The *Journal of Cotton Science* 3:139-152 (1999)

CONTEMPORARY ISSUES

Public Cotton Breeders - Do We Need Them ?

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INTERPRETIVE SUMMARY

The number of public cotton breeders declined from 1974 to 1998 by nearly 50% while the number of private cotton breeders increased more than sixfold. Funding for public cotton breeding programs was stagnate or has decreased during those years. Should this be a concern for the cotton community? To answer this question, the summary of a 1992 USDA-ARS cotton breeding workshop was used to identify the accomplishments of the U.S. cotton breeders. The workshop highlighted cotton breeding research needs that were or should be addressed.

Half of the influential cotton breeding programs have been public programs, but half of those public programs have been terminated or drastically reduced in the last few years. Ironically, those terminations have been in spite of the advances that have been made in disease resistance, primarily by public breeders with improved Fusarium wilt and Verticillium wilt resistance and with the development of nematode-resistant cotton cultivars.

Genetic diversity is a major concern. Yield gains have declined during the last decade, and many believe that decline may be a result of a lack of genetic diversity. Private breeders primarily use their own in-house material as their prime parental source, and use other commercial cultivars as their second source of parental material. Thus private breeders are not necessarily introducing new genes.

Herbicide resistance is primarily handled by the private sector. Resistance to insects such as aphids, whiteflies, and thrips have been researched by public breeders. Private breeders, using publically developed technology, have been successful in developing cottons with the Bt gene for controlling Lepidoptera, and concomitantly reducing aflatoxin contamination.

Lint quality improvements were initiated by USDA-ARS cotton breeders. Improvements have been realized by both public and private breeders in tolerance to acid subsoils although that wasn't a primary breeding objective. Public breeders are researching drought tolerance and water use efficiency. Heat tolerance has been achieved in several cultivars by private breeders. Other abiotic stresses, such as salt, ozone, and pollutant tolerance, have received little attention by breeders.

Improvements in earliness began with efforts by public breeders. Almost no breeding work is going on in the area of narrow row production. Seed quality research has been almost exclusively a public breeding effort.

Public breeders have been influential in providing genetic diversity as well as addressing many of the concerns of the cotton community. Public cotton breeders are needed to train new cotton breeders. It is imperative that all remaining public cotton breeding programs be retained and funded adequately.

ABSTRACT

During the last 25 yr, upland cotton (*Gossypium hirsutum* L.) and pima cotton (*G. barbadense* L.) production in the USA has varied from 4 to 6.9 million ha. Major concerns for breeders have been diseases, fiber quality, insects, and yield. These were addressed by both private and public breeders although most of the concerns, other than yield, were researched by public breeders. There has been a steady decline in public breeding programs and an increase in private breeding programs. One half of the most influential breeding programs have been public programs, but nearly one half of these influential public programs having been terminated or drastically reduced. This review summarizes accomplishments of public breeding programs and their substantial impact on the cotton industry. Continued support of public breeding programs is needed to furnish genetic diversity for continued

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Received 20 April 1999.
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cotton improvement, for the training of students, and to conduct research in areas not addressed by private breeders.

Upland and pima cotton planting in the USA has ranged from 4 to 6.9 million ha per year from 1970 to 1995. During this time boll weevils (*Anthonomus grandis* Boh.) and cotton boll worms [*Helicoverpa zea* (Boddie)] remained a menace, tobacco budworms (*Heliothis virescens F.)* developed resistance to synthetic pyrethroid insecticides, and sweetpotato whitefly [*Bemisia tabaci*] (Genn.) Strain B wreaked havoc on cotton production in the West. The textile industry also set minimum standards in 1991 for fiber quality of upland cotton, namely, fiber strength of 27 g/tex (High Volume Instrumentation), a quantity virtually non existent in the early 1970s for commercial cultivars.

Many of the challenges cited above have been addressed by more than one sector of the cotton industry, others by only one. For example, private breeders are offering bioengineered cultivars for the control of Lepidoptera, especially tobacco budworms and pink bollworms. Both public and private breeders also increased fiber length and strength, which could have been at the expense of yield gains, because lint yield and fiber strength are negatively correlated.

Several researchers at the 1992 Cotton Breeders Workshop (Miller, 1992) addressed how cotton breeding efforts can contribute solutions to these challenges faced by the industry (Table 1). Many of these needs are being, or can only be met by public breeders. But, recently there has been a decline in the number and/or size of public programs. Should this be a concern? Can the cotton industry continue to advance with a reduced public breeding effort? This review (i) summarizes the research accomplishments of public and private breeding programs and their impact on the industry and (ii) will demonstrate the need for continued funding of public cotton breeding. The discussion follows the general list of breeding and research needs found in Table 1.

Advances in Disease Resistance

Cotton germplasm has been evaluated for Fusarium wilt (*Fusarium oxysporum* Schlect f. vasinfectum (Atk.) Synd. & Hans.) resistance since the 1940s. Kappelman (1980) reported increases in resistance to this disease over time. Lines from the state (public) breeders showed a steady increase in resistance from 1969 to 1978, while lines from the private breeders showed a 5-yr lag in improved resistance.

