New Stress Tolerant Corn Germplasm for Higher Water Use Efficiency and Water Conservation

A Final Report for the Project Funded by the Texas Water Development Board

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Executive Summary

This report presents the key findings of a project funded by the Texas Water Development Board. The grant ran from April 19, 2005 to September 30, 2007 and obtained in response to a Request for Applications in the Texas Register (Document TRD 200407354, December 31, 2004).

A field study involving five TAES experimental corn hybrids and three commercial hybrids was conducted under two irrigation treatments at Etter and Halfway in 2005 and 2006. Key findings include:

- A TAES hybrid C3A654 x B110 was 5-days earlier than the widely-grown DKC66-80, but produced the same grain yield and higher silage yield with better quality. This indicates that selection for shorter-season, stress-tolerant hybrids is a feasible approach to reduce irrigation without yield penalty. Use of short-season and high yielding hybrids may save one late-season irrigation (or up to 10% of total irrigation water).

- Drought stress reduced grain yield by 50.1% from 157.5 bu/a to 78.6 bu/a, reduced forage yield by 29.3% from 22196.1 kg/a to 15682.8 kg/a, delayed pollen shedding by 0.8 days, downsized plant height by 14% from 251.7 cm to 216.6 cm, and lowered ear height by 11.0% from 104.4 cm to 92.9 cm. The grain yield reduction due to drought stress was 1.7 times higher than the forage yield. This may have significant implication for water management of grain and silage corn production. When one needs to reduce irrigation, silage field may be a advantageous choice. But this requires further economic analysis.

- Compared to well-watered treatments, the silage from drought stressed plants had 4.5% higher crude protein, 17.5% higher ADF, 15.1% higher NDF, 5.5% lower total digestible nutrients, 30.7% higher lignin contents, and 26.1% lower starch. All key silage quality traits were significantly different between two irrigation treatments. Drought stress significantly reduced the silage quality.

- The project trained a graduate student and provided employment and research opportunities to four Texas Tech undergraduate students.
- The TWDB-funded research has significantly enhanced our silage corn research capability and helped us to secure funding from other agencies to purchase a silage chopper. With the equipment and experience from the TWDB project, we have initiated state silage corn performance tests in the Texas High Plains.
- New multiple stress tolerant corn lines and hybrids have been developed by introgressing genes from tropical corn into the germplasm adapted to Texas envionemnt. These lines have been selected for good drought and heat tolerance, aflatoxin resistance, and/or corn earworm resistance and can be used for feed, food or silage production.
- The results from this and our other studies show that new corn germplasm and accompanying strategies for watering and crop management can save 10% of the irrigation needed to produce equal amounts of grain and reduce aflatoxin levels by at least 70%.

Relevance of the Project to Agricultural Water Conservation Activity

Corn is an important crop in Texas, second only to cotton in terms of gross receipts. It is planted on about 2 million acres annually in Texas, and about 60% of grain is produced in the High Plains. Silage corn acreage in Texas has doubled from 70,000 acres in 1995 to 160,000 acres in 2006. Most of this increase has occurred in the High Plains where the number of dairies has more than doubled since 2000. Seven of the top milk producing counties in Texas are now located in the High Plains. In September 2007, a new cheese plant was opened in Dalhart by the

Hilmar Cheese Company. The Dalhart plant can process 5 millions pounds of milk per day, and requires the milk production from 64,000 cows. Silage corn production will continue to grow in this region because it must be produced locally. Corn production plays an increasingly important role in the economic development of the state. All corn in the Texas High Plains is watered from the Ogallala Aquifer. Declining water levels of the Ogallala Aquifer and heightened irrigation costs pose serious economic strains for corn producers. Use of stress tolerant corn hybrids and the best crop management practices are crucial for conserving the Ogallala Aquifer and sustaining economic development in this region.

Drought, heat stress and aflatoxin are common constraints for corn production in Texas. Frequent drought and heat stress negatively affect crop growth and development. Heat stress irreversibly damages the crop. Drought and heat cause plant senescence early, significantly reduce yield and quality, and increase aflatoxin. Although producers typically have little control over the natural occurrence of biotic and abiotic stresses, reduction of these occurrences can be made by the development and choice of hybrids that are locally adapted and require less irrigation water. The problem is that commercial corn hybrids used in Texas have been developed primarily for the Midwest and lack adaptation to more dry and hot environments. Major seed companies have reduced their breeding efforts for Texas and other Southern states, i.e., fewer new corn hybrids are specifically bred for this 'marginal market region' from a national perspective. This is a serious problem for Texas corn production as well as for cotton (lack of rotation with corn) and the livestock industry (short supplies of local corn). Continuous mono-cropping with cotton is vulnerable in terms of economics as well as soil and water conservation. Developing and using new corn hybrids tolerant to drought and other stresses is an important and viable water saving approach. A combination of new multiple-stress tolerant hybrids with efficient irrigation and cropping systems can maximize benefits from all investments in water conservation programs.

