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CONTEMPORARY ISSUES

Attributes of Public and Private Cotton Breeding Programs

Daryl T. Bowman*

INTERPRETIVE SUMMARY

Cotton breeding in the USA began in the 1800s with individual farmers selecting outstanding plants in the field, then controlling pollination to varying degrees. Private seed companies began developing unique genotypes in earnest in the early 1900s, ushering in the current era of plant breeding and genetics.

In the 1990s foreign genes were being inserted into the cotton genome. Given the evolution of the techniques used in manipulating gene combinations in cotton, the growers' rapid acceptance and use of genetically modified cottons, and the perceived need for more students trained in cotton breeding, I undertook to survey public and private cotton breeders about their breeding methods.

Private breeders continue to place major emphasis (65% of their efforts) on conventional cotton breeding, with the remainder of their time devoted to transgenic cotton breeding. Public breeders spend nearly half of their time on conventional cultivar development, with the remainder of their time on germplasm enhancement.

Private breeders primarily use their own in-house germplasm lines as parental sources. Public breeders, on the other hand, use a more balanced source of in-house material, commercial cultivars, and other public germplasm. New genetic combinations are created by both public and private cotton breeders at a similar rate of around 100 per year.

The pedigree breeding method is followed by the vast majority of breeders, who begin selecting in the F_2 generation. Selection pressure increases in later generations. Private breeders have six times the number of nursery plots that public breeders have and make three times as many plant selections.

Yield testing begins in the F_4 generation for most cotton breeders. The number one factor in choosing parents continues to be yield; stability is the number two factor. Because the bulk of cotton breeders use traditional methods, the few educational institutions still involved in graduate education for cotton breeders should place a high priority on teaching traditional breeding methods.

ABSTRACT

Reduction in number and size of public cotton (*Gossypium barbadense* and *hirsutum* L.) breeding programs and the parallel increase in private breeding efforts have resulted in many younger breeders not being trained in cotton breeding. As a service to these younger breeders and the well-established breeders, I surveyed U.S. cotton breeders, both public and private. The objective of this study was to report on many aspects of breeding methods used by private and public breeders. There continues to be a major effort in conventional cotton breeding by private breeders; nearly half of the public breeders' effort is in conventional cultivar development using conventional breeding methods. Transgenic cultivars occupied the majority of the U.S. cotton acreage in 1999, but only 35% of private breeders' efforts are in this area. Pedigree breeding schemes are followed by most private and public breeders. The majority of parental material for private breeders is from lines developed in-house, while public breeders use a more balanced source of in-house material, commercial cultivars, and other public germplasm. Both private and public breeders average 100 genetic combinations each year, resulting in 3700 nursery plots for private breeders and 600 nursery plots for public breeders. Selection pressure is low in the F_2 and F_3 generations but increases in the F_4 generation for private breeders. Public breeders average 40% for all three generations. Breeders, both private and public, tend to start yield testing with F_4 lines more than in any other generation. For all

Daryl T. Bowman, Crop Science Dep., North Carolina State Univ., Raleigh, NC 27695-8604. Received 18 Nov. 1999. *Corresponding author (daryl_bowman@ncsu.edu).

breeders, yield continues to be the prime factor in choosing parents.

Cotton breeding has evolved from individual farmers in the 1800s making selections and manipulating pollen to the gene transformations of the 1990s. The number of professional cotton breeders today is greater than at any time in U.S. history; private cotton breeders increased sixfold from 1974 to 1998 (Bowman 1999).

The number of public breeding programs fell by nearly half during that same period (Bowman, 1999). The number of public institutions that train applied cotton breeders has dwindled to five universities: Louisiana State, Mississippi State (USDA and AES), North Carolina State, Texas A&M, and the University of Arkansas. Geneticists are being trained at these institutions and at New Mexico State University. Consequently, many of the younger cotton breeders were not trained in applied cotton breeding per se. These breeders are learning on the job, but often are not being mentored by seasoned, experienced cotton breeders.

The Delta and Pine Land Seed Co. has recognized the problem and is establishing associate breeder positions. These positions will be similar to post-doctoral positions at public institutions in that they will provide on-the-job training to those who will serve as assistants to the main breeder at a particular station.

It was against this backdrop that I decided to survey and compare U.S. private and public breeding programs. The results published here should serve to inform new cotton breeders as well as established breeders about how their colleagues operate.

