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BREEDING AND GENETICS

History, Changes, Impacts, and Perspectives of the National Cotton Variety Test (NCVT): Sixty Years of the Program

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ABSTRACT

The National Cotton Variety Test (NCVT) is a USDA-ARS national program to evaluate cotton varieties/lines developed by major U.S. cotton breeding programs for lint yield, fiber quality, and seed quality in annual trials across the U.S. Cotton Belt. This year is the 60th anniversary of the program, and this review article provides the background, leadership history, original objectives and their changes, and a summary of the impacts in cotton production and accomplishments of the program in cotton research. The NCVT history reflects the efforts of U.S. cotton breeders to improve cotton varieties by addressing environmental influences in cotton production and increasing competition in the global market of raw cotton fibers. The scientific accomplishments reviewed in this article can be used as references and guidelines for future cotton breeding.

In the U.S., cotton breeders are facing challenges due to dramatic changes in the U.S. cotton (*Gossypium hirsutum* L.) industry and increasing environmental influences on cotton production. The rise in dominance of transgenic cotton in U.S. cotton production since the late 1990s is one of the major changes due to innovative new technologies in modern agriculture. Although the impacts of transgenic crops on agricultural environments are controversial, the impact of transgenic cotton on crop diversity appears minimized due to an increasing number of transgenic cultivars in production and recurrent parents used in breeding (Bowman et al., 2003). Another major change is the transition of the U.S. cotton industry from a domestic cotton raw-fiber consumer to a major cotton fiber exporter since early in this century. This transition has increased demand for high fiber quality in U.S. cotton because it must compete in the international market. Environmental issues, such as increasing occurrences of drought, flooding, storms, and extreme temperatures, as well as disease and pests, are creating challenges to crop breeders. In cotton production, climate changes in temperature, wind, humidity, and rainfall have impacts on lint yield and fiber quality (Bange et al., 2004; Dodds, 2011; Jans et al., 2020; Pettigrew, 2008; Sawan, 2017). The missions of USDA-ARS agencies have been updated for dealing with these challenges by pursuing the main objectives of making U.S. cotton more competitive in global markets and more profitable for cotton growers. The National Cotton Variety Test (NCVT) program has gone through a series of changes, especially in recent history, in response to these challenges. A review of the history and impacts of the NCVT program on U.S. cotton production will help track how changes in the program history reflect the efforts of U.S. cotton breeders in dealing with the new challenges and identify major accomplishments and perspectives of the program that can be used as guidelines for different regional cotton breeding programs.

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HISTORY OF THE PROGRAM LEADERSHIP

A planning meeting was held in 1958 in Houston, TX to discuss a potential national program to conduct tests that would evaluate cotton varieties and experimental lines for yield and fiber quality across the U.S. Cotton Belt. An outcome of that discussion was the first NCVT meeting, which was held in 1959, and the first NCVT test conducted in 1960. USDA-ARS scientist Charles Lewis became the first chair and coordinator of the NCVT program in 1959 and continued to direct the program until 1979 (Suszkiw, 2010). After Charles Lewis, another USDA-ARS scientist, William Meredith, served as the program chair and coordinator from 1980 to 2010. In 2011, the program changed to a joint-management format whereby a cotton breeder representing State Agricultural Experiment Stations (SAES) serves as the chair and a scientist representing the USDA-ARS agency serves as the coordinator. The responsibility of the USDA-ARS agency remains in coordinating seed distribution, data collection, fiber and seed quality measurements, data archival, as well as producing annual reports. From 2011 to present, the program has been chaired initially by John Gannaway and subsequently Fred Bourland representing SAES and coordinated by Lawrence Young and then Linghe Zeng representing the USDA-ARS (Table 1).

OBJECTIVES OF THE PROGRAM AND THEIR CHANGES IN HISTORY

The NCVT program objectives have undergone a series of changes over time. The original objectives were set up to (1) identify a small number of cotton lines that represented regional cotton production in yield and planting acreages that would serve as "national standards" in annual tests; (2) partition the U.S. Cotton Belt into six regions: East, Delta, Central, Plains, West, and San Joaquin to conduct regional tests; and (3) clarify the responsibility of USDA-ARS to measure fiber quality traits, prepare annual reports, and archive yield and fiber quality data from all regional tests. In 1963, Pima (*G. barbadense* L.) tests were added and conducted in Texas, New Mexico, Arizona, and California. In 1964, Regional High Quality (RHQ) tests were established to conduct tests across states from Carolinas to East Texas. In 2005, the RHQ tests were extended to Las Cruces, NM. The RHQ was established to encourage genetic improvement of fiber quality and promote exchange and utilization of exotic germplasm. In 1977, seed quality traits of oil content, nitrogen content, and free gossypol were added to the tests. In 1980, High Volume Instrument (HVI) measured fiber properties were added and in 2012, Advanced Fiber Information System (AFIS) measured fiber properties were added to the list of fiber quality traits.