Verticillium wilt (*Verticillium dahliae* Kleb.) tolerance was a breeding objective of the USDA-ARS cotton breeding program in Shafter, CA since the 1930s. The result was the release of Acala SJ

Table 1. Cotton breeding and genetics research needs mentioned at the 1992 USDA-ARS Cotton Breeding Workshop, Dallas.

Research need	Initially addressed by
Disease resistance	
-Fusarium/verticillium wilt	USDA-ARS Auburn, USDA-ARS Shafter, TX-AES College Station
-Nematodes	USDA-ARS Auburn, LA-AES
-Southwestern cotton rust	USDA-ARS
Genetics	
-Broaden the germplasm base	USDA-ARS Mississippi State
-Gene expression/regulation	
-Genome mapping/gene identification	LA-AES, TX-AES College Station, USDA-ARS College Station, USDA-ARS Mississippi State, USDA-ARS Stoneville
Herbicide resistance	Private Sector
Insect resistance	
-aphids/whiteflies	TX-AES College Station
-thrips	AR-AES, NC-AES, TX-AES College Station
Lint	
-fiber strength	USDA-ARS Florence
-fiber uniformity	
-non-lint content	LA-AES, USDA-ARS
-resistance to bark shedding	
Abiotic stress	
-Acid subsoil	LA-AES
-Drought	AZ-AES, TX-AES Lubbock
-Heat	AZ-AES, NM-AES
-Salt	USDA-ARS Maricopa
Production	
-Early maturity	MS-AES-DREC
-Ease of defoliation	
-Improved yield	Private and public sectors
-Response to fertilizer	
-Row width	
Seed	
-Index	
-Quality (oil %, etc.)	USDA-ARS College Station
-Vigor	AR-AES, TX-AES CollegeStation
-Yield	

cultivars with markedly improved resistance (Turner, 1974). The Texas A&M programs at College Station (MAR) and Lubbock have been breeding for Verticillium resistance since the 1960s. Today, private and public breeders in the West routinely screen for Verticillium wilt resistance.

Nematodes are found in all cotton growing areas of the USA. Orr and co-workers (1982) estimated a 12.5% loss annually from nematode infestations. Both public and private breeders currently conduct screening trials for resistance to various nematodes. The pioneering work on nematode resistance was conducted by Jack Jones of LSU, Al Smith and Raymond Shepherd of USDA-ARS Auburn, and A. H. Hyer of USDA-ARS Shafter, California. The first truly root-knot nematode [*Meloidogyne incognita* (Kofoid & White) Chitwood] resistant cultivar was developed by Jack Jones and co-workers (Jones et al. 1991). The source of resistance was LA 434-RKR which also has resistance to reniform nematodes [*Rotylenchus reniformis* (Linford & Oliveira)] (Jones et al. 1988). Major efforts in developing resistant material are continuing in the programs of Wayne Smith at Texas A&M, Shelby Baker at the University of Georgia, and the USDA-ARS at Mississippi State, and CPCSD at Shafter, CA. Charlie Cook, formerly with USDA-ARS Weslaco, Texas, released several nematode resistant lines.

Southwestern cotton rust (*Puccina cacabata* A&H) is potentially a pest in the U.S. Southwest. Breeders have used tolerant germplasm developed by the USDA-ARS (Gil, 1988) in cultivar development efforts. A few race stocks of *G. arboreum ,G. herbaceum, G. anomalum, G. bickii, G. aridum, and G. barbosanum* are resistant to this disease (Blank, 1971). These exotic sources of resistance are unlikely to be included in any private breeding program because of the large amount of time needed to transfer the resistance to an agronomically acceptable phenotype. However, Luther Bird *did* incorporate resistance into acceptable phenotypes of *G. hirsutum* in the late 1970s (Percy and Bird, 1985).

Many of the advances in host plant resistance to diseases not covered in this discussion have been documented by Ranney (1995). Significant disease losses continue to occur and the need for sources of resistance will dictate on-going research efforts by breeders.

Genetic Diversity

Genetic diversity and the need to broaden the germplasm base have been cited by a number of scientists as an area of concern (Duvick 1984; Meredith 1991). Others (Rasmusson and Philips 1997; Van Esbroeck and Bowman 1998) have questioned that. Whether one debates the importance of genetic diversity or not, it still falls to the public agencies to accept the challenge (Jones and Beeler 1973). The National Academy of Sciences recognized the problem in cotton in 1970 when six cultivars occupied 68% of the U.S. cotton hectarage (National Academy of Sciences 1972).

More than 350 upland cotton cultivars were released between 1970 and 1995 (Calhoun et al. 1994; Calhoun et al. 1997). At first glance it would appear that the large number of lines would insure genetic diversity. For instance, when Bowman et al. (1997) used pedigree information found in Calhoun et al. (1994) to calculate the coefficient of parentage (CP), they found that the average CP for 260 of these 350 cultivars was 0.07, indicating considerable genetic diversity. When one examines the diversity of the actual cotton being grown, however, a different picture emerges.

