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Evaluation of Synthetic Varieties of Upland Cotton Developed Under Two Levels of Natural Outcrossing[1]

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ABSTRACT

For the development of synthetic varieties of cotton (*Gossypium hirsutum* L.), we chose four parental strains expected to exhibit high heterotic responses for yield. The synthetic varieties were developed over a three-year-period in an area of high natural crossing, and in an area of low natural crossing. In each area, combinations of self- and open-pollination were imposed to vary the level of heterozygosity in the resulting synthetic varieties.

The synthetic variety produced by open-pollination in the area of high natural crossing contained a calculated 42% heterozyosity, and it yielded equal to the bulk of F_1 hybrids among the parent strains. The synthetic variety produced by open-pollination in the area of low natural crossing contained a calculated 12% heterozygosity, and it exhibited no significant heterosis.

The largest expressions of heterosis were for yield and to a lesser extent for boll size. Heterotic performance was correlated with the calculated heterozygosity of the synthetic varieties. The performance of the remaining characters appeared to be controlled by additive gene action.

Additional index words: Heterosis, *Gossypium hirsutum* L.

THE existence of the phenomenon of heterosis in cotton is a well-established fact. Loden and Richmond (1951) pointed this out 18 years ago in a review of the research on heterosis in *Gossypium*. They also called attention to some of the difficulties to be encountered or anticipated in the commercial production of hybrid cotton planting seed, not the least of which was the lack of success in developing a practical cytoplasmic genetic male-sterile system. The substantial increases in crop production that have been realized in corn, sorghum, and several other commercial crops, through the use of F_1 and double-cross hybrids, is well recognized and appreciated. The inability to utilize heterosis in cotton in a similar manner continues to frustrate cotton breeders and geneticists. In spite of the difficulties encountered, the search for useful cotton materials and practical methods for hybrid cotton production continues. During the past two decades cotton workers have vigorously researched various aspects of the problem.

In recent years, published reports by Marani (1967 and 1968), Miller and Marani (1963), White and Kohel (1964), and White and Richmond (1963) have strengthened earlier evidence that yield of lint in cotton shows a greater heterotic response than the other agronomic characters measured. These investigations have shown that the predominant genetic variation associated with yield results from additive effects. Furthermore, the cotton plant is an indeterminant fruiting organism, and the longer the plant grows and the larger it becomes, the more fruiting positions it develops. Most of the cotton yield heterosis has been associated with increased plant size (Galal, Miller, and Lee, 1966; Marani, 1968; White and Kohel, 1964; and Young and Murray, 1966). Therefore, we are inclined to think that the yield effects observed in certain cotton hybrids may more properly be considered a manifestation of luxuriance rather than heterosis in its strictest sense.

Several genetic male sterile genotypes, ranging from partial to complete sterility, have been discovered (Allison and Fisher, 1964; Justus and Leinweber, 1960; Justus, Meyer, and Roux, 1963; Richmond and Kohel, 1961; and Weaver, 1968). In spite of extensive testing, none have interacted with "foreign" cytoplasms to produce a cytoplasmic genetic male-sterile system. Meyer (1969) has reviewed the various forms of male sterility in cotton, and their interactions with heritable and environmental factors.

Various systems have been proposed for the practical use of genetic male sterility (see the review by Duvick, 1966). Shortly before the discovery of cytoplasmic genetic male sterility in sorghum, Stephens (1937) proposed a method for using a genetic male-sterile for the production of F_1 hybrids. Wiebe (1960), working with barley, proposed the use of male-sterile genes linked to genes for DDT susceptibility and he suggested a breeding system based on this association. Though never published formally, several cotton workers have proposed growing genetic male-sterile plants under frost-free conditions in the tropics and producing hand- or control-pollinated F_1 hybrid seeds for a period of years under a system of periodic ratooning. Interesting though these systems may be, none have been put to practical use. Kohel and Richmond (1962) pointed out that even if a suitable cytoplasmic-genetic male-sterile system eventually is developed in cotton, serious seed production problems still must be solved, because seed production is severely reduced on male-sterile plants by limited pollen vectors. Since cotton pollen is so heavy that it is seldom, if ever, wind blown, cross-pollination under natural conditions is mainly effected by insect vectors. Honey-