OVERALL IMPACT OF THE NCVT PROGRAM IN U.S. COTTON PRODUCTION

One of the NCVT's major functions has been to serve as a uniform evaluation platform for the major private and public cotton breeding programs in U.S. This platform is an unbiased stage where different breeding programs can compare their products with others. During 1960 to 2010, NCVT tested 1,300 lines including germplasm accessions, strains, and cultivars (Suszkiw, 2010). From 2011 to 2019, NCVT tested 419 lines including 308 transgenic lines from private industry and 111 conventional breeding lines from public breeding programs. As a consequence of the entry selection criteria, the lines tested in the NCVT represent a majority of the planted acreage in the U.S. in recent years. From 2010 to 2019, the lines tested either as national standards or regional standards in the NCVT were planted on 44 to 67% of Upland cotton acres in the U.S. by growth area (Fig. 1). There is no doubt that the NCVT has had a significant impact in U.S. cotton production and that the program will continue to improve its roles and contributions to cotton production.

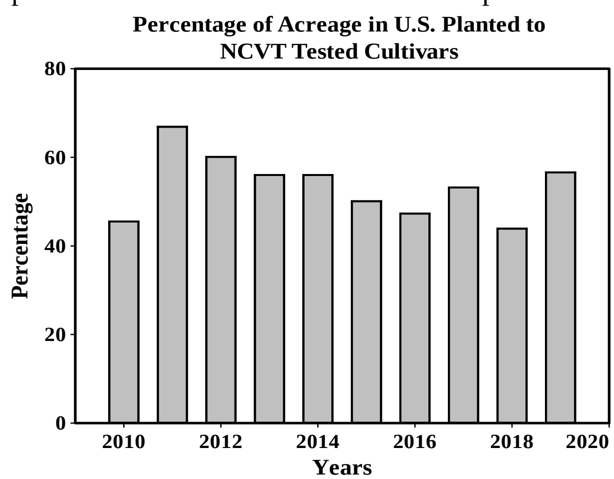

Figure 1. Percentage acreage in U.S. of Upland cotton cultivars tested as national or regional standards in NCVT. The cultivars tested in NCVT between 2010 and 2019 were calculated for their planting acreage from the next years Cotton Varieties Planted published by U.S. Agriculture Marketing Service (2010-2019).

Table 1. History of the NCVT program leadership

Years	Cotton scientists	Organization	Leadership Role
1959-1979	Charles Lewis	USDA-ARS	Chair and Coordinator
1980-2010	William Meredith	USDA-ARS	Chair and Coordinator
2011-2012	John Gannaway	Texas A&M University	Chair
2011-2015	Lawrence Young	USDA-ARS	Coordinator
2013-current	Fred Bourland	University of Arkansas	Chair
2016-current	Linghe Zeng	USDA-ARS	Coordinator

SUMMARY OF MAJOR SCIENTIFIC IMPACTS OF THE PROGRAM IN EARLY HISTORY

The scientific impacts from the 60 years since the program's establishment in 1960 are tremendous and can be summarized into two major parts: the 30 years from 1960 to late 1980s and the 30 years since the 1990s. The major scientific impacts of the program in the first 30 years can be summarized as the promotion of using high fiber quality germplasm in cotton cultivar development and the early research using NCVT historical data on investigating genotype-by-environmental interactions.

One of the early problems identified by cotton breeders was the narrow genetic base in cotton germplasm. Because the boll weevil (*Anthonomus grandis* Boheman) problem prevailed in cotton production, high yield and early maturity were long-term breeding objectives to escape damage by the pest, which resulted in a limited number of parents in cultivar pedigrees before the 1990s (Van Esbroeck and Bowman, 1998). The Pee Dee program of USDA-ARS at the Florence, SC station was initiated to broaden the genetic base of yield and fiber quality through introgression of genes from *G. arboreum* L. and *G. thurberi* Tod. into Upland cotton (Culp and Harrell, 1974). Because selection for high fiber quality was a secondary objective in most commercially oriented cultivar development programs at that time, the Pee Dee germplasm was barely used in breeding. The use of Pee Dee germplasm for high fiber quality was promoted by RHQ tests in 1960s. Nearly half of RHQ entries in the tests of 1964 to 1968 were derivatives of "triple hybrids" involving *G. arboreum* and *G. thurberii*. Eight cultivars were developed from these germplasm lines and planted to 12% of the U.S. cotton acreage in 1968 (Kerr, 1969). 'DES 56' was developed from a cross of 'Stoneville 213/PD 2164'. 'DP 2164' is a sister line from one of the eight cultivars described above. DES 56 was tested through the NCVT program in the 1970s and released in 1978 (Bridge and Chism, 1978). This cultivar has been involved in the pedigrees of many cultivars planted in the East, Delta, and Central regions (Suszkiw, 2010).

