The *Journal of Cotton Science 10:17–28 (2006)*
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BREEDING AND GENETICS

Stability Comparisons Between Conventional And Near-isogenic Transgenic Cotton Cultivars

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ABSTRACT

Multi-environment trials are conducted yearly and mean performance is often calculated as an average of cultivar performance over years and locations; however, comparisons of mean performance are not sufficient for cultivar evaluation without an understanding of genotype by environment (GE) interactions. Studies were conducted in 2001 and 2002 to evaluate the performance and stability of fiber yield (boll weight, lint per boll, lint percentage, fuzzy seed index, seed index of acid-delinted seed, and lint weight) and quality characters (micronaire, strength, length, uniformity, and elongation) among conventional cotton cultivars and their backcross-derived transgenic counterparts. A graphic summary of the data using GGE Biplot was used to characterize GE interactions and make comparisons between conventional and transgenic cultivars. Statistical analyses were performed to determine which traits were affected by GE interactions. Traits that were affected by GE interactions were analyzed in GGE Biplot, and differences, based on environment, between conventional and transgenic cultivars were further examined. Plant height, number of nodes, height to node ratio, fuzzy and delinted seed index, and yield had significant GE interactions. Transgenic cultivars were taller, had greater height to node ratios, larger seed, and lower lint percentages. Transgenic cultivars containing the Bollgard gene yielded more than their conventional parents. The cultivar with the lowest GE interaction for lint yield was Stoneville 4691B, which was also the highest yielding cultivar in the study.

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Transgenic cotton (*Gossypium hirsutum* L.) cultivars became commercially available in 1995 with the introduction of bromoxynil (BXN) herbicide-resistant cultivars, BXN 57 and BXN 58 (Collins, 1996). Commercial transgenic cotton cultivars expressing the Cry1Ac insecticidal protein from *Bacillus thuringiensis* spp. *kurstaki*, commonly called *Bt* cotton, were introduced in the USA in 1996 (Hardee and Herzog, 1997). Glyphosate-resistant cotton cultivars (Roundup Ready) became available in the USA in 1997 (Kerby and Voth, 1998). The development of insect- and herbicide-resistant genetically engineered cotton originated as a new approach to control insect pest injury and weeds in production agriculture. In 1995, 82% of U.S. cotton acreage was infested with the tobacco budworm (*Heliothis virescens* L.)/bollworm (*Helicoverpa zea* L.) complex that caused yield reductions of 3.97% (Hardee and Herzog, 1996). In 1996, 77% of U.S. cotton acreage was infested with the tobacco budworm/bollworm complex, and 12% of US cotton acreage was planted in Bt cotton. Yield reductions declined to 2.37% (Hardee and Herzog, 1997). In 2000, 39% of the total U.S. cotton acreage was planted with *Bt* cotton and damage caused by the tobacco budworm/bollworm complex was reduced to 1.43% (Hardee and Burris, 2001).

Transgenic cotton acreage continues to increase in Louisiana and the United States. A survey conducted by the National Agricultural Statistics Service (NASS, 2004) in 2004 showed that 86 and 46% of cotton planted in Louisiana and the United States, respectively, contained transgenes for insect resistance. In Louisiana, stacked-gene acreage (cotton containing 2 transgenic traits) increased (46 to 60%), while *Bt* alone decreased (30 to 26%) during the 2003 and 2004 seasons. Commercialization of transgenic cottons has enabled producers to increase lint yield and reduce the impact of agriculture on the environment by providing an effective strategy to limit the impact of insect and weed pests. This strategy has reduced overall chemical use and promoted safer more effective and environmentally friendly approaches (Benedict and Altman, 2001; Gasser and

Fraley, 1989). In 1994, prior to the introduction of transgenic cultivars, total active ingredient per year of herbicide and insecticide in Louisiana totaled 1.36 and 1.73 million kg, respectively (NASS, 1994). In 2001, after the widespread adoption of transgenic cottons, total active ingredient of herbicide and insecticide applications per year in Louisiana declined to 1.15 and 1.00 million kg, respectively (NASS, 2001). In addition to increased weed and insect control and a lower impact on the environment, the ease of use of transgenic cottons was desirable for a majority of the cotton producers.