The CP of all upland cultivars that were planted on 1% or more of the hectarage in any region averaged 0.12 in 1970 and increased to 0.20 in 1995 - an alarming trend (Van Esbroeck et al. 1998). When one weights these CP values by the hectarage planted to each cultivar, genetic uniformity is even more apparent with an average CP around 0.30 for 1970 to1995 (Van Esbroeck et al. 1998). This genetic uniformity is substantiated by the work of Wendel et al. (1992) who found few polymorphic genetic markers in cotton.

Why has this apparent lack of genetic diversity occurred? There are several possible reasons. One is the chief breeding method followed over the years. Reselection (selecting individual plants within an established cultivar) was used in the process of developing 236 of the 260 cultivars examined between 1970 and 1990 (Bowman et al. 1996). Few, if any, alleles are being introduced when one reselects. Instead, reselection with improvement is based on the assumption the breeder capitalizes on residual hetereozygosity and/or heterogeneity or useful spontaneous mutations. Of course, the latter can be deleterious more times than not. On the other hand, the variability leading to successful reselections might actually stem from an outcrossing.

Second, the repeated use of the same parents increases genetic uniformity. From 1970 to 1990 Stoneville cultivars, primarily Stoneville 2 or its relatives, occurred 383 times in the pedigrees of 216 cultivars released (Bowman et al. 1996). The bulk of the cultivars released between 1980 and 1990 fell into four cluster groups based on coefficient of parentage (May et al. 1995). There was a single common parent in each group; the largest group had Stoneville 2 as the common parent. Lankart, Empire, and Stoneville 7 were the common parents of the other three groups; Stoneville 2 and Stoneville 7 are related through Lone Star 65.

A third reason for the lack of diversity has been the reluctance of breeders to use unadapted germplasm. More than 800 pima and upland germplasm lines have been released since 1972 (Van Esbroeck et al. 1997) with only four of the upland lines showing up in the pedigrees of commercially grown upland cultivars (Van Esbroeck and Bowman, 1998). Apparently germplasm lines will not be used by upland commercial breeders unless the lines are developed virtually to the point of commercialization. There has been extensive use of public germplasm by commercial breeders in pima cultivar development. However, the pima fiber industry was solely supported by public breeding for more than 70 yr, resulting in highly adapted germplasm now being available to commercial breeders.

There are a number of reasons why genetically diverse, unadapted germplasm has not been introduced into breeding programs. These include the breakup of favorable linkage groups or introduction of unfavorable linkage groups (Percival and Kohel 1990) that can result in reduced yields (Robinson et al. 1997). In addition, commercial upland breeders may not have the time to cross unadapted material with adapted material merely for the sake of adding to or ensuring field diversity. Herein lies another dilemma. In order to develop germplasm to the point of adaptation, the public breeder will either backcross the desired genes into an established, adapted cultivar or cross to an adapted cultivar and select in the resulting generations. Either way the resulting germplasm line may carry little genetic material from the exotic source.

The number one objective of the breeder - increased lint yield - has been the ultimate deterrent to the introduction and maintenance of genetic diversity. Breeders routinely select sources of high yield genes that are harbored by the current high-yielding adapted cultivars (Van Esbroeck and Bowman 1998). This does not always mean that only closely related materials are being crossed; the relationship (CP) between parents used in the development of the most popular upland cultivars from 1985 to 1995 ranged from 0 to 0.875 (Van Esbroeck and Bowman 1998). At least one or both of the parents, however, were adapted cultivars no matter what their relationship was. The pressure for commercial breeders to develop cultivars does not allow for very wide crosses, because these types of crosses require a long-term commitment.

Trends to patent private material also are counter productive to the maintenance of genetic diversity. Patents and proprietary agreements restrict the free exchange of germplasm. Most public breeders have limited or no access to certain alleles since many have several patents constraining their use. A patent on a single gene, in effect, removes the possibility of using that genotype for breeding purposes. Even though public material may be sold exclusively to a private seed company, typically that material can be used in a crossing program with the maximum of one backcross. Material transfer agreements are being demanded by private companies and public institutions prior to seed shipment for cultivar testing to insure that their material will not be used in a crossing program; again this is limiting free exchange of germplasm. Terminator technology being developed by one of the private companies not only limits use by the grower but effectively removes that genotype as a parental source in another breeding program.

Gene expression and regulation

Gene expression and regulation research will be conducted by both public and private programs. Genome mapping and gene identification are being carried out at several ARS and AES labs (Table 1).

Influential public breeding programs

The most visible current program, public or private, contributing to genetic diversity and broadening the germplasm base is Jack McCarty's (USDA-ARS Mississippi State) program of inserting day-neutral genes in *G. hirsutum* racestocks. In the process he has identified genetic material having boll weevil resistance, tobacco budworm resistance, unique yield and fiber properties, and nematode resistance (McCarty et al. 1982, 1987; McCarty and Jenkins 1992; McCarty and Jones 1989; McCarty et al. 1995; McCarty et al. 1996; McCarty et al. 1998a,b,c; Tang et al. 1993). A few breeders, both public and private, are now using this material in their programs. Vesta Meyer (MS-AES) (1974) introgressed genes and cytoplasm from 30 different *Gossypium* species into upland cotton, but that program has since been terminated.

