BREEDING & GENETICS

Relationships of Yield Component Variables to Yield and Fiber Quality Parameters

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ABSTRACT

Indirect selection for cotton yield using yield component variables may provide improved yield, yield stability, and fiber quality. Data from irrigated and non-irrigated tests conducted in 1999 through 2006 at four Arkansas locations were evaluated. Parameters included lint yield (LY), basic yield components of number of seed per area (SPA) and lint index (LI), secondary yield components of seed index (SI), number of fibers per seed (FPS), and fiber density (FDEN), lint percentage (LP), and seed percentage (SP), and fiber quality traits of micronaire (MIC), length (LEN), uniformity index (UI) and strength (STR). Seed index and LP were dropped from further consideration due to collinearity. Locations and genotypes varied in most of the tests for most of the variables. Genotype × location (G×L) was most frequently found for LY and SPA and least frequently found for LEN and UI. Path coefficients from PathSAS were used to identify the direct effects and relationships among variables. Higher instability was found in non-irrigated tests and in tests of more recently developed genotypes. Lint yield was influenced by SPA, but SPA exhibits low heritability. Lint index was influenced by FPS, MIC and LEN with FPS having the strongest influence. Among the fiber quality parameters, MIC and LEN had a negative relationship while UI and STR had strong direct effects on LEN. Fiber density via FPS tended to be related to lower MIC. These data suggest that FDEN could serve as a selection criterion for increased LY without negatively impacting fiber quality traits.

Effective use of yield components may provide an opportunity to improve both the quantity and stability of yield production by upland cotton (*Gossypium hirsutum* L.) without adversely affecting fiber quality. Lint yield of cotton is most simply defined as a function of number of seeds area^{-1} (SPA) multiplied by weight of fiber seed^{-1} (Lewis et al., 2000). Seed per area is the product of multiple yield components including number of plants area^{-1}, bolls plant^{-1}, and seed boll^{-1}. Seed per area and many of its components may be affected by numerous biochemical reactions under quantitative genetic control and by environmental conditions (Bednarz et al., 2006).

Over the last 100 years, cotton breeders have seemingly come full circle in an attempt to identify appropriate cotton yield component selection criteria. Cook (1908) suggested that lint index (grams of fiber 100 seed^{-1}) could serve as an improved selection method over the commonly used lint percentage method. He proposed to select lines based upon the absolute weight of lint seed^{-1} instead of the relationship of lint to seed. Over a period of time, selection for increased lint index resulted in increased lint seed^{-1} accompanied by concurrent increased seed size.

Lint frequency, defined and used by Hodson (1920), measured the weight in grams of fiber of uniform length produced cm^{-2} of seed surface area. This method served to select for improved yield while standardizing seed size. Thurman (1953) refined lint frequency with lint density index, which measured the weight of fibers 100 cm^{-2} seed surface area. The lint density index included all lint on seed, and removed the fiber length uniformity parameter used in determining lint frequency. Lint density index was positively correlated with lint percentage and lint index. Since lint percentage does not require an estimate of seed index or seed surface area, it has been widely used by most cotton breeding programs. Selection based upon lint percentage has led to increased lint yield, but has resulted in smaller seeded cultivars.

Breaux (1954) noted the majority of cotton breeding programs were focusing on fiber quality improvement. Additionally, he observed that high lint density and small- to medium-sized seed offered the best possibility of obtaining high yielding lines. Mechanized harvest equipment provided a more efficient measurement of yield, and allowed breeding programs an op-

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portunity to focus on lint yield improvement by directly measuring lint yield rather than yield components. In addition to harvested yield, multiple combinations of lint and fiber parameters have served as selection criteria. Among these, high lint percentage combined with an increased number of small- to medium-sized seeds has been the most utilized method (Bridge et al. 1971; Culp and Harrell 1975; Harrell and Culp 1976; Miller and Rawlings 1967).

Renewed interest in fiber quality and economic sustainability has led to research designed to develop improved yield components and fiber quality parameters. Results from a multi-state, north Delta study observed a low correlation between lint yield and yield stability (Bourland et al., 2005; McNew et al., 2005). Results of their study also showed a negative correlation between micronaire and stability suggesting early maturing, high micronaire cultivars were more stable in yield performance. A weak positive correlation between number of fibers seed^{-1} (FPS) and fiber weight seed^{-1} as related to yield stability was also observed. Fiber length was negatively correlated with micronaire and FPS. Fiber length may influence other high volume instrument (HVI) fiber measurements including uniformity, strength and elongation (Smith and Coyle, 1997). Considering the number of associated traits, fiber length would be a likely source for yield variability.

Negative relationships between yield and fiber quality traits have long restricted the genetic improvement of cotton. If this were not true, improvement in fiber quality would have accompanied recent improvements of yield. Using data from the United States (U.S.) Regional High Quality Strain Test and Australia, Clement et al. (2012) showed that negative associations still exist between yield and fiber quality. These negative associations were weaker in the Australian data than in the U.S. data.