The introduction of only a few transgenic technologies has resulted in many transgenic cotton cultivars, all sharing a genetic base that is perceived to be relatively narrow by many breeders (Benedict and Altman, 2001). Multiple herbicide- and insect-resistant cultivars have been commercialized, and there are several transgenic cultivars that are similar to conventional (non-transgenic) high-yielding cultivars. Historically, the recurrent backcross method has been used for introgression of insect resistance traits, such as high terpenoid concentration (Lee, 1978; Lukefahr and Martin, 1966), absence of leaf nectaries (Meyer and Meyer, 1961), leaf pubescence (Lukefahr et al., 1975; Meyer, 1957), and gossypol level (Lukefahr and Houghtaling, 1969; McMichael, 1960), from wild species. In this same manner, transgenic cultivars have been developed by backcrossing a transgene-containing line into a high-yielding conventional cultivar until a transgene-containing line is developed that has regained a large percentage of the conventional recurrent parent (Benedict and Altman, 2001; Bowman, 2000; Robinson and McCall, 2001). Backcross-derived transgenic lines are not completely isogenic to the recurrent parent and the degree of similarity between the two for both mean performance and stability has been questioned. Each transgenic line results from a separate insertion event, is usually stable, and segregates with Mendelian expectations (Kohel et al., 2000; Umbeck et al., 1989), although some evidence exists that not all transgenes behave according to strict Mendelian inheritance (Sachs et al., 1998). Researchers have addressed the long-term viability of the recurrent breeding methods for transgene introgression (Benedict and Altman, 2001; Meredith, 1995; May et al., 1995).

Numerous methods for analyzing cultural differences based on their consistency in response to environments have been developed (Lin and Binns, 1988; Kang and Pham, 1991; Pinthus, 1973). One strategy involves factorial regression of the genotype by environment (GE) matrix against environmental factors, genotypic traits, or their combinations (Baril et al., 1995). A second strategy, the additive main effects and multiplicative model (AMMI), involves correlation or regression analysis that relates the genotypic and environmental scores derived from a principal component analysis of the GE interaction matrix to genotypic and environmental covariates (Zobel et al., 1988). A recently released Windows-based software package, GGE Biplot, can be used to perform analyses similar to the popular AMMI model; however, GGE Biplot removes the effect of the environment (E) and focuses on the genotype (G) and GE interaction components relevant to cultivar evaluation. Stability comparisons between conventional parents and their backcross-derived derivatives can be made with higher precision by removing the noise caused by E.

The objective of this research was to use GGE Biplot to evaluate the performance and stability of fiber yield (boll weight, lint per boll, lint percentage, fuzzy seed index, seed index of acid-delinted seed, and lint weight) and quality characters (micronaire, strength, length, uniformity, and elongation) among conventional cotton cultivars and their backcross-derived transgenic counterparts.

MATERIALS AND METHODS

Seven field studies were conducted at four different locations in Louisiana from 2001 and 2002. Commercially available cotton cultivars were planted at four locations that represent the major cotton-growing areas in Louisiana: the Red River Research Station in Bossier City in 2001 (BC1), the Dean Lee Research Station in Alexandria in 2001 (A1) and 2002 (A2), the Northeast Louisiana Research Station in St. Joseph in 2001 (S1) and 2002 (S2), and the Macon Ridge Research Station in Winnsboro in 2001 (W1) and 2002 (W2). The weather, soil type, geographic location, and management decisions to achieve optimal growth throughout the growing season are different at the four locations.

At each location, a randomized complete block design was used and four-row plots were replicated three times. Rows were 15 m long and spaced 102 cm apart. Cultivars included in this study were Stoneville 474, 4691B, 4793R, 4892BR, and BXN47 (STV; Stoneville Pedigreed Seed Company; Memphis, TN), and Suregrow 501 and 501BR (SG; Delta and Pine

Land Company; Scott, MS). The cultivars chosen for this study comprised the range of commercially-available conventional and transgenic cultivars and included at least one cultivar with glyphosate resistance (Roundup Ready; Monsanto Co.; St. Louis, MO), the gene for the insecticidal protein from *Bacillus thuringiensis* spp. *kurstaki* [Bollgard; Monsanto Co.), bromoxynil resistance (BXN; Bayer Advance; Peoria, IL), or the stacked-gene version containing both Roundup Ready and Bollgard technologies.

Plant height and number of main stem nodes were collected at 60 and 90 days after planting (DAP) and at harvest. Plant height was calculated by averaging the distance from the soil surface to the plant terminal for five arbitrarily selected plants. Main stem nodes between the cotyledonary node and the plant terminal were counted on five arbitrarily selected plants and averaged. Yield components measured included boll weight, lint per boll, lint percentage, fuzzy seed index, seed index of acid-delinted seed, and lint weight. Fiber properties analyzed were fiber micronaire, strength, length, uniformity, and elongation. Yield components were determined from 50 randomly selected bolls taken prior to harvest and cotton fiber quality measurements were obtained using high volume instrumentation (HVI) testing at the Cotton Fiber Testing Laboratory in Baton Rouge, Louisiana.