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bees can be effective when employed in extremely large numbers (Grout, 1955), but the principal vectors are the wild or bumble bee, *Bombus* spp. (Thies, 1953). Thus, the practical limitations on producing F_1 hybrid cotton planting seed have outweighed the theoretical advantages.

Even in certain of the crop species in which planting seed is customarily produced by the F_1 hybrid or double-cross method, certain researchers [including Lonnquist (1949) who worked with corn] have suggested that the synthetic variety system of seed production might eventually prove to be most profitable. Basically, the synthetic variety system involves: *(1)* massing several tested strains; *(2)* allowing these strains and their progenies to intercross naturally for a number of years; and *(3)* using this intercross population as a source of planting seed.

Until a practical method for producing F_1 hybrids in commercial quantity is developed, we believe the synthetic variety system offers an opportunity to take advantage of heterosis in breeding to increase cotton yields. Duncan, Pate, and Porter (1962) and Duncan, Pate, and Turner (1963) evaluated synthetic varieties composed of related varieties and attributed significant increases in yield to increased heterozygosity.

This paper describes an experiment designed to test the effects of heterosis in synthetic varieties developed under regimes of high and low natural crossing. The original population was composed of parental strains of diverse origins, pairs of which were known to exhibit heterosis when crossed. The parental strains employed were chosen to give maximum yield heterosis in their F_1 progenies. Whether or not naturally occurring outcrossing would suffice to influence the performance of a synthetic variety was an important consideration. The parents differed in fiber properties; this was not necessarily desirable from a practical point of view, but it provided a means of evaluating the consequences of differing fiber types in the selection of parents.

MATERIALS AND METHODS

The experiment called for parental material that had been developed under, and which had proved adaptable to, widely different geographical and ecological conditions. We set out to obtain two parental strains from the eastern and two from the southwestern parts of the cotton belt. J. B. Pate and E. N. Duncan (personal communication) recommended 'Acala 5675' and 'Empire 9' as two eastern strains that had demonstrated favorable heterotic yield responses. 'DM62' and 'MW147' were recommended by G. A. Niles as two Texas station strains that had performed exceptionally well in hybrid combination. The performance of hybrids between the eastern strains and those from this station was not known, but the presumed genetic divergence was expected to enhance heterotic yield responses. The parental strains were maintained by self-pollination, and they were considered homozygous.

In 1962, equal numbers of seeds from each strain were bulked for field planting. We were interested in a comparison of the performance of synthetic varieties produced under conditions of high and low natural outcrossing. Half of the mechanical mixture of seeds was planted in an area of high natural outcrossing (Texas A&M Upland Farm) and the other half in an area of low natural outcrossing (Texas A&M Brazos Valley Farm). These areas represent different agricultural areas, although they are only 8 miles apart. The Upland Farm is undesirable for cotton production, and it is characterized by small cultivated plots and extensive areas of uncultivated land that supports large populations of wild bees, the predominant natural pollen vectors for cotton. Plant growth at the Upland Farm, in response to the soil type, results in relatively small plants and a short growing season.

The Brazos Valley Farm is located in a river flood plain with a deep, fertile, alluvial soil. The agriculture is intensive row crops typical of a good cotton producing area, and the cultural practices, including frequent plowing and extensive use of insecticides, limit the population of pollen vectors.

At each location, the original planting consisted of 20 rows (1 m $\times$ 10 m) and, in each subsequent planting, each pollination treatment was maintained at this size. The seeds were drill-planted and thinned to a stand of 20 to 30 plants per row.