Lint index (Lewis et al., 2000; Owens and Wallace, 2004) and lint frequency (Bednarz et al., 2006) have been identified as possible selection criterion to improve lint yield and stability. Lint index (LI, weight of fibers 100 seed^{-1}) is a function of seed surface area and selection for increased LI tends to result in larger seeds. May (2004) found number of fibers per seed (FPS) was correlated with lint yield and observed that lines with increased FPS tended to have larger seed size than those with fewer FPS. Large seed (with large cotyledons) may be advantageous under adverse environmental conditions, but may be unfavorable due to the inherent development of thinner seed coats

and lower lint percentages. In contrast, smaller seeds may improve lint percentage values, but have smaller cotyledons which could result in decreased plant stands, lower seedling vigor, and increased ginning problems (seed and/or seed fragments pulled through gin ribs with lint). Minton and Supak (1980) indicated medium-sized seed were optimal.

Yield components may be affected by several production factors. For example, plant density has been correlated with main stem nodes, monopodial branches (Bednarz et al., 2000) and other parameters such as lint percentage, boll size, seed index and micronaire (Bridge et al., 1973).

Yield stability and production sustainability might be enhanced by utilizing selection criteria which include both fiber and seed parameters. Preliminary evaluations of fiber density appear to show promise as a selection criterion. Within the University of Arkansas Cotton Breeding Program, FDEN has been defined as the number of fibers mm^{-1} of seed surface area and estimated by dividing FPS by a derivative of seed index (Groves and Bourland, 2010). The use of FDEN would normalize seed size and decrease emphasis on increased SPA. Based on the energy requirements of seed production, this should allow for increased efficiency of photosynthates and, therefore, increased yield stability (Lewis 2001). By selecting for increased fiber density, Clement et al. (2014) have improved fiber fineness without adversely affecting yield.

The objective of this study was to evaluate the relationships among certain fiber and yield component traits and their relation to yield over a range of cotton genotypes and environments. The goal of studying these relationships was to develop selection strategies that might improve yield and yield stability without adversely affecting fiber quality.

MATERIALS AND METHODS

A total of 128 year × location sites were utilized as the database to evaluate relationships of lint yield, yield components and fiber quality data. Data were collected from four Arkansas locations including the Northeast Research and Extension at Keiser on a Sharkey silty clay (very-fine, smectitic, thermic Chromic Epiaquerts); the Delta Branch Station at Clarkedale on a Dundee silt loam (fine-silty, mixed active thermic Typic Endoaqualf); the Lon Mann Cotton Research Station at Marianna on a Calloway silt loam (fine-silty, mixed, active, thermic Aquic

Fragiudalfs); the Rohwer Research Station at Rohwer on a Herbert silt loam (fine-silty, mixed, thermic Aeric Ochraqualf). Following the 2004 season, the Clarkedale site was terminated and studies were initiated at the Judd Hill Cooperative Research Station near Trumann, which is approximately 44 km northwest of Clarkedale. These two locations share the same soil series, season length and management system. Therefore, these two locations were treated as a single site for these analyses.

Data were extracted from cultivar trials of the Arkansas Cotton Variety Testing Program from 1999 through 2006 (Benson et al., 2001, 2002; Bourland et al., 2000, 2003, 2004, 2005, 2006, 2007). These years were chosen because data from duplicate irrigated and non-irrigated trials were available and the data files included the specific yield component variables. Non-irrigated trials were dropped from this testing program after 2006. Annual cultivar trials included two tests (Main Test and First-year Test) conducted at multiple locations. For each year, cultivars evaluated in the previous year of the Arkansas Variety Test were included in the Main Test. Otherwise, the cultivar was evaluated in the First-year Variety Test. Both Main and First-year Variety Tests were evaluated annually in irrigated tests (V1ir and V2ir) at four locations, and in non-irrigated tests (V1ni and V2ni) at one or two locations. Over these years, the number of genotypes evaluated in V1 tests ranged from 25 to 52 while the number of genotypes in V2 tests ranged from 23 to 65.

Data were also collected from strain tests associated with the University of Arkansas Cotton Breeding Program (Bourland, 2004; 2013). The strain tests (all irrigated) included an Advanced Strain Test (AST) and a New Strain Test (NST) conducted annually from 1999 through 2006 at each of four locations listed above. Genotypes in the NST were selected $F_{4:7}$ lines that were evaluated as Preliminary Strain Tests in the previous year. If a line performed well, it was promoted and evaluated for up to two years in the AST, then was either released or dropped from the program. Each strain test included 18 strains and two check cultivars. Data from the 2001 AST were excluded because the test included only 11 strains and one check cultivar.