Other major impacts of the NCVT program can be summarized as the early efforts of using NCVT trial data in analysis of genotype × environment (GE) interactions. Abou-El-Fittouh et al. (1969a, b) were the first to use NCVT trial data to group environments in the Cotton Belt to reduce GE interactions. The trial data of four national standards planted at 39 testing locations during 1960 and 1962 were analyzed for yield by cluster analysis. Based on distance coefficients, the 39 testing locations in the Belt were grouped into six regions and a Western location.

The research of Meredith (1986) is worthy of mention for its pioneering study of the causes for GE interactions associated with differential fiber quality of cotton cultivars across regions. Historical trial data of four national standards in NCVT tests from 1961 to 1984 were analyzed for their fiber quality across different regions in Cotton Belt (Table 2). The fiber quality traits of length and yarn strength were higher in Delta than that in San Joaquin, whereas the reverse was observed for whiteness. Meredith attributed these differences to the contrasting environments between the two regions (desert and irrigated environments in San Joaquin and humid environments in Delta).

Table 2. Fiber quality of four National Standards in NCVT tests (1961-1984) (Meredith, 1986)

Region	Rd	+b	Length (mm)	Micronaire	Yarn strength
East	7.4	8.7	28.5	4.50	131
Central	7.2	8.3	27.9	4.61	136
Delta	7.4	8.2	29.0	4.57	136
Plains	7.2	8.4	27.9	4.43	133
San Joaquin	7.5	8.0	28.5	4.02	131
West	7.5	8.2	28.7	4.42	130

SUMMARY OF MAJOR SCIENTIFIC IMPACTS OF THE PROGRAM SINCE 1990

Research on GE Effects of Yield, Fiber Quality, and Seed Quality. Meredith et al. (2012) analyzed RHQ data from 2001 to 2007. When variance components for lint yield were expressed as a percentage of the total variance, environment (E), genotype (G), and GE were 84, 7.4, and 8.4, respectively; whereas for fiber properties, the components ranged 26 to 74% (E), 16 to 52% (G), 9 to 23% (GE), respectively. Campbell and Jones (2005) analyzed NCVT data from 2000 to 2003 and found variance components of E, G, and GE for lint yield were 90, 2, and 8, respectively, as a percentage of the total variance; for fiber properties, the components ranged from 14 to 81 (E), 10 to 63 (G), 8 to 24 (GE), respectively. Zeng et al. (2015) analyzed variance components for seed quality traits in RHQ tests from 1996 through 2013 in six testing cycles. The G × Location (GL) effects were highly significant for oil content, N content, and free gossypol contents. However, the proportions of G to the total variance for oil, N, and free gossypol ranged from 20 to 57%, 9 to 27%, and 5 to 44%, respectively. In summary, highly significant GE in recent history indicates that multiple location tests for yield, fiber quality, and seed quality traits are still required. The GE effect was larger than G for lint yield, whereas G effect was larger than GE for fiber properties and seed quality traits. Therefore, fewer testing locations would be required for fiber quality and seed quality traits than yield in the NCVT tests.

Environmental factors contributing to GE effects on yield were analyzed using RHQ tests of 2003 to 2009 (Zeng et al., 2014). The daily minimum temperature was detected as significantly contributing to GE effects with correlation between it and yield being r =-0.41 and r = -0.30, at early and late growing season stages, respectively. It was further identified that the testing locations Belle Mina, AL; Las Cruces, NM; and Lubbock, TX had the lowest minimum temperature during the early and late growing season stages. These results suggested that greater yield stability might be achieved through genetic improvement in Upland cotton cultivars for tolerance to low temperature during seedling growth and boll development/boll opening stages at these locations.