A few flowers on each plant at each location were self-pollinated and the remaining flowers were allowed to open-pollinate (see Fig. 1 for a diagram of the pollination system). In the first year, self- and open-pollinated seeds were harvested on an individual plant basis. Seeds for the next year's planting were obtained by bulking seeds from only those plants that had both self- and open-pollinated bolls. This restriction was imposed to prevent selection pressures that would cause a divergence of self-and open-pollinated populations. Seeds were obtained from approximately 300 plants in each treatment. Ten self-pollinated seeds from each plant were bulked for one planting, and 10 open-pollinated seeds from each plant were bulked for another planting. This experimental planting procedure was repeated for 3 years at each location. Each year the planting doubled in size from the previous year.

Complete isolation from other cotton plants was not possible. At the Upland Farm, where outcrossing was the greatest, the material was planted adjacent to non-flowering (photoperiodic) cottons or genetic lines that could be detected and eliminated in outcross progeny. In the low-outcrossing area, the plots were located at the outside edge of the field to provide minimum contact with other cottons. This had the effect of providing close contact with available pollen vectors, thus increasing the outcrossing. Green and Jones (1953) have shown that outcrossing between cottons decreases rapidly as the distance increases. Crossing between adjacent rows was 19.5%, and outcrossing decreased to 6% at a distance of 5 m.

Each year, at both locations, 10 plants homozygous for the recessive glandless seed character were grown to provide a measure of natural outcrossing, following the method suggested by Cross and Richmond (1959). Glandless plants were transplanted into the plots and placed to provide minimum contact with each other through pollen vectors.

Ali and Hadley (1955) presented the formula $H = 2pqa(1\text{-}r^n)(1\text{-}r)^{-1} + hr^n$ for the prediction of the percent heterozygosity in a population with a given amount of outcrossing, where:

H = percent heterozygosity,
h = proportion of heterozygosity in the initial population,
p and q = gene frequencies,
r = ½ of the self-fertilization proportion,
a = proportion of outcrossing, and
n = number of generations.

This formula was followed in the calculation of the percentage of heterozygosity in the various populations in this study. We made the simplifying assumptions that there were only two alleles per locus and gene frequency was one-half. The ex-

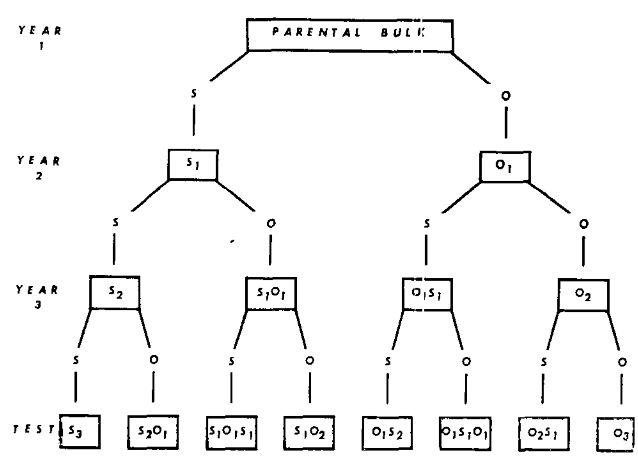

Fig. 1. Pollinations system followed in both the high and low outcrossing areas to develop the synthetic variety test material (S = self pollination, O = open pollination).

pected percent of heterozygosity at different levels of outcrossing is shown in Fig. 2. The largest increases were predicted after three generations of outcrossing, and the percent heterozygosity was near the theoretical limit. Based on these theoretical expectations, the developmental phase of the experiment was continued for three years.