The Proc Mixed model (release 9.0; SAS Institute; Cary, NC) was used to create an analysis of variance (ANOVA) table to determine the presence or absence of GE interactions. The percentage of total variation attributed to E, G, or GE interaction was calculated using the sums of squares from the ANOVA table. Response variables that had significant G or GE interactions were analyzed in GGE Biplot, and stability and mean performance of conventional and transgenic cultivars were characterized. Similar to the widely accepted AMMI model, GGE Biplot is a recently released Windows-based software package designed to examine G main effects and GE interactions using rank-two matrix multiplication and singular value decomposition (Yan et al., 2000; Yan, 2001; Yan and Hunt, 2001). Using the analyses included in GGE Biplot, comparisons of stability and mean performance between transgenic and conventional cultivars were made for plant height, height to node ratio, lint percentage, delinted seed index, fiber strength and length, and yield.

Biplot interpretation. The mean vs. stability coordination biplot is a two-dimensional graphical representation of a multi-environment data set with principal components PC 1 and PC 2, which are unitless measurements, on the x- and y-axis, respectively. The average environment, defined by the average PC 1 and PC 2 scores across all environments and denoted by a circle, is bisected by a line with a single arrow that passes through the biplot origin, the average-tester axis (ATA). The direction of the arrow indicates higher values for the variable measured. The dotted lines are unit-less measures and exist only to rank or evaluate the cultivars for mean performance. The line containing an arrow at each end, called the stability line, which runs perpendicular to the ATA and also passes through the biplot origin, indicates the stability of any given cultivar. A longer projection from a genotype onto the stability line, or an increasing distance from the ATA, indicates a greater tendency for GE interactions of a genotype, or a greater tendency to be more variable and less stable across environments. In contrast, genotypes with a short projection onto the stability line and clustered on or near the ATA would be highly stable and perform consistently across those environments. GGE Biplot also computes a stability statistic for each cultivar. Cultivars with greater absolute stability statistics are less stable, and cultivars that have lesser absolute values near zero are more stable.

RESULTS

Analysis of variance. The percentages of the total sums of squares accounted for by G, E, and GE interactions were used as an indicator of the total variation attributed to each component (Table 1). Variation due to G or GE interactions is a measure of how cultivars respond across environments or differently in different environments. The environmental component (E) represents how the cultivar means are different between environments. Studies have shown that environment typically accounts for >80% of total variation in yield, which is expected considering the large effect that location has on plant growth and morphology; however, traits with high heritability are typically influenced less by environment (Epinat-Le Signor et al., 2001; Ethridge and Hequet, 2000; Kerby et al., 2000). The total sums of squares ranged from 11 to 92% for environment, from 3 to 55% for genotype, and from 5 to 34% for the interaction. Environment accounted for >70% of the total varia-

Table 1. Degrees of freedom, sums of squares, significance level, and percentages of total variation of genotype (G), environment (E), and genotype by environment (GE) interaction by trait

Trait	ANOVA[x]				Total variation (%)[z]
	Source	Df	SS	Pr>F[y]	
Height	E	5	12731	0.0684	70
	G	9	1957.2	<0.0001*	11
	GE	40	3383.2	<0.0001*	19
Nodes	E	5	1704.9	0.0242*	51
	G	9	1249.3	<0.0001*	37
	GE	40	397.78	0.0288*	12
Height to node ratio	E	5	12.696	<0.0001*	85
	G	9	0.88118	0.0001*	6
	GE	40	1.2825	0.3333	9
Boll weight	E	6	4.3765	0.0203*	36
	G	9	4.6131	0.0186*	38
	GE	26	3.1476	0.9177	26
Lint per boll	E	6	1.7653	0.0015*	46
	G	9	1.3829	<0.0001*	36
	GE	26	0.648	0.3008	17
Lint percentage	E	6	131.87	0.0980	28
	G	9	175.01	0.009*	38
	GE	26	157.23	0.6159	34
Fuzzy seed index	E	6	16.205	0.0002*	26
	G	9	29.101	<0.0001*	47
	GE	26	16.408	0.0005*	27
Delinted seed index	E	6	5.4086	0.0236*	11
	G	9	26.708	<0.0001*	55
	GE	26	16.156	0.0005*	33
Micronaire	E	6	36009	<0.0001*	49
	G	9	24145	<0.0001*	33
	GE	26	13021	0.0659	18
Strength	E	6	166.64	<0.0001*	56
	G	9	78.268	<0.0001*	27
	GE	26	50.471	0.0907	17
UHM	E	6	0.0444	<0.0001*	57
	G	9	0.01501	0.0011*	19
	GE	26	0.01812	0.0802	23
Elongation	E	6	15.78	0.0002*	61
	G	9	6.64	<0.0001*	26
	GE	26	3.4401	0.4246	13
Uniformity	E	6	132.19	<0.0001*	82
	G	9	8.3766	0.1191	5
	GE	26	21.079	0.8430	13
Yield	E	6	117088771	<0.0001*	92
	G	9	3529769	<0.0001*	3
	GE	49	6148915	0.0008*	5

[x] Analysis of variance (ANOVA) was generated using Proc Mixed procedure of SAS.