Seed for all genotypes in the cultivar tests were submitted by their respective originators. Seed for genotypes in the AST and NST were produced and processed at the Northeast Research and Extension Center (Keiser, AR), so that there were no differences among the genotypes with regard to seed source or processing. For all tests, plots were planted with a constant number of seed (about 13 seed/row m). All entries were planted in two-row plots on 0.96-m centers, and ranged from 12.2 to 15.2m in length. Each test was arranged at each location in a randomized complete block and replicated four times. For each cultivar and strain test, identical entries were evaluated each year at all locations, but entries differed over years.

Although exact inputs varied across locations and years (Benson et al., 2001, 2002; Bourland et al., 2000, 2003, 2004, 2005, 2006, 2007), cultural inputs in each test were based on University of Arkansas Cooperative Extension Service recommendations for cotton production, including COTMAN rules for insecticide use, termination and defoliation. All plots were machine-harvested with two-row cotton pickers modified with load cells for harvesting small plots.

Lint yield and SPA data were collected from four replications in each test. All other variables were determined using data derived from hand-harvested 50-boll samples taken from two replications of each test prior to machine harvest. The samples were bulks of 25 bolls from each row, with samples including all bolls from consecutive plants. The boll samples were ginned on a ten-saw laboratory gin (without lint cleaners) and weights of seed cotton, seed and lint were determined. After ginning, High Volume Instrument (HVI) fiber parameters on each sample were determined by the LSU AgCenter Cotton Fiber Lab (Baton Rouge, LA). In addition, two 50-seed sets of fuzzy seed were counted from each sample and weighed to determine seed index. If weights of the two sets varied more than a preset tolerance limit, additional sets of seed were counted and weighed.

The variables included:

- Lint yield: After converting weight of seed cotton harvested per plot to yield per hectare, lint yield was determined by multiplying seed cotton yield per hectare by lint percentage (averaged by location and entry within each test).
- Primary (or basic) yield component variables (Lewis et al., 2000):
  Seed per area: determined by multiplying seed cotton yield (kg/ha converted to g/ha) times the average seed percentage (the percentage of seed weight to seed cotton weight in ginned sample, averaged by entry and location over replications), then divided by average seed weight (average seed index by entry over replications divided by 100).

Lint index: Weight (g) of lint per 100 seed was determined from boll sample data by dividing lint weight of ginned sample by the number of seed per sample (seed weight of sample divided by average seed weight) then multiplying by 100.

- Secondary yield component variables:
  Lint percentage: the percentage of lint weight to seed cotton weight in each sample.
  Seed percentage: the percentage of seed weight to seed cotton weight.
  Seed index: Weight (g) of 100 fuzzy seed.
  Fibers per seed: was estimated by dividing LI by weight per fiber. Average weight per fiber was estimated as the product of (fiber length × length uniformity × (micronaire / 1.0×10^6)).
  Fiber density: is an estimate of the number of fibers per mm^2 of seed surface area and was calculated by dividing FPS by SSA, where SSA was estimated by the regression equation $(SSA = 35.74 + 6.59SI)$ established by Groves and Bourland (2010).

- Fiber quality variables:
  Micronaire: Fiber fineness is estimated by the relative degree of restriction to air flow caused with a standard weight of fiber.
  Fiber length: The upper half mean length (mm) of a beard of cotton fibers.
  Length uniformity index: The degree of fiber length uniformity in a sample is expressed as ((mean length of fibers / LEN) × 100).
  Strength: the force in grams required to break a bundle of fibers equivalent to 1,000 meters of fiber. Fiber strength is expressed in $kN\ m\ kg^{-1}$.

Each variable (LY, SPA, LI, LP, SP, SI, FPS, FDEN, MIC, LEN, UI and STR) was analyzed as a split plot with location as the whole plot (fixed effect), and genotype (fixed effect) as the subplot on a yearly basis. All data were analyzed using the PROC GLM procedure in SAS Version 9.1 (SAS Institute, Cary, NC).

Data were analyzed as six categories of tests (V1ir, V2ir, AST, NST, V1ni, and V2ni). Multiple regression analysis was used to detect collinearity between independent variables. Two variables, LP and SI, were excluded because of collinearity with other variables. Once these collinear variables were excluded, a path diagram was established for the other ten variables, and path coefficient analysis was conducted with PATH-SAS (Cramer et al., 1999). Path analysis uses multiple regression coefficients to establish probable paths and relative contributions of independent variables, particularly those relating to yield components, on lint yield.

RESULTS AND DISCUSSION

Analyses of Variables. Data for the ten variables were collected from 31 irrigated trials associated with the V1ir, V2ir, AST and NST, which were evaluated at four locations within each year. Sixteen non-irrigated tests associated V1ni and V2ni were evaluated over two locations for six years and at one location for two years. Identical entries were included at all locations of each test (V1ir, V2ir, AST, NST, V1ni, and V2ni) each year.

Locations differed for most of the parameters within most years in the irrigated tests (Table 1). Given the variation in climatic and production conditions, location effects were expected, and indicated that the data represent a wide range of environments. Location effects were relatively lower in the non-irrigated tests compared to the irrigated tests (Table 2). These lower effects might be due to fewer non-irrigated test locations (two non-irrigated compared to four irrigated locations) or to greater unexplained variance in non-irrigated tests.