The material produced during the developmental phase of the experiment was evaluated in a five-replicate-test grown on the Brazos Valley Farm in 1965. Each entry was planted in a 1-m by 10-m plot. Included in the test were the four parental strains; a bulk of equal numbers of seeds from each of the parental strains (F_0MIX); a bulk of equal number of seeds from each of the six possible F_1's among the four parental strains produced by hand-cross pollinations (F_1MIX); and eight pollination treatments from each of the two locations (see Fig 1). This provided a total of 22 entries. Examples of the designation or identification of the pollination treatments follow: LS_3 designates seeds from plants grown in the low-outcrossing area that had been self-pollinated for three generations; HO_2S_1 designates seeds from plants grown in the high-outcrossing area that had been open-pollinated generations one and two and self-pollinated the third generation; etc.

The following characters were measured: *(1) Yield*—in kilograms of lint per plot; *(2) Boll size*—expressed as grams of seed cotton (seeds plus lint per boll); *(3) Earliness*—expressed as the percentage of the total seed cotton harvested in the first of two pickings; *(4) Lint index*—grams of lint per 100 seeds; *(5) Seed index*—gram weight of 100 seeds; *(6) 2.5% span length*—one of two common measures of fiber length; *(7) 50% span length*—the other common measure of fiber length; *(8) T_1*—strength of cotton fibers in grams of force measured with 3.2-mm gage; *(9) E_1*— percent elongation of the cotton fiber bundle before breaking; and *(10) Micronaire*—measurement of fiber thickness.

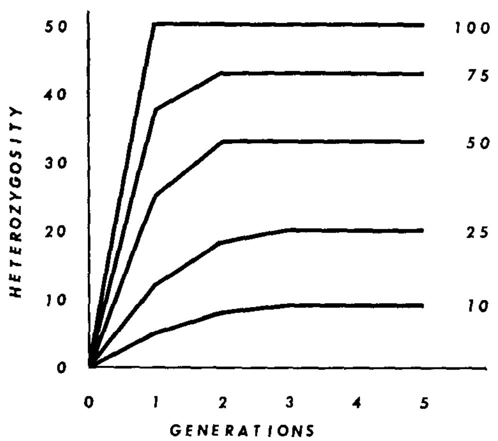

Fig. 2. Percent heterozygosity expected in each generation with each of five levels of outcrossing (%).

Significant differences among the entries for each character were determined by the analysis of variance, and a series of nonorthoganal contrasts were designed to contrast the results of the different pollination treatments. The contrasts are described as follows: *(1)* F_1 MIX vs. F_0 MIX, and *(2)* F_1 MIX vs. $\overline{F}_0$ were planned to determine whether or not there were heterotic effects displayed in the F_1 hybrids. *(3)* HS_3 vs. HO_3, and *(4)* LS_3 vs. LO_3 were made to determine whether or not the levels of outcrossing were high enough to detect heterotic effects. Outcrossing would not change the mean values unless there were heterotic or selection effects. The procedures used in this experiment held selection to a minimum. The level of outcrossing was not expected to be great enough in the low natural crossing area to cause differential heterotic response. But we expected to encounter some differences in the high natural crossing area. *(5)* HS_3 vs. F_1 MIX, and *(6)* HO_3 vs. F_1 MIX were expected to determine the level of heterotic response as it was affected by the level of natural outcrossing. *(7)* HS_3 vs. F_0 MIX, *(8)* HS_3 vs. $\overline{F}_0$, and *(9)* F_0 MIX vs. $\overline{F}_0$ were designed to determine whether or not the mixed planting performed differently than the average of the parental strains. *(10)* HS_3 vs. LS_3 was designed to determine the effects of producing seeds at different locations.

RESULTS

Seven of the 10 characters analyzed by the analysis of variance differed significantly among entries. The significantly different characters were: yield, boll size, elongation (E_1), micronaire, earliness, 2.5% span length, and fiber strength (T_1). Mean entry values for each of these seven characters, and results of the multiple range tests of significance, are presented in Table 1. In addition to the 22 entry means, the arithmetic average of the four parents is shown.