The full impact of the racestock conversion program on private breeding programs remains to be seen. However, several public breeding programs that have been instrumental in supplying genetic material that eventually became incorporated into commercial cultivars can be cited. New Mexico AES was second only to Stoneville Pedigreed Seed Company in influencing released cultivars between 1970 and 1990 (Bowman et al. 1996). The New Mexico AES program released 11 cultivars and their material was found in the pedigrees of 112 other cultivars.

Of the 16 most influential breeding programs during this era, half were public programs. Of these eight public programs, the New Mexico program has been reduced to only 0.2 FTE (fulltime equivalent) while the Missouri, Oklahoma, and USDA-ARS Shafter breeding programs have been terminated. In other words, nearly half of the public cotton breeding effort, which was highly influential in the last two decades, has been lost (Table 2). These four public programs had genetic material that appeared 195 times in the pedigrees of 156 of the 260 cotton cultivars released between 1970 and 1990 (Bowman et al. 1996).

Other influential public breeding programs include the Texas A&M program at College Station, Texas (Tamcot) under the direction of Luther Bird and later Kamal El-Zik and Peggy Thaxton. This program released cultivars adapted to the South Central region. Starting in 1973, hectarage of their cultivars increased until 1982 when 10% of the entire U.S. hectarage was planted to Tamcot cultivars (USDA 1982). In the late 1970s, 90 to 100% of the cotton in some counties in Texas were planted in Tamcot cultivars. These cultivars had black root rot tolerance, seedling disease and bacterial blight resistance, and led to the revival of cotton production in certain areas of Texas. They also had early maturity, which provided escape from boll weevils and unfavorable weather patterns that can occur in August and September in that area.

Table 2. State (AES) applied upland cotton breeding programs in the United States in 1998.

Location	Organization	Breeder	Estimated FTE
AR	Univ. of Arkansas	Fred Bourland	0.8
AZ	Univ. of Arizona	Hal Moser	0.75
GA	Univ. of Georgia	Shelby Baker	1.0
LA	Louisiana State Univ.	Gerald Meyers	0.9
MS	Delta Branch	John Creech	1.0
	MS State Univ.	Ted Wallace	0.72
NC	North Carolina State Univ.	Daryl Bowman	0.3
NM	New Mexico State Univ.	Roy Cantrell	0.2
TX	College Station	Kamal El-Zik	1.0
	College Station	Peggy Thaxton	1.0
	College Station	Wayne Smith	0.67
	Lubbock	John Gannaway	1.0
		Total	9.34

From 1970 to 1990 the Tamcot program was one of the more influential breeding programs in the USA (Bowman et al. 1996). During this 20-yr period the program released 11 cultivars. In addition, 48 other commercial cultivars had genetic material tracing back to Tamcot material. The breeders used the MAR (multiple adversity resistance) approach to improve seedling vigor, resistance to seedling disease *Rhizoctonia solani* Kuhn and *Pythium* spp., resistance to bacteria blight (*Xanthomonas malvacearum* (E.F. Sm.)), Fusarium wilt (*Fusarium* spp.), Verticillium wilt, Phymatotrichum root rot, boll rot (*Colletotrichum* spp.), and resistance to insects such as fleahoppers, bollweevil, Heliothis spp., and pink bollworm (Bird, 1982). As a result of the use of Tamcot cultivars in the 1970s, average lint yields doubled in the Texas Coastal Bend area.

The Texas A&M program at Lubbock released 22 influential lines that have contributed to 59 cultivars of the 260 released between 1970 and

1990 (Bowman, et al.1996). That program does not produce cultivars but impacts Texas High Plains cultivars through release of stormproof material with improved earliness, fiber quality, and increased resistance to Verticillium wilt.

As previously mentioned, the USDA-ARS pima breeding program supported the pima fiber industry for more than 70 yr. Since the establishment of a private pima breeding industry in the early 1990s, the focus of the USDA-ARS program has shifted to germplasm enhancement and genetics. From 1990 to the present, more than 235 germplasm lines have been released by this program in support of private industry (Percy and Turcotte, 1993, 1997, 1998; Turcotte et al., 1991). At present, all American pima cultivars have some ancestory in this program.

These public programs not only contributed a supply of enhanced traits in cotton germplasm, they also contributed to increasing genetic diversity by making wide crosses involving exotic material and unique gene combinations. This can be verified by examining the pedigrees of the material being released by these programs (Calhoun et al. 1997). Public breeders make more complex crosses and/or use more noncommercial germplasm in their final cross than private breeders.

Herbicide resistance

The sensitivity of cotton to various herbicides limits their use; thus there is a perceived need for cotton cultivars to be resistant to a broader spectrum of herbicides. Currently this need is being addressed by the private sector with glyphosate and bromoxynil resistance. Research on resistance to other herbicides is ongoing by the private sector while public efforts will be minimal.

Insect resistance

Resistance to aphids and whiteflies (particularly after the whitefly epidemics of the early 1990s) is now a high priority. Wayne Smith's program at Texas A&M has explored resistance to the whitefly (Smith et al. 1993; Meagher et al. 1997), and the agrichemical industry has developed more effective insecticides.