[y] Trait/source combinations marked with an asterisk are significantly different ($P = 0.05$).

[z] Variation due to each source as a percentage of the total sums of squares of E, G, and GE.

tion for plant height, height to node ratio, and yield, traits that are expected to be heavily influenced by environment. The relatively small contribution of G to the total sums of squares for plant height, height to node ratio, and yield was 11, 6, and 5%, respectively (Table 1). These results generally agree with Kerby et al. (2000), who conducted a study in 1997 and 1998 including nine cultivars at nine locations in North Carolina. They found that contributions by E, G, and GE to the total sums of squares for yield were 94, 1, and 6%, respectively, and for plant height were 97, 1, and 2%, respectively.

In this study, for fiber quality, which has a higher heritability than yield, the percentage of total variation attributed to G was 33, 27, 19, 26, and 5% for micronaire, strength, length, elongation, and uniformity, respectively, indicating that genotype was relatively more important concerning fiber characteristics compared with yield or plant height (Table 1). GE interaction contributions were 8 to 17% greater for micronaire, strength, length, elongation, and uniformity than for yield. It is within the traits exhibiting the greatest G or GE variation that breeders can most efficiently identify and exploit variation and maximize performance for each environment or mega-environment. Traits with the least amount of variation attributed to environment were lint percentage (28%), fuzzy seed index (26%), and delinted seed index (11%). For lint percentage, and fuzzy and delinted seed index, the primary increase in total contribution to sums of squares was attributed to G (38 to 55%), although contributions from GE interactions were also higher (27 to 34%) than in other traits (Table 1). Kerby et al. (2000) found that the contribution of GE for lint percentage, strength, length, and micronaire to the total variation in sums of squares ranged from 9 to 21%, which was higher than the 6 and 2% for yield and plant height, respectively. Traits for which a large amount of the total variation in sums of squares can be attributed to G have great potential for genetic gains through breeding and selection. For traits in which a large amount of variation is attributed to GE, there are two likely possibilities: 1) the existence of a discriminating, or vastly different environment or range of environments, or 2) traits inherent to a group of cultivars that respond positively or negatively to a stimulus in the environments tested. If the environments influencing the relatively high GE can be identified and characterized, a mega-environment, in which cultivar rankings are different from other environments, might be identified and exploited.

GGE Biplot is a graphical analysis tool that produces a two-dimensional biplot based upon G and GE information; therefore, only variables that were significant for G or GE ($P \leq 0.05$) were suitable for analysis in GGE Biplot. All variables were significant for either G or GE (Table 1) which indicates that analysis in GGE Biplot was appropriate. In this study, plant height, height to node ratio, lint percentage, delinted seed index, strength, length, and yield were analyzed.

Plant height. There were significant GE interactions for plant height and number of nodes. Data taken in Bossier City in 2002 was excluded due to extreme stand loss. For plant height, PC 1 and PC 2 accounted for 92% of the total variation in G and GE, which suggests that this biplot is a good approximation of mean performance and stability (Fig. 1). The derivatives of STV 474, STV 4793R, STV 4691B, and STV 4892BR, were the most stable cultivars for plant height, even more so than the conventional parent (Fig. 1). In contrast, the first commercially-available transgenic cultivar, STV BXN47, was the least stable cultivar for plant height. It is possible that the latter transgenic cultivars have been selected more rigorously and over a broader range of environments than the earlier transgenic releases, thereby increasing their stability. Using the biplot to view the genotype main effect, it is apparent, in all cases but one, that the transgenic derivatives were taller than their conventional parents at 60 DAP, regardless of their level of stability (Fig. 1; Table 2).

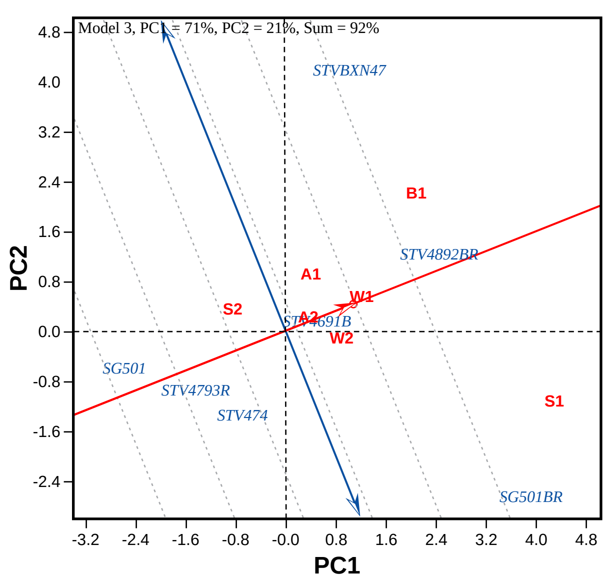

Figure 1. Mean vs. stability coordination biplot for plant height at 60 d after planting. Environment: A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