Meredith (1980) conducted a survey of breeding objectives in 1979 and from that was able to predict a flush of new, earlier-maturing cultivars, which came about in the early 1990s. Breeding objectives were not part of my survey, although breeders were asked what traits they looked for in parents.

METHODS

I surveyed most private cotton breeders and all public cotton breeders in the USA in spring 1999. Although almost all private breeders were sent the survey, constant changes in personnel in the seed industry prevented a complete sampling. Fifteen of 22 private breeders responded as did 7 of 12 public breeders; the private respondents were from California to South Carolina while public respondents were from Arizona to North Carolina.

Many public breeders, like myself, are not full-time breeders. For example, I have a 0.3 full-time equivalent (FTE) in cotton breeding, and Roy Cantrell of New Mexico State University has 0.2 FTE. No attempt was made to adjust the data to FTE basis for any respondent. If data for a particular attribute were not normally distributed, a median number was determined; otherwise, averages are shown.

RESULTS AND DISCUSSION

The bulk of the survey data is shown in Table 1. One of the original purposes of the survey was to determine the size of the applied cotton breeding efforts in the private and public sectors, which was published in a separate paper (Bowman, 1999). Public efforts were broken down to USDA-ARS and state AES positions, which are nearly the same, 10.8 vs. 9.3 FTE (Bowman, 1999). However, only three individuals - for a total of 2.8 FTE in the USDA-ARS - are involved in germplasm enhancement (and that number is lower now than when the survey was taken). One individual is involved in germplasm collection and maintenance, and another is involved in the national variety testing program. The remainder of the USDA-ARS positions are involved in basic genetics. Five AES positions are full-time cotton breeders; all others have teaching or other responsibilities as well. As reported by Bowman (1999), private breeding efforts have increased sixfold while public efforts have declined to nearly half of the 1974 level.

The increase in private breeding efforts can be partially explained by the passage of the Plant Variety Protection Act in 1971; similar increases in private breeding efforts were seen in other self-pollinating crops such as soybean [*Glycine max* (L.) Merr.] and wheat (*Triticum aestivum* L.).

Obviously private breeders are interested primarily in cultivar development (Table 1). Cultivar development occupied nearly half (45%) of the breeding efforts of public breeders as well. No figures are available for historical breeding efforts of the public sector, so I was unable to determine if

Table 1. Attributes of private and public cotton breeding programs in the USA, 1999.

Attribute	Private	Public
Number of breeders (full-time equivalents)	27	20.1
Breeding Objective		
Germplasm Development	0%	55%
Cultivar Development	100%	45%
Average time devoted to		
Transgenic breeding	35%	1%
Conventional breeding	65%	99%
Breeding Method Used		
Pedigree	82%	71%
Backcross	6%	28%
Reselection	29%	14%
Bulk	18%	14%
Single seed descent	6%	0%
Use of Coefficient of Parentage	30%	0%
Source of Parental Material		
In-house	56%	40%
Commercial cultivars	28%	32%
Public germplasm	15%	25%
Other	1%	3%
Averge no. of genetic combinations yearly	105	102
Median number of nursery plots	3700	600
Median number of plant selections	7500	2800
Generation plant selections start		
F_2	28%	71%
F_3	14%	29%
F_4	58%	0%
Average population/cross at		
F_2	975	1,000
F_3	1950	760†
F_4	1280	1036
Average selection pressure at		
F_2	42.5%	50%
F_3	48%	35%
F_4	14%	37%
Average number of yield test locations		
First year	2	1.8
Second year	2	3.2
Third year	6	3.2
Median number of yield trial plots	2000	2650
Generation yield testing begins		
F_1	6%	0
F_2	24%	0
F_3	6%	14%
F_4	41%	57%
F_5	18%	14%
F_6	12%	28%
Parental selection criteria		
Yield	100%	86%
Stability	87%	71%
Disease resistance	73%	43%
Insect resistance	53%	57%
Pubescence	53%	43%
Nectariless	20%	28%
Fiber properties	47%	57%

† Median

there has been any apparent shift, but many public institutions are engaging in exclusive releases of their cultivars. This latter activity brings in royalties, some of which returns to the breeding project and, in some cases, a small portion may end up personally benefiting the breeder. In Texas, public breeders are required to make their released cultivars available exclusively to Texas cottonseed producers for 3 yr prior to their being universally available.