Genotypes differed for almost all of the variables in most of the tests. None of the irrigated tests had more than one year that genotypes did not differ (Table 1). In the non-irrigated tests, four of the variables (LY, SPA, UI, and MIC) lacked variation among genotypes in two of the eight years.

The genotype × location (G×L) interaction for LY was significant in 90% of all irrigated tests (Table 1). For the basic yield component variables, significant G×L's were found in 84% of the tests for SPA, but only 29% of the tests for LI. For the secondary yield component variables, G×L was significant for SP (41% of tests), FDEN (26%), and FPS (16%). Among all variables, G×L's were most rarely found for three fiber quality variables, LEN (13% of tests), STR (13%), and UI (10%). As expected, G×L occurred more frequently for MIC (35% of tests) than any other fiber quality variable. Variables having lower frequency of G×L's might respond favorably to direct selection.

For the non-irrigated tests, G×L was significant in only 33% of tests for LY and for SPA, and did not exceed 42% for any of the variables in the non-irrigated tests (Table 2). These lower occurrences of G×L's associated with LY and SPA in non-irrigated tests may be associated with fewer number of sites and lower yields in non-irrigated tests. As found in the irrigated tests, the lowest incidence of G×L occurred for the fiber quality variables.

Table 1. Percentage of years that location, genotype and genotype × location interaction effects differed (P>0.10) in irrigated trials of the Main (V1ir) and 1st year Arkansas Cotton Variety Tests (V2ir), Advanced Strain Tests (AST), and New Strain Tests (NST) from 1999 through 2006

Test[z]	Years	Variable[y]									
		LY	SPA	LI	SP	FPS	FDEN	LEN	UI	MIC	STR
	no.	% of years with location differences									
V1ir	8	100	100	100	100	100	100	100	100	100	100
V2ir	8	100	100	100	75	88	100	100	88	100	88
AST	7	100	100	100	86	71	86	100	86	100	100
NST	8	100	100	100	75	100	88	100	88	100	75
		% of years with genotype differences									
V1ir	8	100	88	88	100	88	88	100	88	88	100
V2ir	8	100	100	100	100	100	100	100	100	100	100
AST	7	86	100	100	100	100	100	100	86	100	100
NST	8	100	100	100	100	100	100	100	100	100	100
		% of years with genotype × location differences									
V1ir	8	88	72	25	50	13	38	0	0	38	13
V2ir	8	100	100	13	38	38	38	25	25	63	25
AST	7	71	86	71	71	14	14	29	0	43	14
NST	8	100	75	13	13	0	13	0	13	0	13

[z] V1ir included entries that had been evaluated in the previous year; V2ir included entries not previous evaluated. Irrigated variety and strain tests were conducted at four locations each year.

[y] Variables included lint yield (LY), number of seed per area (SPA), seed percentage (SP), lint index (LI), number of fibers per seed (FPS), fiber density (FDEN), upper-half mean fiber length (LEN), length uniformity index (UI), micronaire (MIC), and strength (STR).

Table 2. Percentage of years that location, genotype and genotype × location interaction effects differed (P>0.10) in non-irrigated trials of the Main (V1ni) and 1st year Arkansas Cotton Variety Tests (V2ni) from 1999 through 2006

Test[Z]	Years	Variable[Y]									
		LY	SPA	LI	SP	FPS	FDEN	LEN	UI	MIC	STR
	no.	% of years that locations differed									
V1ni	6	67	100	67	33	83	83	100	100	50	67
V2ni	6	100	100	50	33	67	83	100	83	67	67
		% of years that entries differed									
V1ni	8	75	75	100	100	100	100	100	88	75	100
V2ni	8	75	100	88	100	100	100	100	75	100	100
		% of years that location × entry differed									
V1ni	6	17	17	50	33	33	33	0	17	17	33
V2ni	6	50	50	17	50	50	50	17	17	0	17

[Z] V1ni included entries that had been evaluated in the previous year; V2ir included entries not previous evaluated. Non-irrigated variety tests were conducted at two locations in 1999-2004, and at one location in 2005 and 2006.

[Y] Variables included lint yield (LY), number of seed per area (SPA), seed percentage (SP), lint index (LI), number of fibers per seed (FPS), fiber density (FDEN), upper-half mean fiber length (LEN), length uniformity index (UI), micronaire (MIC), and strength (STR).

The lowest mean values for LY and SPA were associated with non-irrigated tests, while the greatest mean values were observed in irrigated tests (data not shown). Additionally, a much larger average and range of C.V. were observed for the non-irrigated tests compared to the irrigated tests. The greatest influence of irrigation on fiber quality traits occurred for MIC and LEN (data not shown). Non-irrigated tests had the lowest LEN values and the highest MIC values. These findings support the findings of McNew et al. (2003) and Lewis et al. (2000).