Results of the contrasts, outlined in the *Materials and Methods* section, are presented in Table 2 for the seven significant characters. Significant heterotic effects were displayed for yield, boll size, and perhaps fiber length as measured by contrasts 1 and 2. Contrasts 3 and 4 indicated that the significant heterotic effects were expressed only in the area of high natural crossing. Yield was the character for which the heterotic effects were most fully realized in the high outcross population (HO_3), as measured by contrasts 5 and 6. Comparison of the heterogenous parental plant populations (HS_3 and F_0 MIX) with the average of the parental strains ($\overline{F}_0$), contrasts 7, 8, and 9, suggested that the mixed populations differed for some of the fiber properties from the average of the parental strains. There were some differences in micronaire,

Table 1. Means and calculated percent heterozygosity of the entries.

Entry	Percent heterozygosity	Yield*	Boll size	E_1	MIC	Earliness	2.5% SL	T_1
A 5675	.000	3.93 de	5.21 f	6.85 cde	4.13 c	41.8 bc	1.11 cd	22.61 b
DM 62	.000	4.57 bcde	5.92 e	7.84 b	5.37 a	59.9 a	1.01 a	16.03 g
Emp 9	.000	5.09 bc	6.70 abcd	5.92 g	3.77 d	48.2 abc	1.17 a	23.07 a
MW 147	.000	3.25 e	6.98 ab	9.05 a	4.10 c	10.5 d	1.13 bc	17.37 g
F_0 MIX	.000	4.28 cde	6.27 cde	6.91 cde	4.27 bc	40.4 c	1.14 abc	20.22 cdef
LS_3	.000	4.62 bcde	5.95 e	6.57 def	4.56 b	54.7 ab	1.09 d	19.42 ef
HS_3	.000	4.56 bcde	6.28 cde	6.49 efg	4.09 c	44.4 bc	1.15 ab	21.22 bc
$LS_1O_1S_1$	.023	4.80 bcd	6.19 cde	7.04 cde	4.45 bc	60.4 a	1.11 cd	19.54 def
LO_1S_2	.031	4.49 cde	6.17 cde	6.16 fg	4.41 bc	48.0 abc	1.13 bc	20.98 cde
LO_2S_1	.051	5.13 bc	6.62 bcd	6.51 efg	4.57 b	49.9 abc	1.11 cd	19.34 ef
LS_2O_1	.078	4.36 cde	6.14 de	6.75 cdef	4.31 bc	53.6 abc	1.12 bcd	20.15 cdef
HO_1S_2	.079	4.41 cde	6.42 bede	6.45 efg	4.30 bc	53.3 abc	1.13 bc	21.10 cd
LS_1O_2	.097	4.22 cde	6.02 e	7.00 cde	4.55 b	56.0 ab	1.09 d	19.23 f
$LO_1S_1O_1$	.104	4.58 bcde	6.45 bcde	6.63 cdef	4.45 bc	54.8 ab	1.11 cd	19.53 def
LO_3	.121	4.32 cde	6.30 cde	6.94 cde	4.45 bc	51.3 abc	1.11 cd	19.35 ef
$HS_1O_1S_1$	.167	4.40 cde	6.45 bcde	8.78 cdef	4.30 bc	46.8 abc	1.12 bed	20.85 cdef
HO_2S_1	.193	4.54 bcde	6.63 bed	6.77 cdef	4.29 bc	53.0 abc	1.12 bcd	20.34 cdef
HS_2O_1	.362	5.07 bc	6.62 bcd	7.23 c	4.41 be	49.7 abc	1.11 cd	19.95 cdef
$HO_1S_1O_1$	.384	5.05 bc	6.74 abc	6.90 cde	4.30 bc	54.0 abc	1.14 abc	20.47 cdef
HS_1O_2	.408	4.99 bc	6.48 bcde	6.89 cde	4.36 bc	50.5 abc	1.14 abc	20.50 cdef
HO_3	.416	5.46 ab	6.64 abcd	7.22 cd	4.31 bc	55.3 ab	1.13 bc	20.35 cdef
F_1 MIX	.667	5.96 a	7.18 a	6.96 cde	4.39 bc	46.8 abc	1.13 bc	19.53 def
$\overline{F}_0$	.000	4.21	6.20	7.42	4.34	40.1	1.10	19.77

* Means followed by the same letter within each column do not differ (P> 0.05, Duncan's multiple range test).