Thrips (Thysanoptera: Thripidae) resistance breeding and research has been conducted at the Univ. of Arkansas by James McD Stewart's program, at Texas A&M by Kamal El Zik and Peggy Thaxton, and at North Carolina State University by the author. Commercial cultivars with some level of resistance have been released by Texas A&M (Bird 1982). The primary source of resistance in *G. hirsutum* is the presence of trichomes. Trichomes are undesirable, creating trash in the lint (Lee 1985). The best source of resistance may come from other cotton species (Bowman and McCarty 1997; Stanton et al. 1992). Obviously the private breeding sector will not devote resources to such a long term project as transferring resistance from exotic species to cultivated cotton, thus necessitating public research in this area.

Private breeding efforts in insect resistance has resulted in the release of transgenic cotton cultivars carrying the Bacillus gene (Bt) for control of Lepidoptera. This includes control of the pink bollworm, tobacco budworm, and partial control of the cotton bollworm. Bt cottons have been highly successful allowing growers to produce cotton where insects have become resistant to various insecticides. Much of the research perfecting the techniques to produce transgenic cottons was performed at public institutions, e.g. cotton tissue culture work at USDA-ARS Lubbock (Trolinder and Goodin, 1987).

Fiber

The physical parameters required for good spinning performance of cotton fiber challenge breeders. Textile mills want cotton fiber with specific micronaire values and high fiber strength, but premium miconaire and high fiber strength are often associated with reduced yield potential. The issue of fiber quality, particularly fiber strength, was first addressed by the public sector. Research by Miller and Rawlings (1967), and Culp, et al. (1979) showed that random intercrossing reduced the negative correlation presumably due to the tight linkage between fiber strength and yield.

The USDA-ARS program at the Pee Dee Research Station near Florence, SC was instrumental in breaking the linkage between yield and fiber strength (Culp, et al. 1979). Fiber strength in the USDA-ARS Pee Dee program stemmed from Beasley's triple hybrid (Beasley 1940). This program contributed to 33 upland cultivars released between 1970 and 1990 and thus became one of the most influential breeding programs during this era (Bowman et al. 1996). The full impact of the Pee Dee work is yet to be realized, given the continued use of cultivars containing Pee Dee germplasm.

Other factors affecting the spinning quality of cotton fiber include bark content, trash, neps, and motes. The cotton industry has called for reductions in these deleterious factors and public researchers have responded. As early as 1929 there were genotypic differences detected for motes (Rea, 1929). There are also genotypic variations for nep production (Hughs and Lalor 1986; Miravalle et al. 1986) and seedcoat fragments (Anthony et al. 1988). Some morphological traits can improve crop quality, e.g. semi-smooth leaf can reduce motes and trash, super-okra leaf reduces motes and small leaf trash (Novick et al. 1991). Currently, such research is only being addressed by the public sector.

Abiotic stress

Among the numerous abiotic stress factors affecting cotton production are nutrient deficiencies, drought stress, heat stress, salt sensitivity, and soil acidity. Problems vary with locality, but where they occur, breeding has been used as a tool to combat them. In the Mid-South, growers have expressed a need for cotton cultivars with improved root penetration into acid subsoils (pH < 5.0) and better tolerance to Al and Mn which are associated with acid subsoils. Only by serendipity will the private sector release cultivars adapted to acid subsoil conditions. A study by Foy et al. (1980) revealed several genotypes more tolerant to acid Al-toxic subsoil than other genotypes. The range of more tolerant genotypes in descending order were Acala 4-42, pima S-2, Louisiana lines, Stoneville 213, Delcott 277, and McNair 612 and showed no relationships for tolerance. Stoneville 825, one of the most popular cultivars in the mid-South in the late 1970s, and pima S-5 showed greater tolerance to acid soils than Deltapine 41 and Auburn 56 (Kennedy et al. 1987). In each case the more tolerant genotypes were not specifically bred for acid subsoil tolerance. The research by Foy et al. (1980) showed that top growth was a good indicator of Al tolerance so that breeders may unknowingly be selecting for this trait in their nurseries.

Drought resistance is an important trait in the humid Southeast. This will require long-term research, which means the private sector will not likely address this issue except through indirect selection. Jerry Quisenberry (USDA-ARS) conducted pioneering work on drought tolerance in the 1970s and early 1980s. Basically all research in this area has been conducted in areas outside the Southeast and also includes work by John Gannaway at Texas A&M Lubbock and Robert McDaniel at Arizona. Some work in this area is being initiated at North Carolina State University.

While drought is a concern in the humid Southeast, water use efficiency is critical in the West where nearly all cotton is irrigated. There are genetic differences for water use efficiency (Quisenberry et al. 1981.) Water use efficiency research has been conducted by Quisenberry and McMichael (1988) and John Gannaway's program (Love et al. 1988) in the High Plains area of Texas.