Across the ten yield, yield component, and fiber traits, some general aspects were observed. First, prevalent location effects indicate that the environment strongly influenced the expression of these variables. Secondly, genotype effects for most traits in most tests suggested that genetic variation exists for the traits. Thirdly, significant location and G×L effects were most frequently found associated with LY and SPA in the irrigated tests. The occurrence of G×L effects impedes direct selection for a trait. This demonstrates the need for identification of yield components for improving LY. Fourthly, irrigation appeared to have the greatest influence on LY, SPA, LEN and MIC. These data suggest that irrigation served as a stabilizing environmental factor. Finally, data from these 47 tests (45 with multiple locations) provide a wide range of environments and genetic backgrounds to evaluate the relationships of these ten traits.

Path Analysis and Models. All independent variables were subjected to regression analysis to identify potential collinearity. Collinear variables were identified and removed as independent variables for lint yield based upon degree of collinearity. This process continued until collinearity was alleviated. All remaining significant variables were again subjected to regression analysis to determine the strength of relationships. The fewest number of independent variables involved in the explanation of the greatest amount of variation were included as influential. This process continued for each variable and across all six categories of tests (V1ir, V2ir, AST, NST, V1ni, and V2ni). Analysis for each test revealed similar path models and a standard model was adopted.

Relationships associated with primary yield component traits. Across all six categories of tests, SPA had the greatest direct and total effects on LY. The direct influence of this trait accounted for at least 84% of the contribution to LY in each test (Fig. 1-3). The greatest influence was observed in the non-irrigated tests, V1ni and V2ni with 90 and

91%, respectively (Fig. 3). The greatest total effect was also observed in V1ni and V2ni tests (Table 3), where SPA accounted for 95 and 89%, respectively. Lint index has the second greatest total effect on LY in all tests.
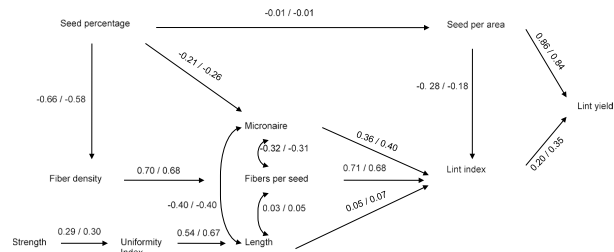

Figure 1. Sequential path model showing interrelationships among yield component and fiber quality variables that contributed to cotton lint yield in Irrigated Main (V1ir) and Irrigated 1st year (V2ir) Cultivar Tests across four Arkansas locations (Keiser, Clarkedale, Marianna and Rohwer in 1999 through 2006 with the Clarkedale location was replaced by Judd Hill in 2005 and 2006). Coefficients for V1ir and V2ir displayed left and right of slashes, respectively.
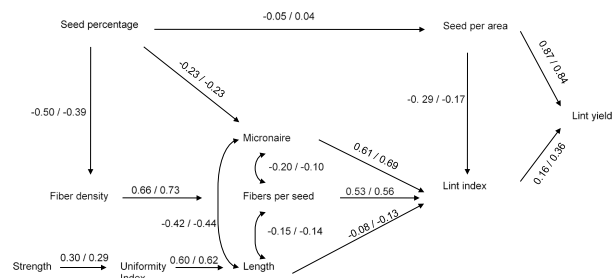

Figure 2. Sequential path model illustrating interrelationships among yield component and fiber quality variables that contributed to cotton lint yield in Advanced Strain Tests (AST) and New Strain Tests (NST) across four Arkansas locations (Keiser, Clarkedale, Marianna and Rohwer in 1999 through 2006 with the Clarkedale location was replaced by Judd Hill in 2005 and 2006). Coefficients for AST and NST displayed left and right of slashes, respectively.
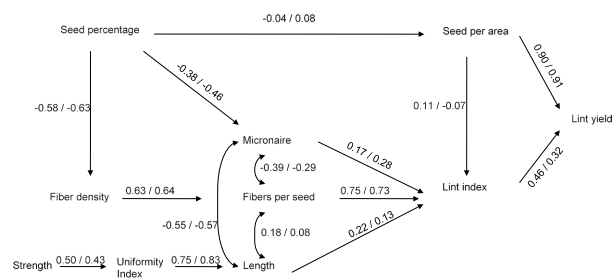

Figure 3. Sequential path model showing interrelationships among yield component and fiber quality variables that contributed to cotton lint yield in Non-irrigated Main Cultivar Tests (V1ni) and Non-irrigated 1st year (V2ni) at Keiser from 1999-2006 and at Marianna from 1999 through 2005. Coefficients for V1ni and V2ni displayed left and right of slashes, respectively.

These data suggest that SPA was the principle factor determining LY and are consistent with those of Culp and Harrel (1975) and Bednarz et al. (2006). Seed per area is a function of the number of plants per area and number of seed per plant. Since plant density was relatively constant in these tests, number of seed per plant determined SPA. Number of seed per plant is related to bolls per plant, which is to some degree determined by plant size. Water stress in non-irrigated trials directly affected plant size and bolls per plant.