Table 2. Mean plant height (cm) at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	69	79	97	76	89	81	66	81	-0.404
SG501BR	71	81	102	91	81	89	71	84	1.380
STV4691B	69	84	102	84	99	89	66	84	-0.044
STV474	66	81	99	81	97	84	69	81	0.176
STV4793R	69	81	97	79	94	84	66	81	-0.143
STV4892BR	71	79	107	86	89	91	69	84	0.051
STVBXN47	76	84	109	81	91	91	69	86	-1.030
Mean	71	81	102	81	91	86	69	84	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

Table 3. Mean plant height to node ratio at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	1.95	2.14	2.38	2.41	2.27	2.62	2.03	2.31	0.479
SG501BR	2.17	2.20	2.60	2.66	2.15	2.81	2.26	2.41	0.780
STV4691B	1.92	2.27	2.56	2.41	2.30	2.68	1.85	2.28	-0.697
STV474	1.92	2.14	2.40	2.38	2.24	2.41	1.83	2.19	0.298
STV4793R	2.03	2.08	2.29	2.34	2.23	2.59	1.84	2.20	0.132
STV4892BR	2.11	2.29	2.52	2.41	2.17	2.83	1.90	2.32	-0.829
STVBXN47	2.06	2.11	2.55	2.45	2.15	2.66	1.89	2.27	-0.163
Mean	2.02	2.18	2.46	2.43	2.22	2.66	1.94	2.28	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

Plant height to node ratio. The height to node ratio was not significant, but there was a significant G effect for height to node ratio that justified GGE Biplot analysis (Table 1). The mean vs. stability coordination biplot for plant height to node ratio explained 85% of the total variation with PC 1 and PC 2 (Fig. 2). Figure 2 indicates that the two least stable cultivars, SG 501BR and STV 4892BR, are also the two with the highest average height to node ratio, and that their conventional recurrent parents are more stable, although their height to node ratio is lower (Table 3). This suggests that SG 501BR and STV 4892BR had a high height to node ratio in some environments, but were subject to rank changes across all seven environments. In fact, SG 501BR, which is located near S1 and W2 in the biplot, had the highest height to node ratio in those environments but not in all environments, which indicates

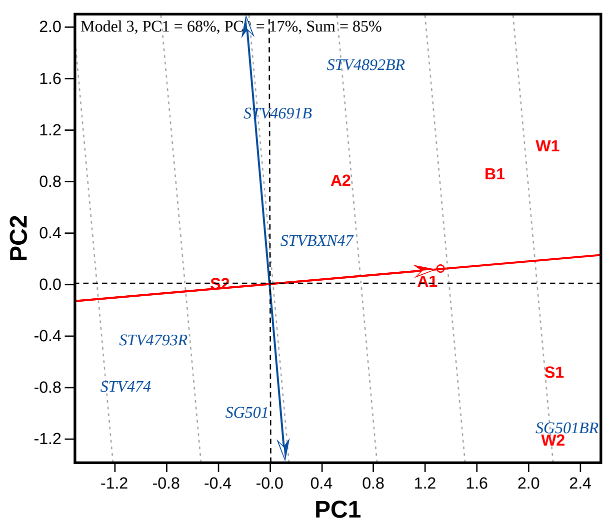

Figure 2. Mean vs. stability coordination biplot for height to node ratio at 60 d after planting. Environment: A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

the instability of this cultivar (Fig. 2; Table 3). A similar situation exists for STV 4892BR, which had the highest height to node ratio in A2 and W1, but one of the lowest in S2 (Fig. 2; Table 3). Interestingly, the most unstable cultivars, SG 501BR, STV 4892BR, and STV 4691B, were the only cultivars that contained the Bollgard gene, yet they had higher than average height to node ratios. Jones et al. (1996) found that Deltapine NuCOTN 33B was taller and had improved seedling vigor and a greater height to node ratio than its conventional, recurrent parent, Deltapine 5415. Considering the insect tolerance imparted by the Bollgard gene, it is reasonable to assume that the relative differences among cultivars might be accentuated over a range of environments in which insect pressure varies, thereby increasing the GE interaction, or instability, of the cultivars containing insect tolerance while maintaining a high average height to node ratio regardless of the level of insect pressure.

