 28.68 | abc | AA | -122.07 | e |
| DE | 27.41 | abc | DD | -123.82 | e |
| CE | 24.23 | abc | BB | -134.72 | e |
| AC | 12.13 | abc | | | |

* Using Duncan's multiple range test and the appropriate standard errors, the effects were tested for significance.

Table 2—General combining ability effects for 11 characters of the 5 parents used in the diallel crossing scheme, calculated from $S_1$ progenies and $F_1$ hybrids.

| Character | Parents: A | B | C | D | E | LSD* | Significance grouping† |
|---|---|---|---|---|---|---|---|
| Seedling height | -0.145 | -1.795 | 7.405 | -2.720 | -2.745 | 6.423 | C A B D E |
| Days to flower | 1.81 | 1.81 | -9.43 | -4.19 | 9.99 | 19.86 | E A B D C |
| Plant height | -6.940 | -2.765 | -27.815 | 10.560 | 26.960 | 39.84 | E D B A C |
| Relative fruitfulness | -235.62 | -1607.00 | 561.60 | 390.78 | 890.23 | 1505.58 | E C D A B |
| Fruiting index | -1198.75 | -1546.79 | 1564.65 | 1370.41 | -189.52 | 2131.37 | C D E B A |
| Total yield | -2.36 | 122.72 | -73.56 | -52.36 | 5.54 | 29.33 | B E A D C |
| Boll size | 1.90 | -9.37 | 0.85 | -0.05 | 6.67 | 3.96 | E A C D B |
| Lint percent | -6.34 | 17.71 | 8.93 | -29.31 | 9.01 | 9.65 | B E C A D |
| Seed index | -0.48 | 9.82 | -6.98 | 5.62 | -7.98 | 6.49 | B D A C E |
| Lint index | -19.85 | 109.63 | -17.22 | -48.15 | -24.42 | 46.24 | B C A E D |
| Earliness | -61.22 | -8.90 | 181.38 | -62.04 | -49.22 | 107.84 | C B E A D |

* The least significant difference is the product of the standard error of the difference between two means and the value at the .025 level.
† Effects belonging to the same subgroup (as indicated by underscoring) are not significantly different from one another.

error used in testing the significance of the difference between two effects depends on whether the effects are those of a self, an $F_1$ involving one of the same parents, and $F_1$ involving completely different parents, or various combinations of these three.

Inspection of the significance groupings reveals that the selfed parents were in a class by themselves, all low. Parent B, which had the highest GCA effect for yield, is well represented in the highest ranking group; only BE is absent.

## DISCUSSION

### Heterosis

A critical test of several agronomic and fiber characters for the expression of heterosis (significant superiority of the $F_1$ hybrid over the better performing parent that entered into the cross) was one of the main objectives of this experiment. Throughout the entire experiment, seven individual cases of heterosis were found. Five of these were in the fiber character, upper half mean. These $F_1$ hybrids exceeded their greater parent in UHM by 3 to 6%. Because of the stability of this character, these small differences proved to be statistically significant.

The remaining two cases of heterosis were found in the complex character yield. The $F_1$ hybrid of 2–8–7–6♀ × MU8b♂ (EA) yielded significantly more than 2–8–7–6 ($E^2$) and MU8b ($A^2$). Also, the $F_1$ hybrid of Texas 63♀ × CB 3150♂ (DC) yielded significantly more than Texas 63 ($D^2$) and CB 3150 ($C^2$). However, the reciprocals of these hybrids (AE and CD) did not show a significant heterotic effect, even though each outyielded its higher yielding parent by about 11%. Apparently the heterotic effect is real, since no reciprocal differences were noted in the combining ability analysis. Each of the cases of heterosis represented an increase of about 30% over the higher yielding parent. Thus, EA yielded 216 pounds per acre more than $E^2$, its better-yielding parent, while DC yielded 173 pounds per acre more than $D^2$, its better-yielding parent. This increase, however, was not sufficient to make the $F_1$'s significantly outyield the best open-pollinated commercial check variety; in the case of DC, the hybrid still yielded significantly *less* than the best yielding check.