Although SPA is an extremely important factor in determining LY, it generally exhibits low heritability and is highly influenced by environmental conditions. The effects of environmental conditions on SPA were demonstrated by the differences between irrigated and non-irrigated tests and by the high frequency of genotype × location interactions associated with SPA.

Seed per area had a negative influence on LI in the irrigated tests (Fig. 1-2), but was less consistent in the non-irrigated tests (Fig. 3). The negative association with LI may have been associated with smaller seed sizes. Across tests with similar plant populations, SPA would likely be increased with smaller seeds and increased number of bolls. However, with soil moisture as a limiting factor, plants produced fewer bolls and seed size increased. These findings are consistent with those of Bednarz et al. (2006) who observed increased lint percentages with reduced seed and boll sizes in modern cultivars.

Lewis et al. (2000) suggested that since more energy is required to produce seed than lint, LI should be a more stable contributor to LY than SPA. However, these data showed less stability than expected. The sum of path coefficients on a given trait should theoretically equal 1.0. Values greater than 1.0 would indicate variability or instability. Lint index exhibited a higher negative influence on LY and the sum of path coefficients was closer to 1.0 in the V1ir and AST than in the other tests (Fig. 1-3). This suggests that lower yield stability was expressed in the non-irrigated tests (Fig. 3) and in the more newly developed lines (V2ir in Fig. 1 and NST in Fig. 2). Higher instability in the non-irrigated tests (V1-ni and V2ni) was certainly expected. Higher instability associated with newly developed lines (V2ir and NST) might be associated with less screening of these lines in Arkansas environments. The V2ir and NST tests should represent a wider range of genetic diversity including relatively more poorly adapted genotypes than the V1ir or AST. Decreased adaptability might explain the observed instability associated with LI in these irrigated trials.

Relationships associated with secondary yield component traits. Among the secondary yield component traits, FPS tended to have stronger total effect on yield than did FDEN and SP (Table 3). The direction of direct influences of secondary yield component traits on the SPA and LI was similar across all six categories of tests (Fig. 1-3). Seed percentage had essentially no influence on SPA with path coefficients ranging from 0.08 in the V2ni (Fig. 3) to -0.05 in AST (Fig 2). Seed percentage is the near-reciprocal of LP, and would affect the weight of seed produced per area but appeared to be independent of SPA. Seed percentage was negatively related to MIC with effects greater in non-irrigated (Fig. 3) than in irrigated tests (Fig. 1-2). Seed percentage also had a negative influence on FDEN across all tests with path coefficients ranging from -0.39 in NST (Fig. 2) to -0.66 in the V1ir (Fig. 1), and with values slightly higher in V1ir, V2ir, and AST compared to the V1ni, V2ni, and NST, respectively.

Table 3. Total effects of basic and secondary yield component traits and fiber quality traits on lint yield in cultivar (V1ir, V1ni, V2ir & V2ni) and strain (S5&6) tests[Z]

Component	V1ir	V2ir	AST	NST	V1ni	V2ni
Seed per area	0.86	0.84	0.87	0.84	0.90	0.91
Lint index	0.20	0.35	0.16	0.36	0.46	0.32
Fibers per seed	0.14	0.24	0.08	0.20	0.34	0.23
Fiber density	0.10	0.16	0.06	0.15	0.22	0.15
Seed percentage	-0.09	-0.14	-0.09	-0.08	-0.19	-0.06
Micronaire	0.07	0.14	0.10	0.25	0.08	0.09
Upper-half mean length	0.01	0.02	-0.01	-0.05	0.10	0.04
Uniformity index	0.01	0.02	-0.01	-0.03	0.08	0.03
Strength	0.00	0.00	0.00	-0.01	0.04	0.01

[Z] University of Arkansas Irrigated Main Cultivar Tests (V1ir), Irrigated 1st year Cultivar Tests (V2ir), Advanced Strain Tests (AST), New Strain Tests (NST), Non-irrigated Main Cultivar Tests (V1ni), and Non-irrigated 1st year Cultivar Tests (V2ni) from 1999 through 2006

Fibers per seed and LI were positively related in every test with lower path coefficients in the strain tests than in the irrigated and non-irrigated cultivar tests (Fig. 1-3). The lower path coefficients may be due to the lower genetic diversity associated with strain tests compared to cultivar tests. The same argument could be made for the indirect influence of FPS on MIC and LEN. The indirect influence of FPS on MIC appeared less negative for strain tests than for cultivar tests. The association of FPS on LEN appeared negative for the strain tests and positive for the cultivar trials.

The influence of FDEN on FPS was consistently strong in all tests (Fig. 1-3). Path coefficients ranged from 0.73 in NST to 0.63 in V1ni test. These values remained consistent despite varied influence from seed percentage on FDEN and the influence of environment or genetic diversity. These data suggest that by normalizing seed surface area, the influence on FPS would become more consistent. Therefore, FDEN could be an improved selection tool for yield stability.