Public cotton breeding began about 1898. In the first half of the 20th Century, public breeding programs routinely released new cultivars (Ware, 1950). Cultivar development was a major emphasis of the public Acala programs in California and New Mexico (Cooper, 1998; Staten, 1998). Until the early 1990s, all pima breeding was performed by public breeders, specifically USDA-ARS (Feaster, 1998).

It can be inferred that the earlier public programs had cultivar development as their primary breeding objective, with very little emphasis on germplasm enhancement. Release of germplasm lines may not be a worthy objective even today, particularly if the lines are not adaptive and not used by private breeders. Of the 668 upland germplasm lines released between 1962 and 1995, only four have shown up in the pedigrees of popular, commercially grown cultivars from 1970 and 1995 (Van Esbroeck and Bowman, 1998).

Public breeders need to release germplasm lines that are near commercialization or as cultivars. Private breeders are more likely to use commercial cultivars, the second most-used source of parental material, in their breeding program and less likely to use germplasm lines unless they have personally developed them (Table 1).

The policy of the USDA-ARS cotton-breeding programs is to develop germplasm for commercial companies to use. This policy was followed (Culp, 1998) during the 1950s and 1960s as a result of orders from Billy Waddle, cotton division branch chief, not to use public funds to develop cultivars and, thus compete with the private companies such as Coker Pedigreed Seed Co., Delta and Pine Land Seed Co., or Stoneville Pedigreed Seed Co.

It is generally thought that emphasis on conventional breeding by the private sector has declined due to the push to develop transgenic cultivars. However, 65% of the time spent by private breeders is still devoted to conventional breeding (Table 1). Coupled with a sixfold increase in the number of private cotton breeders (Bowman, 1999), more conventional cotton breeding is going on now than in 1974.

Transgenic breeding activities for the private breeder involve testing and screening material after backcrossing or forward crossing. This 35% effort

(Table 1) is justified, given that of the top seven cultivars planted in the USA in 1999, six were transgenic (USDA, 1999). The number-one cultivar in every growing area except California was a transgenic. Transgenic cultivars comprised nearly 60% of the total U.S. cotton production in 1999 (USDA, 1999). Even though a high percentage of U.S. cotton production is in transgenic cultivars, transgenic breeding adds only one or two qualitative traits to an existing cultivar; therefore, a minor effort (35%) in transgenic breeding is justified.

Public cotton breeders spend very little effort in transgenic breeding (Table 1). In fact, only one public breeder claimed to be spending 5% of his time in transgenic breeding. Access to the transgenes by public breeders has been limited, i.e. the private breeder has had first access to the transgenes even though the technology essentially was developed by the public sector (Bowman, 1999). There are multiple patents on most transformations, and many public institutions are not equipped to deal with the myriad aspects of the paperwork. Private companies, on the other hand, feel pressure to compete in the transgenic market, based on grower acceptance of the technology; thus, they will generate partnerships and sign the necessary agreements to advance in this area.

Jensen (1988) stated that mass selection was probably the first breeding method practiced. According to Ware (1950), a vast number of new cultivars in the 19th and early 20th centuries were individual plant selections from an existing cultivar. Obviously the open-pollinated cultivars were heterogeneous populations, given the insect activity and the lack of chemical insecticides in those days. So, in a sense, farmers were practicing reselection.

This breeding procedure, reselection, continues to be a successful practice. Thirty-two percent of the upland cultivars released between 1970 and 1990 were reselections from either established cultivars or germplasm lines (Bowman et al., 1996). In more than 90% of 260 upland cultivars, reselection was used in their development, either directly or indirectly via reselection in the process of developing the parents.

Pedigree selection began in the 1890s or earlier (Jensen, 1988). It is now the most widely used breeding method by both public (82%) and private (71%) cotton breeders (Table 1). Pedigree selection is not always the best method to use; for example, in the early stages of transgenic breeding the breeders used the backcross method to rapidly move a transgene into a known cultivar. Bird (1998) found that pedigree selection was not very effective for increasing disease resistance beyond the intermediate level. I, as a public breeder, have gone to a bulked-population method (Florell, 1929), whereby the selections are bulked by cross in early generations and subjected to pedigree selection just prior to preliminary yield trials.

Reselection is the second most widely used method for private breeders; the backcross method is second most popular among public breeders (Table 1). Reselection and bulk methods are third among public breeders, while the bulk method is third among private breeders. One private breeder uses the single seed descent method but a more descriptive term would be single lock descent. In the North Carolina State program, I use the bulk method for developing germplasm tolerant to thrips (Thysanoptera: Thripidae) by bulking one boll per plant of those remaining after removing thrips-damaged plants early in the season. Surviving plants are allowed to intercross prior to harvest.