In evaluating expressions of heterosis, cotton workers have used various methods or approaches. Some have used the mid-parent (mean of the two parents) as a base with which to compare the $F_1$ hybrid. Others have used the better of the two parents. Still others have compared the hybrids with one or more commercial varieties. Some have measured seed cotton yields and others lint yields. All of these methods are valid, and each is well suited to certain ends. It might be argued that in this experiment rather severe requirements for the determination of expressions of heterosis were laid down, and that the comparison of the $F_1$ hybrids with good-producing adapted commercial varieties enforced an even greater degree of stringency. The writers felt that the measurement of heterosis chosen, comparing the $F_1$ with its better parent, while somewhat arbitrary, represented a sound means of measurement. Furthermore, comparison of the $F_1$'s with open-pollinated commercial varieties was considered essential.

Practically all cotton workers agree that heterosis for yield (including several of its components) and perhaps certain other characters can be demonstrated in hybrids among certain stocks of *G. hirsutum*. But perhaps the more important considerations now, as far as commercial cotton production is concerned, are *(1)* the amount of heterosis (regardless of how measured) that can be obtained, and *(2)* the amount that must be obtained in order to make hybrid seed production economically feasible. Of course, higher yield is not the only possible goal of hybrid cotton. Cases where the $F_1$ hybrid retained the yield of the more productive parent while assuming some important attribute of the other parent, such as fiber quality, earliness, and stormproofness, might be useful. However, yield must remain the primary consideration in any effort to manipulate characters for $F_1$ hybrid usefulness. To the farmer, the first consideration, regarding what amount of heterosis can be obtained, must be expressed in relation to the best commercial varieties already available. This same line of thinking necessarily occupies commercial breeders and seedsmen, but for them the second consideration also is of major importance.

The writers, in designing this study, endeavored to control as many variables as possible in a way which would enhance the probability of the expression of heterosis. Productive parents were selected, as is confirmed by the yield values in Table 1. The yields of the parents of the hybrids, as well as those of the commercial checks, covered the array of mean yields; the best-yielding parent was in the same sub-group as the best-yielding check, while the lowest-yielding parent was in the same sub-group as the lowest-yielding check. The parents, of necessity, were day-neutral in photoperiodic response. But within the productive, day-neutral stocks in the extensive regional collection at College Station, the stocks chosen as parents in this experiment represented widely related types of *G. hirsutum*. Even so, genetic diversity apparently was not great enough to result in abnormal behavior of crosses or even unusual combining ability effects.

The analyses reported were conducted on a fixed model basis (5), and the conclusions must therefore apply to the population as constituted by the experimental material. While no "useful" heterosis (exceeding the best open-pollinated commercial variety) was found in the experiment reported, it cannot be inferred that heterosis may not be found in other hybrids, or in these same hybrids over a period of years, or at other locations. But, since everything possible was done to permit the expression of heterosis, and, as has been stated, the parents used were selected because they represented as wide a range of genetic variability as possible, and in so far as they represent the types within the species *G. hirsutum* from which commercially useful $F_1$ hybrids may be made, the results of this experiment are not encouraging.

*Source of yield heterosis*—Although none of the components of yield initially studied showed heterosis, an attempt was made to trace the heterosis observed to its contributing source. Using the data on yield and boll size the number of bolls per plant was calculated for all plots in the experiment. In this new set of data and analysis, one case of hybrid vigor was found: EA was significantly higher than $E^2$ and $A^2$ in number of bolls per plant. This case corresponded to the case in yield where EA was found to significantly exceed both $E^2$ and $A^2$. DC did not show significant heterosis in number of bolls per plant corresponding to its heterosis observed in yield; although it exceeded both parents, it did so significantly only for $C^2$.