Research efforts have attempted to determine desirable testing locations and if fewer testing locations could be used in multiple-locations tests. The most straight-forward approach would be to identify an optimum environment. Unfortunately, this approach is not feasible due to unpredictable environmental conditions across testing years. Grouping of testing locations in the Cotton Belt for similar environments could be a more feasible approach. Geng et al. (1990) grouped testing locations of NCVT based on their discriminating ability and repeatability of potential productivity. Thirty-two locations in NCVT tests were grouped into four clusters that were different from geographic zoning. However, no conclusions were made on mega-environments in the Cotton Belt. Myers (2002) analyzed 28 testing locations for lint yield of 101 varieties in NCVT tests from 1997 to 2000 and determined that testing environments fell into three groups based on the discriminating varieties and further analysis based on location correlations identified five environmental clusters, a reduction from the current seven regions. Campbell and Jones (2005) assessed GE interactions for yield using an additive main effects and multiplicative interaction model in 12 environments of South Carolina from NCVT Eastern regional tests for 2000 to 2003. The environment of Blackville was identified as different from Florence, Calhoun, and Dillon. Therefore, the Blackville environment and environments and the remaining locations represent two mega-environments in South Carolina for yield test. Zeng et al. (2014) analyzed GE interactions for lint yield at 10 testing locations of the RHQ tests from 2003 to 2009 using GGE biplot (Yan, 2001) and no clear mega-environments were identified. However, locations of Lubbock, TX and Las Cruces, NM were identified as being different from other locations.

Another less commonly applied approach is to determine which testing locations are near "ideal environment" and could be used as representative locations using GGE biplot. Zeng et al. (2019a) analyzed eight locations in RHQ tests of 2011 to 2016 for their distance to an ideal environment as designated by GGE biplot for its discriminating ability and representativeness. By averaging of the distances across testing years, the locations of Stoneville, MS; Keiser, AR; Lubbock, TX; and College Station, TX were identified with smallest distance to the ideal environment based on means of fiber properties, and therefore, these locations were most representative sites for fiber properties in RHQ tests.

Other efforts to determine a desirable number of testing locations in NCVT tests have looked at changes of variances with reducing numbers of testing locations. The main idea of this type of research was to understand how to reduce testing locations while maintaining statistical power of detecting GE interaction effects. RHQ tests of 2005 to 2013 for seed quality traits were analyzed for changes in standard deviations of seed traits mean by omitting one location at a time from the original tests (Zeng et al., 2019b). When two locations were omitted, the standard deviations of seed traits mean increased by 10%, whereas when three locations were omitted, the standard deviations increased by 23 to 25% when compared to zero locations omitted. It was suggested that two to three locations could be reduced in RHQ tests for seed quality traits with loss of statistical power up to 25%. In another study, a simulation analysis was employed to simulate fiber quality data of the RHQ tests of 2011 to 2016 with varying number of testing locations omitted from the original tests (Zeng et al., 2019a). Covariance parameters of G, L, and GL were estimated in simulation. When testing locations were reduced to five, the standard deviations of GL increased from 18 to 37%, whereas further reduction of locations increased the standard deviations from 30 to 217%. Therefore, five locations were determined to be efficient in evaluation tests for fiber quality the Cotton Belt.

Analyzing Yield Changes and Genetic Gain in the U.S. Cotton Breeding History. There are two major approaches to estimate genetic gain in yield and how it changes over years: (1) to regress variety yield of a location to the years of their release and (2) to estimate genetic gains by a comparison of obsolete and modern varieties in the same tests when all varieties could be studied under same environments. Seventeen cultivars released from 1910 through 1979 were analyzed by regression of variety yield to their years of release in two-year tests in 1978 and 1979 (Bridge and Meredith, 1983). Genetic gain was found to be 9.46 kg ha^{-1}year^{-1}. Meredith (2000) analyzed four tests conducted at Stoneville in 1967 to 1968, 1978 to 1979, 1992 to 1993, and 1998 to 1999, respectively. The genetic gains were 10.2, 9.5, 6.1, and 5.3 kgha^{-1}yr^{-1} for releasing years of 1922 to 1968, 1910 to 1978, 1938 to 1993, and 1938 to 1999, respectively. A reduction of genetic gain for yield was observed from early released cultivars to the late 1990s released cultivars. To estimate genetic contributions to yield changes, a modified approach was employed in which common varieties planted in all regions and across testing years were used as a covariant to adjust yield of all varieties in the tests across environments to a common base (Meredith and Bridge, 1984). In the NCVT program, every three years a new testing cycle is established, and three to five cultivars are planted across years in each testing cycle as national standard cultivars, with one of the national standards planted across two testing cycles. These standard cultivars can be used to estimate genetic gain. Campbell et al. (2014) estimated yield genetic gain of cotton cultivars in NCVT tests of 1980 to 2012. In this study, the overlapping national standard cultivars across testing cycles were used to create standardized national standard cultivars and they calculated the deviation of three highest yielding cultivars in each year from the standardized national standard cultivars. The deviations were regressed to the testing years. A genetic gain of 21.6 kgha^{-1}yr^{-1} was identified over testing years 1996 to 2012, which coincided with the adoption of transgenic technology.