Extremes in temperature (low and high) typically result in delayed growth and/or aborted fruiting sites. Heat tolerance can be genetically manipulated. Certain genotypes perform well under typical temperature ranges but are adversely affected by high nighttime temperatures. Robert McDaniel (AZ-AES) is developing heat-tolerant genotypes. Private breeders have been successful in releasing heat-tolerant genotypes (e.g. Deltapine 90), although the mechanism for heat tolerance may not have been understood nor deemed important by the breeder. Rodriguez-Garay and Barrow (1988) at New Mexico State University discovered that one could select pollen grains carrying heat tolerance alleles by heating the pollen to 35 ˚C for 15 h, thus assuring progeny from such crosses would carry the desired gene.

Public breeders have dramatically improved yields in pima cotton by increasing heat tolerance (Kittock et al. 1988). One source of heat tolerance was determined to be higher stomatal conductance (Lu et at. 1998) which is a heritable trait (Percy et al. 1996). There appears to be genetic variability for stomatal conductance (Radin et al. 1994) thus continued improvement for lint yield via greater heat tolerance is possible (Percy et al. 1996).

Salt tolerance is an inherited trait and pima breeders have been successful in increasing germination salt tolerance (Turcotte et al. 1988). Where cotton is routinely irrigated, salt tolerance is needed. In addition to salt tolerance, ozone and pollutant tolerance are needed in California. Very little research is being conducted by breeders to solve these abiotic stresses.

Production

Earlier crop maturity was identified as a critical research need in the area of production in the 1970's. This was addressed by Robert Bridge at Stoneville, Mississippi with his release of 'DES 24' and 'DES 56' (Bridge and Chism, 1978 a,b). DES 24 and DES 56 matured 10 days earlier then 'Deltapine 16' which was the most popular cultivar in the USA in 1970. DES 56 was used as a parent of 'Deltapine 20' and 'Deltapine 50', both early maturing, high yielding, popular cultivars. These latter two cultivars have been used as parents in other commercial cultivars. Deltapine 50 occupied 10% of the hectarage in the USA in 1995. 'Deltapine 51', a reselection of Deltapine 50, has essentially taken over many of the production areas of Deltapine 50 except for south Texas. By 1995, more than half (13 of 24) of the most popular cultivars had an average of 25% of their genes from the early-maturing DES 56 cultivar (Van Esbroeck et al. 1998), indicating a willingness by breeders to release early maturing cultivars but a warning sign of possible genetic uniformity. Earliness continued to be a high breeding priority in 1979, and Meredith (1980) predicted a large number of early-maturing cultivars would be forthcoming.

Another early cultivar in the 1990s was 'Stoneville 132' which was a selection out of MC-T8-27-8c, a line developed by the public breeders at Mississippi State University (Bourland and Bridge 1988). MC T8-27 matured slightly earlier than DES 422 which itself was a result of a cross between a sister line of DES 56 and 'Deltapine 55'.

Many workers recognize that there are genotypic differences for ease of defoliation, but it is a trait that is not examined by breeders to a large extent until commercial production.

Although increased yielding ability seems to be addressed by higher-yielding private cultivars, the public sector contributes much needed genetic variability for future gains in lint yield. In-house private germplasm was the number one source of parental material that resulted in successful cultivars until 1985 (Van Esbroeck et al. 1998). A doubling of publicly developed germplasm occurred in the pedigrees of successful cultivars between 1975 and 1990. Successful cultivars were defined as those occuppying more than 1% of the crop production area.

A recent survey of private breeders (Bowman unpublished) revealed that 15% of their parental material is public germplasm, 28% is commercial cultivars, and 56% inhouse material. Thus it appears that the use of public germplasm may not have been increasing from the 1970s to the 1980s and 1990s as suggested by Van Esbroeck et al. (1998) but that the use of public germplasm may have resulted in a higher success rate of producing grower accepted cultivars.

Improved yields can come from improved resistance to nematodes, diseases, insects, better production practices, and adaptation. Average genetic gain for yield has been estimated at 7.0 to 10.4 kg ha^{-1} yr^{-1} (Meredith and Bridge 1984). However, the trend has been for lower genetic gains in the recent past and genetic gain has virtually plateaued (1.4 kg ha^{-1} yr^{-1}) in the last decade in the Midsouth (Meredith et al. 1997). Emphasis on fiber quality and the apparent lack of genetic diversity may have contributed to the slow down in yield gain (Meredith et al. 1997). With the advent of genetically modified organisms, and the rush to release them via the backcross method, genetic gain for yield may remain stagnant for the short term. In a recent breeders survey (Bowman unpublished), only one public breeder spent any time (5%) developing transgenic genotypes or genetically modified organisms while private breeders spend an average of 15% of their time in this endeavor. Yield gains from other than insect and herbicide resistance are not likely to be effected by bioengineering in the foreseeable future.

At the 1992 workshop, David Guthrie and Tom Burch expressed a need for cultivars adapted to narrow-row production systems (e.g. 76 cm interrow spacing) (Miller, 1992). Today that concept could be extended to ultra narrow rows of 19 cm. Guthrie and Burch also expressed a need for shorter, earlier maturing cultivars with short fruiting branches, altered leaf shape, and earlier, more rapid fruiting. Breeding for narrow row production is not a high priority for private breeders and has not been for public breeders. It has been assumed that cultivars adapted to wide rows also would be adapted to narrow rows, but research by Kerby et al. (1990) revealed a need for a specific plant type for narrow row production.