Relationships associated with fiber quality traits. Relative influences of fiber quality traits on yield were similar across tests. Average total effect of MIC on yield (0.12) was stronger than any other fiber quality trait (Table 3). Average absolute values of the total effects of each of the other fiber quality traits were less the 0.04, indicating little total influence on yield.

Direct effects of LEN and MIC were similarly and inversely related to each other in each category of tests (Fig. 1-3). As LEN increased, MIC tended to decline. The coarseness of fibers (MIC) tends to decrease as the synthesized carbohydrates are dispersed into longer fibers. The magnitude of path coefficients associated with the direct effects of MIC and LEN on LI differed among categories of trials, being strongest in the strain tests and weakest in the non-irrigated cultivar tests. Length was weakly related to LI in each test.

These data suggest that MIC had a greater influence in strains developed in the University of Arkansas Cotton Breeding program than in cultivars from other sources (Fig. 1-3). For the strain tests, MIC was the dominant trait associated with LI. However, that was not the case for the cultivar trials, which tested a much wider genetic base. For both irrigated and non-irrigated cultivar tests, FPS was the most influential trait on LI.

Uniformity index was consistently strong and positively related to LEN for each category of test (Fig 1-3). The non-irrigated trials tended to have greater path coefficients (0.75 and 0.83) for UI on LEN than the irrigated trails, which suggest that LEN is more sensitive to UI under moisture stressed conditions. Strength tended to be positively related to UI, with coefficients ranging from 0.29 to 0.50 with highest coefficients in the non-irrigated tests (Fig 3). Again, the influence of the trait was increased under moisture stressed environments.

Summary of Relationships. These findings highlight the effect of genetic and environmental influences on yield components and fiber quality traits. The direction and magnitude of influences of the traits on each other were relatively similar over all of the categories of tests. Compared to the irrigated cultivar and strain tests, non-irrigated cultivar tests exhibited increased influence for five interrelationships (SPA-LY, SP-MIC, LEN-LI, STR-UI, and UI-LEN), two of which involved the primary yield components, LI and SPA (Fig. 1-3).

Genetic influence was evident when comparisons between strain tests and cultivar tests were made. Limited genetic diversity among the genotypes in the strain tests contributed to differences between strain and cultivar tests. Compared to strain tests, irrigated cultivar tests had a decreased MIC-LI relationship and an increased FPS-LI relationship (Fig. 1 and 2). Similar values, but contrasting signs were observed for LEN-LI and FPS-LEN relationships. However, variation in diversity had little influence on relationships involving basic yield components or the relationship between FDEN and FPS.

Relationships associated with FPS and FDEN were largely consistent across varying genetic and environmental influences (Fig. 1-3). The consistent relationship among variables related to basic yield components would infer yield stability is attainable. Consistency for any selection index is difficult when components vary. Unfortunately, FPS is subject to variation in seed size. By normalizing seed size, FDEN should be more stable over time. As a selection index, FDEN could provide a much-needed emphasis on fiber quality while maintaining yield stability.

ACKNOWLEDGEMENT

REFERENCES

Bednarz, C.W., D.C. Bridges, and S.M. Brown. 2000. Analysis of cotton yield stability across population densities. Agron. J. 92:128-135.

Bednarz, C.W., R.L. Nichols, and S.M. Brown. 2006. Plant density modifications of cotton within-boll yield components. Crop Sci. 46:2076-2080.

Benson, N.R., F.M. Bourland, W.C. Robertson, J.M. Hornbeck, and F.E. Groves. 2001. Arkansas cotton variety tests 2000. Arkansas Agric. Exp. Stn. Research Series 481.

Benson, N.R., F.M. Bourland, A.B. McFall, J.M. Hornbeck and F.E. Groves. 2002. Arkansas cotton variety tests 2001. Arkansas Agric. Exp. Stn. Research Series 491.

Bourland, F.M. 2004. Overview of the University of Arkansas cotton breeding program. p. 1093-1097. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 5-9 Jan. Natl. Cotton Counc. Am., Memphis, TN.

Bourland, F.M. 2013. Novel approaches used in the University of Arkansas cotton breeding program. p. 409-418. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 7-10 Jan. Nat'l, Cotton Counc. Am., Memphis, TN.

Bourland. F.M., N.R. Benson, J.M. Hornbeck and C.D. Capps, Jr. 2000. Arkansas cotton variety tests 1999. Arkansas Agric. Exp. Stn. Research Series 473.

Bourland. F.M., B.S. Brown, J.M. Hornbeck, R.C. Doherty and W.C. Robertson. 2005. Arkansas cotton variety tests 2004. Arkansas Agric. Exp. Stn. Research Series 526.