Table 2. Mean squares of contrast for characters found significant by the analysis of variance.

Contrast	Yield	Boll size	E_1	Mic	Earliness	2.5% SL	T_1
1. F_1 MIX · F_0 MIX	345,588**	2.043**	.006	.035	101	.0004	1.19
2. F_1 MIX · $\bar{F}_0$	702,430**	38.025**	.980*	.011	208	.0040*	0.26
3. $HS_3 \cdot HO_3$	97,417*	.324	1.320**	.119	297	.0005	1.87
4. $LS_3 \cdot LO_3$	11,156	.310	.338	.029	28	.0005	0.01
5. $HS_3 \cdot F_1$ MIX	239,012**	2.010**	.530	.225	14	.0006	7.09*
6. $HO_3 \cdot F_1$ MIX	31,248	.718*	.177	.017	182	.0000	1.67
7. $HS_3 \cdot F_0$ MIX	9,797	.000	.428	.083	40	.0000	2.47
8. $HS_3 \cdot \bar{F}_0$	28,010	.250	3.970**	.300*	86	.0095**	9.86**
9. F_0 MIX · $\bar{F}_0$	996	.202	1.198*	.023	0	.0079**	0.97
10. $HS_3 \cdot LS_3$	490	.269	.015	.548**	264	.0073**	8.05*

*, ** Mean squares significantly large at the .05 and .01 levels, respectively.

2.5% span length, and T_1 between locations (contrast 10), and this may have represented some differential selection between locations.

The amount of natural outcrossing was estimated from the 10 glandless plants grown at each location each year, and these values are shown in Table 3. The values are higher than those probably realized in the experimental material. The glandless plants flowered later than the experimental material, and outcrossing increased at the end of the season when the total number of flowers available for the insect vectors decreased. The percent outcrossing observed each year was used in the formula of Ali and Hadley to calculate the percent heterozygosity expected in the entries tested. These values are presented in Table 3. The correlation between the mean performance of the 16 pollination treatments and their calculated percent heterozygosity was computed for yield, boll size, and elongation. The correlations were .65, .70, and .65 for yield, boll size, and elongation, respectively, and they were all significant. These results indicate that significant changes in performance were associated with changes in heterozygosity.

The percentage increases in performance over the parental bulk (F_0 MIX) of the F_1 hybrid bulk (F_1 MIX), the high open pollination treatment (HO_3), and the low open pollination treatment (LO_3) are presented in Table 4. Yield showed the highest increases of the F_1 MIX and HO_3 over the F_0 MIX. It was noteworthy that with a calculated 42 percent heterozygosity the HO_3 treatment yielded exceptionally well, whereas, with 12 percent heterozygosity the LO_3 treatment performed about equal to the F_0 MIX. Although earliness showed some large differences on a percentage basis, it was variable; and these differences were not significant. Inspection of the means indicated some selection against the late maturing types.

DISCUSSION AND CONCLUSIONS

This study was designed with material expected to exhibit heterotic responses for yield to enable us to determine whether or not natural outcrossing was adequate to produce measurable heterosis, and we found that it was. This material was evaluated in only one year. Undoubtedly, the level of heterotic performance will vary with locations and environments, but we were concerned with determining what proportion of the heterotic response could be recovered by the use of a synthetic variety. Whether or not there is sufficient heterotic response among the best available varieties to be of practical significance remains to be answered.

Table 3. Observed percentages of natural outcrossing.

Year	Brazos Valley Farm	Upland Farm
1962	25	63
1963	9	67
1964	16	72

Table 4. Relative performances of F_1 MIX, HO_3, and LO_3 to F_0 MIX.