Comparison of Transgenic Varieties and Non-Transgenic Varieties. The NCVT provides a unique platform in the U.S. to evaluate cotton experimental lines and cultivars from both private and public breeding programs in a uniform manner and thus allows a comparative study of transgenic and non-transgenic cotton for their agronomic performance and fiber quality. Zeng et al. (2021) compared transgenic and non-transgenic cultivars for yield and fiber quality in RHQ tests from 2002 to 2018. In each year, transgenic cultivars yielded higher than non-transgenic, whereas the reverse was observed for fiber quality between the two types of cotton. Variance components of yield and fiber properties were analyzed in six testing cycles between 2002 and 2018. When proportions of genetic variance components (V_g) to the total variance were compared between the two types of cotton in each testing cycle, the proportion of V_g in the transgenic cotton was smaller than that in the non-transgenic cotton for lint yield and fiber properties of length, strength, uniformity, and micronaire. The results indicate a reduction of genetic variance in transgenic cotton and a possibility that transgenic cotton is less stable under environmental influence for their yield and fiber quality.

MOST RECENT CHANGES OF THE PROGRAM

From the beginning, the NCVT program functioned to coordinate multiple location tests, analyze data, publish annual reports, and archive the information. With increasing challenges from domestic and international markets, the expectations from cotton breeders on the program have changed. Based on a 2017 survey among cotton breeders and researchers organized by the USDA ARS program coordinator, distribution of the preliminary yield data in NCVT and RHQ tests was listed as a top priority. Compared to the lag in reporting in years prior to 2019, preliminary data is now being distributed within just months after harvest to all NCVT participants. The continuation of this annual practice requires an improvement of communications between the program participants and coordinating USDA ARS program staff in the Crop Genetics Research Unit to guarantee the completion of this time-sensitive task before the annual planting.

The most recent change in the program is the effort organized by the current NCVT chair, Fred Bourland of the University of Arkansas, in the selection of the national and regional standards in the tests. Historically, cotton breeders included a small number of locally adapted cultivars/lines as regional standards along with the national standards to evaluate performance in the regional trials. The current approach to selecting the standards reflects the improved adaptation of contemporary varieties to the diverse environments in the U.S. and does away with the planting of regional standards—all standards are now national. At the NCVT committee meeting in Austin, TX in January of 2020, the program decided to increase the national standards to eight and eliminate the regional standards in all NCVT trials. Evaluation of the same eight standards over all NCVT locations is expected to provide a balanced dataset across locations, which should increase the robustness and utility of the data.

Another change made at the 2020 committee meeting in Austin was an establishment of a seed distribution system by USDA-ARS. Inconsistent seed sources could have contributed to increasing errors in multiple-location trials in the past years. Now seeds of all eight national standards were requested by the ARS, stored in a -20 ºC cold room, and distributed to breeders on a three-year cycle. This practice is expected to improve the uniformity in tests across locations. Finally, a noteworthy change was the creation of an easy way to access original replicated trial data. Prior to 2019, NCVT data were maintained and archived in ASCII codes with limited access to outside users. In the past two years, all NCVT archived data have been converted to Excel files and became available to all upon request.

PERSPECTIVES

The original program objectives have been updated several times with the addition of different regional tests and different fiber quality measurements that reflect innovations in modern fiber testing systems. With increasing challenges involving adapting the U.S. crop production systems to rapidly changing environments such as more frequent climate extremes, more severe disease and pest stresses, and to a more competitive global market for cotton raw fibers, further changes to the original objectives are expected in future. Providing preliminary yield data to cotton breeders before planting season as mentioned above has been an important addition to the original objectives and this change fits the mission of ARS national program to make U.S. crop more competitive. To enhance research on environmental influences on cotton production in the U.S. Cotton Belt, the coordinated research activities among scientists at different locations in NCVT program will be further promoted. So far, most research projects on environmental influence in cotton production have been conducted at the phenotype level and the causes of GE interactions are mostly unknown. In the future, the NCVT program should promote collaboration with molecular scientists to use rapidly involving biotechnologies to dissect GE interactions at the genomic, phenomic, and envionomic levels especially for quantitative traits. Finally, an open access model for the NCVT program annual reports to cotton breeders will be considered. To achieve this goal, coordinating with a database such as COTTONGEN or more recent projects such as ARS Partnerships for Data Innovation projects will be needed to achieve and create user-friendly files of annual reports.

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