Lint percentage. There was a significant G main effect for lint percentage and E, G, and GE accounted for 28, 38, and 34% of the total variation in the sums of squares (Table 1). Kerby et al. (2000) found that variation in the sums of squares for lint percentage was influenced more by G and GE than E. Averaged across environments, all conventional recurrent parents had higher lint percentages than their transgenic derivatives but were less stable (Fig. 3). The two least stable cultivars for lint percentage were the conventional parents SG 501 and STV 474, which was evident by the highest stability statistics of 1.579 and -0.763, respectively (Table 4). SG 501BR was much more stable than SG 501, but had the lowest lint percentage in the test (Fig. 3). The recent STV 474 transgenic derivatives, STV 4691B, STV 4793R, and STV 4892BR, were more stable than their conventional parent and had instability values of -0.381, -0.102, and 0.243, respectively, compared with the instability value of -0.763 of STV 474 (Table 4). These data show that transgenic cultivars have a lower lint percentage, but are more stable than their conventional parents.

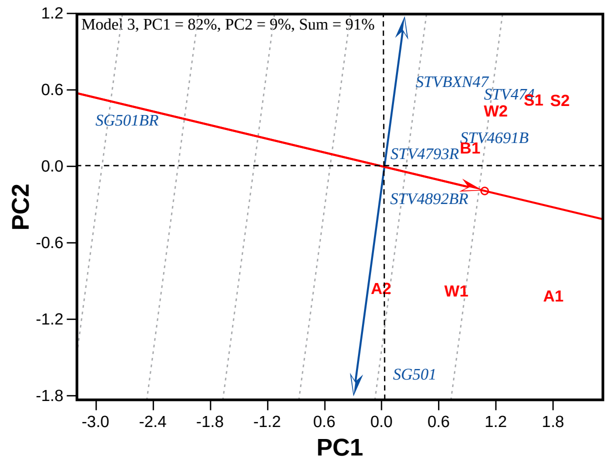

Figure 3. Mean vs. stability coordination biplot for lint percentage. Environment: A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

Delinted seed index. All sources of variation were significant for delinted seed index, and E, G, and GE contributed 11, 55, and 33%, respectively, to the total variation in sums of squares (Table 1). Instability values ranged from -0.857 for STV 4793 to 0.735 for SG 501. There were no apparent stability trends for conventional or transgenic cultivars regarding delinted seed index; however, except for STV BXN47, transgenic cultivars had larger seed than their respective conventional parents averaged across environments

Table 4. Mean lint percentage at each environment and across environments and stability statistics for each genotype

Genotype	Environment[z]							Mean	Stability statistic[y]
	A1	A2	B1	S1	S2	W1	W2		
SG501	40.2	47.3	39.7	42.0	41.1	43.3	41.5	42.0	1.579
SG501BR	36.7	42.0	37.8	40.3	38.8	32.2	39.5	38.2	0.151
STV4691B	39.4	41.2	40.3	42.9	42.6	44.8	43.4	42.1	-0.381
STV474	40.0	40.2	41.0	43.2	42.7	39.2	43.2	41.4	-0.763
STV4793R	39.6	41.0	40.5	42.2	41.7	37.7	41.8	40.6	-0.102
STV4892BR	39.8	40.4	41.3	41.6	41.7	38.6	41.5	40.7	0.243
STVBXN47	39.8	40.8	40.6	42.8	42.0	34.1	42.5	40.4	-0.727
Mean	39.4	41.8	40.1	42.1	41.5	39.0	41.9	40.8	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

(Fig. 4; Table 5). In a study conducted by Jones et al. (1996), seed size was 9% greater for DP NuCOTN33B compared with DP 5415. The results of the gin and in-season data show that transgenic cultivars had lower lint percentages, larger seed, and taller, more vigorous plants than their conventional parents.

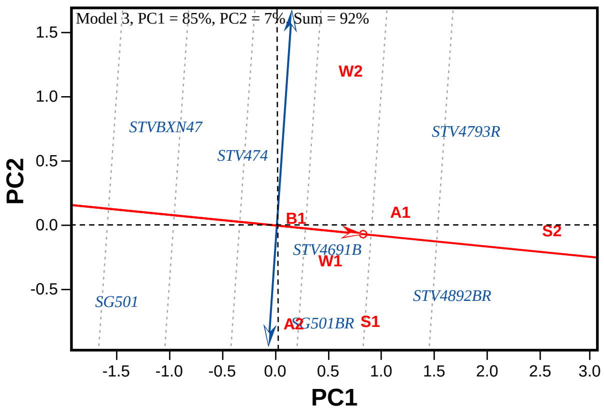

Figure 4. Mean vs. stability coordination biplot for delinted seed index. Environment: A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