Seed

Resistance is needed to field deterioration of cotton seed. Oil mills would like to see reduced gossypol and tannin content in the seed and reduced levels of aflatoxin. These issues will only be addressed by the public breeders and geneticists unless there is a sufficient financial reward to the private sector. Research by the USDA-ARS at Texas A&M involves the transfer of a gossypol-free seed to upland cotton from an Australian diploid species (Altman et al. 1987). Research has shown genetic differences for aflatoxin contamination in cotton seed (Sun et al. 1978). Insect damage to bolls provide an entrance to the *Aspergillus flavius* L. fungus which then forms the metabolite, aflatoxin. Breeding for insect resistance, primarily to the pink boll worm, would reduce aflatoxin levels in the harvested seed. Most success in resistance to the pink bollworm [*Pectinophora gossypielaa* (Saunders)] has been through the incorporation of the Bt gene by the private sector.

There is a need for cotton seed with enhanced emergence force, i.e., seedlings that can break through soil crust thus resulting in better stands. Once emerged, cotton seedlings need to have faster growth. Research in this area will only likely come from the public sector. Luther Bird from Texas A&M selected for slow germination, seed coat resistance to mold and bacterial blight resistance and at the same time indirectly selected for resistance to seedling diseases (Bird 1982). Fred Bourland, Univ. of Arkansas, examined various methods of testing seed quality and screening genotypes for improved seedling vigor (Bourland et al. 1988). Otherwise little research is being conducted in the breeding arena to improve seedling vigor. Improved lint yields typically result in smaller seed size which in turn results in lower seedling vigor. This was revealed by a study where improvement in lint yields in the modern cultivars compared with obsolete cultivars showed a corresponding reduction in seed size (Bridge and Meredith 1983).

Although this has not been an all exclusive list of breeding and genetics research needs, and certainly new needs will arise, it points to the impact that public breeding programs have had on the cotton industry. This is not to say that private breeding efforts have been relegated to the finished product, that is, the commercial cultivar. In fact, the source of smooth-leaf alleles that are used widely in the breeding arena comes from the breeding program at Delta and Pine Land Company. Private breeders also have been successful in developing cultivars that are widely adapted and highly stable, e.g. Deltapine 16, Stoneville 213, Stoneville 825, Deltapine 20, Deltapine 50, Deltapine 51, Deltapine 90, and Stoneville 474. Research should be continued in many of these areas.

Table 3. USDA-ARS Cotton breeding/genetics positions in 1998.

Location	Individual	FTE	Description
Maricopa, Arizona	Percy	1.0	*G. barbadense* enhancement
College Station, Texas	Percival	1.0	Germplasm collection/maintenance
	Kohel	1.0	Basic genetics
Stoneville, Mississippi	Meredith	0.8	*G. hirsutum* enhancement
	Rayburn	1.0	National variety testing
	Ulloa	1.0	Basic genetics
	Kloth	1.0	Basic genetics
Mississippi State, MS	Jenkins	1.0	Host plant resistance
	McCarty	1.0	Race stock conversion
	Saha	1.0	Basic genetics
Florence, South Carolina	May	1.0	*G. hirsutum* enhancement
		10.8	

Size of breeding programs

Public efforts into cotton breeding and genetics research have declined since 1974. USDA-ARS full-time equivalents (FTE) went from 20.5 in 1974 to 17.2 in 1992 to 10.8 in 1998 (Table 3). Of the 10.8 in 1998, one FTE was involved in germplasm collection and maintenance while another was involved in the national variety testing program. Although both are highly critical positions relative to germplasm enhancement, the bulk of the ARS positions are assigned to genetic research (4.0), which are not directly involved in germplasm enhancement. The exceptions are the Jack McCarty position (race stock conversion) at Mississippi State, the Lloyd May position at Florence, SC, and the Richard Percy position at Maricopa, AZ. Bill Meredith at Stoneville, MS, has released improved germplasm as well as conducted genetic research.

Through the years, ARS breeding/genetic positions have been lost at Mississippi, North and South Carolina, Arizona, Texas, New Mexico, and California.

The breeding effort at the state level has been nearly cut in half since 1974. That year there were 16.5 FTE positions assigned to cotton breeding at the agricultural experiment stations. In 1992 that number dwindled to 11.5, with 1998 numbers at 9.34 FTEs (Table 2). All state breeders are involved in germplasm enhancement to some degree. Positions have been lost through the years at Arizona, California, Georgia, Louisiana, Missouri, New Mexico, North Carolina, and Oklahoma.

Many of the breeders (75%) at state agricultural experiment stations and a few ARS scientists must devote a portion of their time to state variety testing. Examples include Wayne Smith at Texas A&M, College Station; John Creech at Stoneville, MS; Ted Wallace at Mississippi State, MS; Lloyd May (USDA-ARS) at Florence, SC; Shelby Baker at Tifton, GA; Fred Bourland at Univ. of Arkansas; John Gannaway at Texas A&M, Lubbock; Hal Moser at Univ. of Arizona; and Daryl Bowman at NC State.