Character	F_1 MIX:F_0 MIX	HO_3:F_0MIX	LO_3:F_0 MIX
Yield	1.39	1.28	1.01
Boll size	1.14	1.06	1.00
E_1	1.01	1.04	1.00
Mic	1.03	1.01	1.04
Earliness	1.16	1.37	1.27
2.5% SL	.99	.99	.97
T_1	.96	1.01	.96

The results bring out some points related to the development of a synthetic variety. The amount of outcrossing encountered in this experiment produced significant heterotic expressions for yield, and it approached the level of the F_1 hybrid. However, growing a heterogeneous seed bulk for several years, without the controls used in this experiment, exposes the material to random selection pressures. The breeder may also exert selection pressure on the population to maintain and direct it toward a desired objective. Most of the characters of concern to the breeder behave in an additive manner, and they can be regulated by the choice of parents and by selection pressure.

Fiber properties of varieties are also an important consideration in cotton breeding. The genetic control of the fiber properties is predominantly additive (Lee, Miller, and Rawlings, 1967; Marani, 1968; and Verhalen and Murray, 1967). The result of bulking fibers from differing parental types is additive (Niles, unpublished), but fibers from heterogeneous populations may have some compensating effects for poor fiber qualities (Richmond and Lewis, 1951; and the present study). It is feasible to utilize a strain, in a synthetic variety, which is deficient in some fiber property, yet which contributes exceptionally well to the overall performance of the variety.

In this experiment, we took an equal sample of seed from each plant for the succeeding generation to maintain the population structure. This situation would not exist in practice. In practice, the populations grown to develop a synthetic variety would be harvested by bulking all the seeds from all the plants, and this would have two important consequences, one beneficial and the other detrimental. If heterosis is present in the population, the hybrids would produce more seeds, and a greater proportion of the next generation would be heterozygous than predictable on the basis of observed outcrossing. The result should favorably effect the yield of the synthetic variety. The second consequence is that selection pressures could change the gene frequencies. Whether or not this would be favorable could not be judged beforehand. Final results would depend on the selection of the parents, and on the environmental conditions under which the material was grown. However, the plant breeder could impose selection pressures of his own design. The amount of natural outcrossing encountered in the breeding and development of a synthetic variety must be recognized as a significant contributing variable. If outcrossing depended on the selection of areas of high natural crossing, the available acreage would be limiting for synthetic variety production

(Kohel & Richmond, 1962). Such areas of high natural crossing also represent environments different from those of commercial production.

There is at present no available means of producing F_1 hybrids of cotton on a large scale. Since heterosis has been demonstrated to be of practical significance in cotton under certain conditions, the use of a synthetic variety offers a practical means by which a large portion of this can be utilized. Selection of parents for inclusion in the synthetic varieties would require a change in cotton breeding methods and increase the cost of planting seed production. The restriction of limited acreages suitable for synthetic variety production, and the added costs, would prevent widespread use of such a procedure and limit it to specific areas or types of production.

LITERATURE CITED

Ali, Mahbub and Henry H. Hadley. 1955. Theoretical proportion of heterozygosity in populations with various proportions of self- and cross-pollination. Agron. J. 47:589-590.

Allison, D. C. and W. D. Fisher. 1964. A dominant gene for male-sterility in Upland cotton. Crop Sci. 4:548-549.

Cross, J. E. and T. R. Richmond. 1959. The use of glandless seed to determine the amount of natural crossing in *Gossypium hirsutum*. Agron. J. 51:511-512.

Duncan, E. N., J. B. Pate, and D. D. Porter. 1962. The performance of synthetic varieties of cotton. Crop Sci. 2:43-46.

Duncan, E. N., J. B. Pate, and J. H. Turner. 1963. Performance of AHA derived synthetic varieties of cotton. Crop Sci. 3:233-234.

Duvick, D. N. 1966. Influence of morphology and sterility on breeding methodology. pp. 85-138. *In.* K. J. Frey [ed.] Plant Breeding. University Press, Ames, Iowa.