Fiber length and strength. Sources E and G were significant for fiber strength and fiber length (Table 1). The percentage of total variation explained by E, G, and GE was 56, 27, and 17%, respectively, for fiber strength and 57, 19, and 23% for fiber length, respectively. Kerby et al. (2000) found in two studies that G contributed more to the total variation in fiber strength than in fiber length. There was no clear trend regarding differences between conventional and transgenic cultivars with respect to stability for fiber length or strength (Tables 6 and 7). SG 501 had greater values for fiber strength and length than any other cultivar, and was also highly stable for both traits. STV 474 was less stable than any transgenic derivative, and had intermediate values for fiber length and strength indicating that in some environments it had higher fiber quality than transgenic cultivars, but had lower fiber quality in other environments. Other studies have yielded similar results in comparisons between conventional and transgenic cultivars (Cooke et al., 2001; Culpepper and York, 1998; Ethridge and Hequet, 2000; Jones et al., 1996; Jordan et al., 2003; Moser et al., 2001; Robinson and McCall, 2001 Silvertooth and Norton, 1998). In general, their studies showed that differences in fiber quality between conventional and transgenic cultivars were minimal or non-existent, and that it was difficult to conclude that a particular transgenic trait resulted in poorer fiber quality in the transgenic cultivars.

Lint yield. All sources of variation were significant for yield (Table 1). E, G, and GE contributed 92, 3, and 5% to the total variation in yield, respectively. Previous studies have shown E to be the predominant source of variation in lint yield (Kerby et al., 2000; Myers and Bordelon, 1997; McPherson and Gwathmey, 1996). The mean vs. stability coordination biplot for lint yield showed that 81% of the total variation was explained by PC 1 and PC 2 (Fig. 5). STV 4691B was the highest yielding cultivar in the study and was highly stable (Fig. 5). Across environments, STV4691B yielded between 205 and 395 kg ha^{-1} more than all other cultivars and was always ranked in the top three cultivars, regardless of environment, hence a high level of stability (Tables 8 and 9). Across environment, the three highest yielding cultivars contained the Bollgard gene despite variable stability rankings of 2,

Table 5. Mean delinted seed index at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	7.70	8.28	8.65	8.73	8.38	7.88	8.20	8.32	0.714
SG501BR	8.63	8.78	8.73	9.23	9.19	8.27	8.48	8.76	0.735
STV4691B	9.00	8.20	9.63	9.17	9.10	8.90	8.66	8.95	0.164
STV474	8.80	7.83	8.90	8.93	8.81	7.33	8.75	8.48	-0.513
STV4793R	9.20	7.93	8.93	9.27	9.79	8.63	9.18	8.99	-0.857
STV4892BR	9.90	8.47	9.03	9.63	9.57	8.27	8.67	9.08	0.415
STVBXN47	8.37	7.86	8.90	8.37	8.46	7.87	8.68	8.36	-0.658
Mean	8.80	8.19	8.93	9.01	9.04	8.14	8.66	8.69	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

5, and 7 (Fig. 5, Table 9). In this study, only the recurrent parent STV 474 had the full range of transgenic technologies. Within that cultivar type, the only clear indication of differences in mean lint yield or stability between conventional or transgenic cultivars was that cultivars containing the Bollgard gene yielded more, and that transgenic cultivars containing the Roundup Ready or BXN technology yielded less, regardless of their level of stability. In a similar study, Moser et al. (2001) found that six of nine Bollgard cultivars and four of ten Bollgard/Roundup Ready cultivars yielded significantly higher than their conventional parents. They also stated that three of ten Roundup Ready cultivars yielded similar to or less than their conventional parents indicating that not all transgenes and insertion events affect yield equally. Similarly, Jordan et al. (2003) showed consistent yield advan-

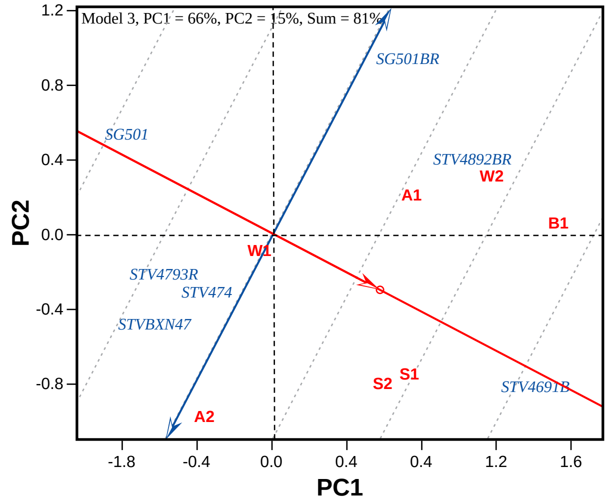

Figure 5. Mean vs. stability coordination biplot for lint yield. Environment: A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

Table 6. Mean fiber strength (cN/tex) at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	30.3	27.8	32.9	33.0	34.1	32.4	36.2	32.5	-0.029
SG501BR	27.6	27.0	28.0	30.5	30.8	31.6	32.8	29.7	-1.254
STV4691B	27.3	27.9	26.0	29.1	30.4	29.3	31.4	28.7	-0.222
STV474	28.0	28.1	28.8	29.0	31.3	28.6	33.3	29.6	1.060
STV4793R	28.2	28.4	28.0	29.9	31.9	30.3	32.1	29.8	-0.032
STV4892BR	28.7	27.5	29.7	29.7	32.3	30.4	33.0	30.2	0.360
STVBXN47	27.6	28.1	28.5	29.1	30.3	29.4	31.9	29.3	0.116
Mean	28.2	27.9	29.3	31.0	31.6	30.5	33.0	30.1	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