In 1970, 12% of the total effort in breeding all crops was devoted to cultivar evaluation (Hodgson 1971). It was thought by the author in 1970 that this area may need to be de-emphasized in lieu of more pressing needs in the future. It turns out that this activity (cultivar evaluation) is just as critical now as it was in 1970; the advent of genetically modified organisms and other new products on the market necessitates their public testing prior to actual commercialization.

In addition to reduction in positions assigned to cotton breeding and genetics, support for the remaining positions has dwindled. The ARS spent more than $4 million (1992 dollars) in 1970 for this endeavor. This figure has dropped to $3.8 million in 1992. Of this figure, only a small portion is actually involved in germplasm enhancement. State support has followed the same pattern ($4.0 million in 1970 to $3.25 million in 1998). In 1992 the cotton breeding project in North Carolina received 28% of the funds it received in 1970.

Outside of the Plains of North Texas, private breeding efforts in 1974 was confined to McNair Seed Co., Laurinburg, NC, one breeder; Coker Pedigreed Seed Co., Hartsville, SC, one breeder; Stoneville Pedigreed Seed Co., Stoneville, MS, one breeder; and Deltapine Seed Co., Scott, MS, one breeder.

In 1999, private efforts expanded to include the following: AgrEvo, Mississippi, two; AgriPro, Arizona, one; CPCSD, California, one; Deltapine, one each in South Carolina, Mississippi, Arizona, and Texas; O & A, Arizona, one; Paymaster, one in Texas and two in Arkansas; Phytogen/Mycogen, two in California and one each in Mississippi and Georgia; Seed Source, Mississippi, one; Stoneville, one each in Georgia, Mississippi, and Texas; Sure Grow, one each in Mississippi and Arizona; Terra, Louisiana, one; and UAP, Texas, one.

Also Jack Jones is an independent breeder in Louisiana. Again, this list does not include all of the private breeders in the High Plains and Rolling Plains of Texas and does not include the international efforts of companies like AgroEvo, Deltapine, Phytogen, and Stoneville. This amounts to a 625% increase in private breeding efforts in 25 yr.

The commercial breeders in California filled the void left when the laws were changed that allowed competition for that market and the state effort was terminated. But this would account for only three of the 25 breeders. However, this increase in private breeding efforts will not likely fill the void left by a smaller number of public breeders.

The total number of cotton breeders (public and private) has actually increased from nearly 38 in 1974 to 45 in 1999. This would appear to be beneficial in contributing to genetic diversity if free exchange of germplasm was practiced, but there are signs that the exchange of germplasm will not be free in the near future. Rather, it will be very restrictive.

Plant breeding training will continue to be conducted by the public sector. Private seed companies are finding it more and more difficult to locate individuals trained in cotton breeding. Training of students in cotton breeding has ceased at Georgia and Oklahoma. Those of us involved in graduate student training must find funds to support the students; the private sector could aid in the training of graduate students by providing student training grants to public breeders.

The National Cotton Council of America has recognized this need and has provided matching funds for two breeding assistantships. Several of the terminated public applied breeding programs have been converted to biotechnology positions. Thus the focus has changed and students coming through those programs are not applied plant breeders.

CONCLUSIONS

Public breeding programs have been instrumental in creating a pool of genetic material for cultivar development, addressing many of the needs for viable cotton production, and training students. Thus, there is a continued need for public cotton breeders. Some of the needs mentioned in the 1992 USDA meeting are being addressed superficially or not at all by breeders. Few of the needs are being addressed by the private sector and must be addressed by public breeders. Private industry has made a large impact in the area of bioengineering to solve such problems as insect and weed management.

The perception that private breeders are devoting the major portion of their time developing genetically modified organisms is simply not true. The lack of effort in this area may not be contributing to the yield plateau, though, given the increase in numbers of private breeders and the small percentage of their time actually devoted to developing genetically modified organisms.

There seems to be a negative correlation between public breeding efforts and yield gains, although nobody has established a cause and effect relationship in this regard. The steady decline in full-time equivalent public positions and in public funding does not bode well for the ability of public cotton breeders to adequately address current and future needs.

It is imperative that current public positions be retained and funded. The private breeding sector could assist in the training of cotton breeders by funding assistantships and collaborating with public breeders by providing additional testing locations (environments) for graduate student research. This recognizes the fact that most public programs have a limited number of test sites to conduct research. There has been a precedence for this since collaborative work between private and public institutions has been ongoing in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.].

The dramatic increase in the private breeding sector should result in increased genetic diversity in the field, i.e. increased competition should be conducive to a situation where more than a few cultivars dominate cotton production. This last statement was based on the assumption that the latest acquisitions of small seed companies by larger seed companies would not quench competition within their organizations. Also it is assumed that private seed companies would not exclusively sell genetically modified organisms.

New genetic diversity will not likely come from the private sector since the bulk of their parental material is inhouse germplasm and commercial cultivars. This is not to say that no new genetic diversity will come from the private sector, e.g. Deltapine 90 is a result of a wide cross of public germplasm. The public breeding sector must continue to supply new germplasm as a source of parental material for the private breeding programs.

ACKNOWLEDGEMENTS

The author expresses deep appreciation for the helpful suggestions of Richard G. Percy, Alternate Technical Editor.

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