The coefficient of parentage has been calculated for 260 cotton cultivars (Bowman et al., 1997). Pedigrees for 367 upland and pima cotton cultivars have been published by Calhoun et al. (1997). Pedigrees of 881 germplasm lines have also been published by Van Esbroeck et al. (1997). Therefore, coefficients of parentage can be hand calculated for combinations not found in Bowman et al. (1997). Coefficients of parentage have proven useful in soybean where there was a positive relationship between genetic variance and genetic distance (Manjarrez-Sandoval et al., 1997). However, in cotton the coefficient of parentage between parents used in the final cross of successful cultivars ranged from 0 to 0.875, so there appeared to be no relationship between genetic distance and success as defined by grower acceptance (Van Esbroeck and Bowman, 1998).

This lack of relationship in cotton might explain the low interest in using coefficients of parentage in choosing parents (Table 1). Meredith and Brown (1998) found that region of adaptation was an important factor in choosing parents for a hybrid program, more so than the coefficient of parentage;

one parent needed to be a well-adapted genotype from the region in which it was to be grown.

In-house germplasm accounts for the largest source of parental material for both private and public breeders (Table 1). However, public germplasm (primarily cultivars but including germplasm lines) was the primary origin of parents of successful cultivars since 1990 (Van Esbroeck et al., 1998). Prior to 1990, in-house germplasm was the primary source of parents of successful cultivars. Even though public germplasm is the third most-used source of parental material for both private and public breeders, all breeders as a group have been more successful using this material than any other.

In the search for that unique genetic combination, both public and private breeders average more than 100 combinations each year (Table 1); the specific numbers vary from as few as five to as many as 300. Genetic combinations could involve single crosses, three-way crosses, backcrosses, or any other genetic crossing. Some breeders handle the large number of crosses by testing F_2 families and carrying forward only the better yielding ones; this procedure was advocated by Green and Culp (1989).

Private breeders have six times the number of nursery plots as public breeders (Table 1). However, the private breeders only make about 2.7 times as many plant selections (7500 vs. 2800), suggesting a higher selection pressure. Jensen (1988) suggested examining individual plants of a successful cultivar in order to sharpen the eye for individual plant selection. I tried this with my own advanced breeding lines and Stoneville 474, which was the highest-yielding, early-maturing cotton cultivar in North Carolina. I looked at boll number (the largest factor in yield) and boll size. Data (rankings based on boll numbers and boll size) from a space-planted nursery were correlated with plot yield data in the same field the same year.

There was no correlation. Stoneville 474 did not appear superior in a space-planted nursery, but my North Carolina lines looked impressive. They yielded less in the yield trials, though.

Among the factors that influence yield, the most visible are boll number and boll size. Other factors - lint percent, fiber length, fiber micronaire, seeds per boll and lint per seed - would be measured after harvesting.

Therefore, if boll number and boll size in a space-planted nursery are misleading or turn out to be misleading, then one would need to select a larger number of plants to yield test; that is, to use a lower selection pressure. Meredith and Bridge (1973) ran correlations between F_2 plants that were visually selected for high yield and F_3 progenies. They calculated a correlation coefficient of 0.48, which was not significant. In the end, the breeder is basically discarding the most obvious low-yielding plants in the population with little hope of selecting the top performers except through yield testing. On the other hand, selection for other traits such as fiber properties can be highly effective.

The bulk of public breeders (71%) start plant selections in the F_2 generation, while the remaining public breeders begin in the F_3 generation (Table 1). Waiting until the F_3 allows another generation of recombination prior to selection. Private breeders begin as late as the F_4 generation, although a few start at the F_2 generation (Table 1).

For those that start selections in the F_2 generation, selection pressures (percentage of plants retained for next cycle) averaged 42.5% for private breeders to 50% for public breeders (Table 1). For public breeders the selection pressure in the F_3 generation increased to 35% (smaller numbers indicate higher pressure and fewer plants chosen) and remained the same through the F_4 generation. For private breeders the selection pressure did not change from the F_2 to F_3 generations, but increased dramatically at the F_4 generation. Within groups of breeders there was considerable variation for selection pressure ranging from 100% (all plants retained) to 2.5%.