Since number of bolls per plant apparently contributed to heterosis for yield, and since there was no apparent heterosis for fruiting efficiency (as measured by relative fruitfulness) the increased number of bolls must have been a function of increased plant size, not as measured by height, but by total weight of the aerial vegetative parts. This proved to be the case. Using the data gathered for purposes of determining the fruiting indices, the mean weights of the vegetative parts of plants in the various entries were determined. When the data were analyzed, again one case of heterosis was evident; EA significantly exceeded both parents, corresponding to the heterosis observed for EA in number of bolls and yield. Again, however, while DC exceeded both parents, the hybrid was significantly greater in weight of vegetative parts than its $C^2$ parent, but it was not significantly greater than its $D^2$ parent.

The findings just described seemed to establish the source of the heterosis expressed by EA, but DC was still in doubt. Turning to the data on boll size (which showed no significant heterosis), EA was intermediate in respect to its parents, while DC exceeded both parents, but significantly so only in the case of $D^2$. With these facts in mind, heterosis for yield in EA must have been due to an increased number of bolls per plant and, in turn, number of bolls per plant was due to an increased size of the plant in aerial vegetative mass. For DC, the relationships did not emerge as clearly; heterosis for yield here seemed to be due at least in part to the number of bolls, as conditioned by plant size, but boll size might also have been a contributing factor.

## Combining Ability

*General combining ability*—It seems appropriate to consider combining ability for the complex characters yield and earliness per se and also in the light of their associated characters. B was the highest-yielding parent and had the largest boll, the highest lint percent, and the highest seed index. B ranked high in GCA effect for each of these characters. In fruiting efficiency (both relative fruitfulness and fruiting index) B ranked lowest. Since B was highest in yield among the parents, it apparently compensated for low fruiting efficiency by its large bolls. Parent C, the earliest parental stock, had the highest GCA effect for earliness, which was significantly different from the effects of B, E, A, and D, while these four did not significantly differ from each other. Parent C required the fewest days to flower; it was highest among the parents for both relative fruitfulness and fruiting index, perhaps because of its short internodes and close-fruiting habit. It was the tallest of the parents while they were in the seedling stage, but shortest when they were mature.

*Specific combining ability*—Yield was the only character for which estimated SCA effects proved to differ significantly. As noted earlier, all the selfed parents were lower in SCA effects than the parents crossed with each other. The SCA effects of B with other parents were relatively good. Also, the two effects AE and CD were high when compared to other effects, and this was to be expected, since they estimated the SCA effects of the two hybrids which showed heterosis for yield.

*Top-crosses as combining-ability estimators*—A great deal has been said about the use of the top-cross method for early detection of good combiners. The results of this study, using only one relatively homozygous top-cross parent (Stoneville 3202), show that while general combining ability in cotton might be predicted fairly accurately by the method, specific combining potential cannot be so predicted.

## SUMMARY


The experiment reported included a diallel cross, top crosses to a commercial variety involving the diallel parental stocks, and commercial checks. Agronomic characters measured were seedling height, days to flower, plant height, fruiting efficiency, yield, boll size, lint percent, lint index, seed index, and earliness. Fiber characters measured were upper half mean, $T_1$, $E_1$, and micronaire.

Analyses of variance in conjunction with Duncan's test were used to determine cases of heterosis and to compare the $F_1$ hybrids with their corresponding top crosses and with the commercial checks.

Seven individual cases of heterosis were found. Five $F_1$ hybrids exceeded their better parent in upper half mean by 3 to 6%. Two $F_1$ hybrids exceeded their higher yielding parent by about 30%, but they did not exceed the highest yielding check.

Number of bolls per plant, as conditioned by aerial vegetative mass, and possibly boll size, apparently were the components of yield contributing to the cases of yield heterosis observed.

General and specific combining ability effects were estimated for certain of the characters studied. The use of top crosses to predict general combining ability might be of some value.


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