Bourland, F.M., B. S. Brown, J.M. Hornbeck, K. Kaufman, and W.C. Robertson. 2006. Arkansas Cotton Variety Test 2005. Ark. Agric. Exp. Stn. Research Series 538.

Bourland, F.M., B.S. Brown, J.M. Hornbeck, and K. Kaufman. 2007. Arkansas cotton variety test 2006. Arkansas Agric. Exp. Stn. Research Series 547.

Bourland. F.M., S.B. Jackson, J.M. Hornbeck and F.E. Groves. 2004. Arkansas cotton variety tests 2003. Arkansas Agric. Exp. Stn. Research Series 513.

Bourland. F.M., J.T. Johnson, S.B. Jackson, M.W. Duren, J.M. Hornbeck, F.E. Groves, and W.C. Robertson. 2003. Arkansas cotton variety tests 2002. Arkansas Agric. Exp. Stn. Research Series 501.

Bourland, F., R. McNew, B. Phipps, C. Craig, and O. Gwathmey. 2005. Stability of yield and fiber quality in the north Delta: II. Comparison of varieties. p. 987. *In* Proc. Beltwide Cotton Prod. Conf., New Orleans, LA. 47 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

Bridge, R.R., W.R. Meredith, and J.F. Chism. 1971. Comparative performance of obsolete varieties and current varieties of upland cotton. Crop Sci. 11:29–32.

Bridge, R.R., W.R. Meredith, Jr., and J.F. Chism. 1973. Influence of planting method and plant population on cotton (*Gossypium hirsutum* L.). Agron J. 65:104-109.

Breaux, R.D. 1954. A genetic analysis of the major components of yield in American upland cotton. Ph.D. dissertation. Louisiana State University.

Clement, J.D., G.A. Constable, and S.M. Liu. 2014. Increasing cotton seed fibre density as a breeding strategy to improve fibre fineness. Field Crops Res. 160:81-89.

Clement, J.D., G.A. Constable, W.N. Stiller, and S.M. Liu. 2012. Negative associations still exist between yield and fibre quality in cotton breeding programs in Australia and USA. Field Crops Res. 128:1-7.

Cramer, C.S., T.C. Wehner, and S.B. Donaghy. 1999. PATH-SAS: a SAS computer program for path coefficient analysis of quantitative data. J. Hered. 90:260-262.

Cook, O.E. 1908. Danger in judging cotton varieties by lint percentage. U.S.D.A Bur. Plant Ind., Cir. 11.

Culp, T.W., and D.C. Harrell. 1975. Influence of lint percentage, boll size, and seed size on lint yield of upland cotton with high fiber strength. Crop Sci. 15:741–746.

Groves, F.E., and F.M. Bourland. 2010. Estimating seed surface area of cottonseed. J. Cotton Sci. 14:74-81. Available at http://www.cotton.org/journal/2010-14/2/upload/JCS14-74.pdf

Harrell, D.C., and T.W. Culp. 1976. Effects of yield components on lint yield of upland cotton with high fiber strength. Crop Sci. 16:205–208.

Hodson, E.A. 1920. Lint frequency in cotton with a method for determination. p. 3-11. Arkansas Agric. Exp. Stn. Bul. 168.

Lewis, H. 2001. A review of yield and quality trends and components in American upland cotton. p. 1447-1452. *In* Proc. Beltwide Cotton Prod. Conf., Anaheim, CA. 9-13 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

Lewis, H., L. May, and F. Bourland. 2000. Cotton yield components and yield stability. p. 532-537. *In* Proc. Beltwide Cotton Prod. Conf., San Antonio, TX. 4-8 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

May, O.L. 2004. Directional selection for average weight of fibers per seed. p. 1192. *In* Proc. Beltwide Cotton Prod. Conf., San Antonio, TX. 5-9 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

McNew, R., O. Gwathmey, C. Craig, B. Phipps, and F. Bourland. 2005. Stability of yield and fiber quality in the north Delta: I. Evaluation of methods. p. 981-986. *In* Proc. Beltwide Cotton Prod. Conf., New Orleans, LA. 47 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

Miller, P.A., and J.O. Rawlings. 1967. Selection for increased lint yield and correlated responses in upland cotton, *Gossypium hirsutum* L. Crop Sci. 7:637–640.

Minton, E.B., and J.R. Supak. 1980. Effects of seed density on stand, Verticillium wilt, and seed and fiber characters of cotton. Crop Sci. 20:345-347.

Owens, B. and T. Wallace. 2004. Comparison of methods for estimating fibers per seed. p. 114. *In* Proc. Beltwide Cotton Prod. Conf., San Antonio, TX. 5-9 Jan. Nat'l. Cotton Counc. Am., Memphis, TN.

Smith, C.W., and G.G. Coyle. 1997. Association of fiber quality parameters and within-boll yield components in upland cotton. Crop Sci. 37:1775-1779.

Thurman, R.L. 1953. The inheritance of two constituents of yield in American upland cotton. Ph.D. dissertation. Louisiana State University.