Galal, Hassan El-Sayed, P. A. Miller, and J. A. Lee. 1966. Heterosis in relation to development in Upland cotton, *Gossypium hirsutum* L. Crop Sci. 6:555-559.

Green, J. M. and M. D. Jones. 1953. Isolation of cotton for seed increase. Agron. J. 45:366-368.

Grout, R. A. 1955. Honey bees make hybrid cotton possible. Am. Bee J. 95:10-11.

Justus, N. and C. L. Leinweber. 1960. A heritable partially male-sterile character in cotton. J. Hered. 51:191-192.

Justus, N., James R. Meyer, and Jean B. Roux. 1963. A partially male-sterile character in Upland cotton. Crop Sci. 3:428-429.

Kohel, R. J. and T. R. Richmond. 1962. An evaluation of seed-yield potential of completely male-sterile cotton in areas of high and low natural cross-pollination. Agron. J. 54:525-528.

Lee, Joshua A., P. A. Miller, and J. O. Rawlings. 1967. Interaction of combining ability effects with environments in diallel crosses of Upland cotton (*Gossypium hirsutum* L.). Crop Sci. 7:477-481.

Loden, H. D. and T. R. Richmond. 1951. Hybrid vigor in cotton—cytogenetic aspects and practical applications. Eco. Bot. 5:387-408.

Lonnquist, John H. 1949. The development and performance of synthetic varieties of corn. Agron. J. 41:153-156.

Marani, A. 1967. Heterosis and combining ability in intraspecific and interspecific crosses of cotton. Crop Sci. 7:519-522.

Marani, A. 1968. Inheritance of lint quality characteristics in intraspecific crosses among varieties of *Gossypium hirsutum* L. and *G. barbadense* L. Crop Sci. 8:36-38.

Marani, A. 1968. Heterosis and F_2 performance in intraspecific crosses among varieties of *Gossypium hirsutum* L. and *G. barbadense* L. Crop Sci. 8:111-113.

Meyer, Vesta G. 1969. Some effects of genes, cytoplasm, and environment on male sterility of cotton (Gossypium). Crop Sci. 9:237-242.

Miller, P. A. and A. Marani. 1963. Heterosis and combining ability in diallel crosses of Upland cotton. Crop Sci. 3:441-444.

Richmond, T. R. and C. F. Lewis. 1951. Evaluation of varietal mixtures of cotton. Agron. J. 43:66-70.

Richmond, T. R. and R. J. Kohel. 1961. Analysis of a completely male-sterile character in American Upland cotton. Crop Sci. 1:397-401.

Stephens, J. C. 1937. Male sterility in sorghum: its possible utilization in production of hybrid seed. J. Amer. Soc. Agron. 29:690-696.

Thies. S. A. 1953. Agents concerned with natural crossing of cotton in Oklahoma. Agron. J. 45:481-484.

Verhalen, L. M. and J. C. Murray. 1967. A diallel analysis of several fiber property traits in Upland cotton (*Gossypium hirsutum* L). Crop Sci. 7:501-505.

Weaver, J. B., Jr. 1968. Analysis of a genetic double recessive completely male-sterile cotton. Crop Sci. 8:597-600.

White, T. G. and R. J. Kohel. 1964. A diallel analysis of agronomic characters in selected lines of cotton, *Gossypium hirsutum* L. Crop Sci. 4:254-257.

White, T. G. and T. R. Richmond. 1963. Heterosis and combining ability in top and diallel crosses among primitive, foreign, and cultivated American Upland cottons. Crop Sci. 3:58-63.

Wiebe, G. A. 1960. A proposal for hybrid barley. Agron. J. 52:181-182.

Young, E. F., Jr. and Jay C. Murray. 1966. Heterosis and inbreeding depression in diploid and tetraploid cottons. Crop Sci. 6:436-438.