Table 7. Mean fiber length (mm) at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	2.84	2.82	2.82	2.87	2.92	2.72	2.82	2.82	-0.397
SG501BR	2.72	2.84	2.74	2.82	2.82	2.72	2.77	2.77	-0.403
STV4691B	2.82	2.79	2.72	2.87	2.92	2.74	2.82	2.82	-0.672
STV474	2.84	2.87	2.72	2.82	2.87	2.62	2.87	2.79	1.255
STV4793R	2.74	2.87	2.69	2.74	2.79	2.72	2.77	2.77	-0.022
STV4892BR	2.82	2.79	2.74	2.82	2.90	2.72	2.79	2.79	-0.347
STVBXN47	2.84	2.84	2.74	2.82	2.87	2.67	2.82	2.79	0.585
Mean	2.79	2.82	2.74	2.82	2.87	2.69	2.82	2.79	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

tages for transgenic cultivars containing the Bollgard gene, whether alone or stacked. Other studies have shown little difference in mean lint yield between conventional and transgenic cultivars (Robinson and McCall, 2001; Silvertooth and Norton, 1998).

DISCUSSION

The results of this study indicate that GE interactions are more likely to occur for some traits and that the percentage of total variation attributed to E, G, or GE is different among traits. There were differences in the level of stability between conventional and transgenic cultivars according to the trait analyzed and transgenic technology. The authors believe that transgenic cultivars, particularly those containing the Bollgard gene, are buffered against variable insect pressure and exhibit a higher level of mean performance and stability as a benefit of that tolerance. Yield increases in Bollgard cultivars can be explained by the season-long insect control inherent to that cultivar, even when insects are present at below-threshold populations and slight yield reductions occur in conventional parents. The level of insect pressure across environments determines the extent of the yield increase and GE interaction. A similar situation might exist for Roundup Ready cultivars if a comparable level of weed control was not provided via other chemistries or methods.

Transgenic cultivars were taller, had a greater height to node ratio, had larger seed, and had lower lint percentages than their conventional recurrent parents. Genotypes with larger seed have an advantage during germination and emergence, and the early-season differences in environment (i.e., temperature, soil-borne pathogen population levels, or rainfall) likely contrib-

Table 8. Mean lint yield (kg/ha) at each environment and across environments and stability statistics for each genotype

Genotype	Environment[y]							Mean	Stability statistic[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	1512	986	2841	2990	2796	1350	1971	2191	-0.06
SG501BR	1795	859	3435	3328	2512	1313	2649	2270	-1.089
STV4691B	1893	1102	3664	3591	3454	1332	2688	2532	0.132
STV474	1259	1132	3098	3410	2742	1332	2195	2167	0.44
STV4793R	1288	1093	2883	3459	2580	1317	2015	2091	0.532
STV4892BR	1620	898	3586	3591	2595	1263	2737	2327	-0.753
STVBXN47	1493	1346	2918	3390	2464	1385	1961	2137	0.8
Mean	1551	1060	3158	3344	2735	1329	2316	2242	na

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Stability statistic for GGE; a higher absolute value suggests greater instability.

Table 9. Ranking of genotypes for lint yield at each environment and across environments and stability ranking for each genotype

Genotype	Environment[x]							Mean[y]	Stability ranking[z]
	A1	A2	B1	S1	S2	W1	W2		
SG501	4	5	7	7	2	2	6	5	1
SG501BR	2	7	3	6	6	6	3	6	7
STV4691B	1	3	1	1	1	3	2	1	2
STV474	7	2	4	4	3	4	4	3	3
STV4793R	6	4	6	3	5	5	5	7	4
STV4892BR	3	6	2	2	4	7	1	2	5
STVBXN47	5	1	5	5	7	1	7	4	6

[x] Ranked according to the stability statistic for GGE; a higher value suggests greater instability and lower rank.

[y] A=Alexandria, B=Bossier City, S=St. Joseph, W=Winnsboro, 1=2001, and 2=2002.

[z] Average yield ranking across environments.

uted to the GE interaction for plant height and height to node ratio. Large-seeded genotypes generally have lower lint percentages than small-seeded genotypes and the results of this study support that concept. It is logical that seed size or any other trait not employed as a criterion to evaluate the recurrent parent recovery in backcross-derived transgenic cultivars may perform differently across environments.

ACKNOWLEDGEMENT

The authors would like to thank Delta and Pine Land for supporting this research.

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