Population sizes were larger for private breeders than public breeders in the F_3 and F_4 generations (Table 1). A median, rather than average, number was given for the F_3 generation for public breeders because one public breeder (me) has an unusually large number (12,000 plants) in the F_3 populations because I retain all F_2 plants (100% selection pressure). My selection pressure in the F_3 generation, on the other hand, is 2.5%.

Private breeders use a larger data set to draw their conclusions. They generally yield test at two locations the first two years and expand to six locations the third year of testing (Table 1). Public breeders, on the other hand, use two locations the first year and three the second and third years.

Public breeders have more yield trial plots - assuming they are not counting official variety trials and regional trials - than private breeders. This fact seems perplexing since all other numbers have been greater for private breeders up to this point. Private breeders also conduct commercial cultivar trials.

The bulk of breeders, both private and public, begin yield testing in the F_4 generation. Although there are no data on past practices, there appears to be no evidence that breeders 30 years ago were yield testing as early as is done today. Jensen (1991) suggests that breeders have, in the past, gone away from mixtures, composites, etc., toward pure-line cultivars and are showing an interest in heterogenous and synthetic populations. Cotton breeders also are no longer concerned about segregating populations and assume that heterogeneity and heterozygosity are beneficial to commercial cotton production.

In past years, yield testing begun in the F_5 generation was considered an early-generation test. An example of a cultivar developed in this way is Acala SJ5. In current practices, few breeders delay yield testing until the F_6 generation. The practice of early-generation testing allows for reselection of a "finished" cultivar at a later time by providing remnant heterogeneity/heterozygosity in the cultivar.

In selecting parents, the breeders' number one trait was yield (Table 1). The second most important trait was lint yield stability across environments. Earliness was a high priority in Meredith's (1980) survey of breeding objectives; it was second only to yield. Earliness was mentioned only once in the current survey; earliness with high yields has been achieved beginning with DES 24 and DES 56 in the 1970s, DES 119 in the 1980s, and SG 125 and Stoneville 474 in the 1990s.

Disease resistance was the third most important trait for private breeders when choosing parents. Insect resistance and pubescence were fourth. Fiber properties were next on the list. Other traits, with only a few breeders examining them, were adaptation, nectarilessness, herbicide resistance, leaf shape, and stormproofness. Adaptation was only mentioned by one breeder but I perceive it to be a major criteria for every breeder. Meredith and Brown (1998) stated that at least one parent needed to be from the area of adaptation when choosing parents.

Plant breeders are not able to perfectly mimic commercial cotton production in their programs. For example, few breeders have access to lint cleaners; most use an experimental 10-saw gin to estimate gin turnout and collect samples for fiber analyses. Without lint cleaners (known to damage fiber), the samples appear to have higher fiber length uniformity (Preston Sasser, 1999, personal communication). Higher fiber strength increases length uniformity (Preston Sasser, 1999, personal communication), so there may be genetic interactions for fiber properties before and after lint cleaning.

Another area in which cotton breeders do not typically mimic commercial cotton production is plant population. Although plant population was not part of the survey, my personal communication with cotton breeders revealed that typical plant spacing in a nursery is 30 to 46 cm, whereas commercial cotton spacing is 7 to 15 cm. At commercial cotton production spacing, it is most difficult for breeders to make plant selections. As mentioned earlier, productivity is difficult to ascertain on an individual plant basis at the plant spacing most breeders use. Several traits can be examined when making plant selections that may affect final yield, including plant structure, boll shape, placement of bolls, and internode length. Research into this area could provide useful information for inexperienced cotton breeders.

Overall, private and public cotton breeders are similar in their mode of operation. Adjusting public breeders' time (FTE) to 100% would close any gap in sheer numbers in the selection process. Public breeders are limited by locations available, but can initiate reciprocal agreements with other public breeders and private breeders for mutual testing of material.

The study shows that the present situation of high genetic uniformity in cotton is unlikely to change. Evidence for this likelihood is the high level of reselection, disregard for coefficient of parentage, and reduced efforts in germplasm enhancement by the public sector.

Despite recent advances in genetic engineering, the bulk of private and public breeders are involved in traditional breeding methods. Thus educational institutions should place a high priority on teaching traditional breeding methods.

Breeding methods vary little among breeders. The majority of breeding efforts use the pedigree method with plant selections at the F_2 to F_4 generations. Very little effort is dedicated to germplasm enhancement.

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