In the Panhandle Regional Water Plan, “change in crop variety” and “change in crop type” was one of the seven recommended major strategies for water conservation (www.twdb.state.tx.us/RWPG/main-docs/regional-plans-index.htm). The 2001 Liano Estacado Regional Water Plan recommended “research and development of drought tolerant crops and technology” as one of the key strategies for water conservation, saying “both public and private agricultural research organizations are presently engaged in research on plant crop breeding, plant nutritional needs, and cultural practices to improve the productivity, quality, and other characteristics of crops that can be produced in the Llano Estacado and other regions of Texas, the United States, and other countries of the world. The Llano Estacado Regional Water Planning Group recommends that funding be continued in adequate levels for research and development of new and improved technology in the fields of drought tolerant strains of crops, new or alternative crops for arid and semiarid regions, plant nutritional needs, irrigation application methods, brush control, weather modification, aquifer recharge, and development of better information about the aquifers and other water resources of the region” (www.twdb.state.tx.us/rwp/O/PDFs/O_Executive%20Summary.pdf).

Objectives

The corn-breeding program at TAES-Lubbock Center has developed multiple-stress (drought, heat, and insects) tolerant lines and hybrids by introgressing tropical germplasm. Our genetic approach for water conservation is to change crop genetics so that less water is used to produce equal or higher yields with better grain and silage quality. This approach involves four steps: evaluate diverse germplasm for stress tolerance (drought, heat, CEW, and grain molds) and agronomic traits; select and develop stress-tolerant lines from temperate x tropical populations; evaluate testcrosses of advanced TAES lines with public or private tester lines for yield and stress tolerance, and finally, select the best crosses with acceptable yields and good abiotic and biotic stress tolerance, and test them for yield, water use efficiency, aflatoxin, fumonisin, and agronomic traits in diverse environments. In each step, we also consider the early maturity of the lines and crosses as a selection criterion.

Our overall goal is to develop inbred lines and hybrids with improved stress tolerance and better water use efficiency to produce equal or better quantity and quality of grain and silage by using less water. Specific objectives of this study were (1) to compare new TAES hybrids with commercial hybrids for their responses to irrigation levels and (2) to determine the optimum combinations of plant populations and irrigation levels with furrow, drip or pivot and develop management practices for these new hybrids under actual conditions of the Texas High Plains.

Materials and Methods

Corn hybrids: Five TAES experimental (C3A654-4 x B110, S1W x CML343, S2B73 x NC300, SGP3 x B110, and Tx205 x B110) and three commercial hybrids (Garst 8288, Pioneer hybrid 31B13, and DKC66-80) were grown under well-watered and drought-stressed conditions at Halfway and Etter in 2005 and 2006. All hybrids are non-transgenic except P31B13 is a Bt-hybrid. They all have 110-118 day maturity. The TAES hybrids have at least 12% exotic germplasm. Three commercial hybrids were widely used at the time of the experiments and were listed as drought tolerant in the companies' product profiles.

Experimental design: At each location, there were two irrigation treatments in the same fields: well-watered (WW) and drought-stressed (DRT). Within each irrigation treatment, eight hybrids were planted in a randomized complete block design with three replications. Each replication consisted of a two-row plot, 18-ft long and spaced 40 inches apart at Halfway and 30 inches at Etter. Row-spacing depends on local production practices. Plots were over-planted and thinned to 26,136 plants per acre at Etter and 22,506 plants per acre at Halfway. Two sets of plots were planted in the same neighborhood, one for silage and another grain yield. Plants were thinned to the target plant density for each area after emergence. The crop was managed in a manner consistent with local practices.

Irrigation treatments: Water was applied through a center pivot system at Etter and a sub-surface drip irrigation system at Halfway. Plants grown under WW and DRT were watered at the same time throughout the growing season. Drought stress was imposed by reducing irrigation by half from V-10 (with 10 fully expanded leaves) to R-3 (two weeks after flowering) stages.

Harvesting and data collection: Data were collected on plant population per plot, pollen shedding and silking dates, plant and ear height, and other agronomic traits. Plots for grain yield were harvested with a plot combine. Silage plots were hand harvested at the half milk line stage (about 50 days after flowering). Eight plants at Etter and 10 plants at Halfway were harvested per plot, processed in a Troybuilt Pro-Tomahawk chipper, and weighed for biomass. Sub-samples were then taken for moisture and quality analysis. Silage quality was analyzed by Dairy One Forage Lab (Ithaca, New York) using NIR method.

Data analysis: Data were analyzed by considering location, irrigation, hybrids and their interactions as the fixed effects; and year, replications and their interactions as random effects. A mixed model was used to test the significance of effects.

Results

Grain Yield

The average grain yield of eight hybrids under WW at two locations in 2005 and 2006 was 157.4 bu/a, ranging from 145.6 bu/a of S1W x CML343 and 178.2 bu/a of P31B13. TAES hybrids C3A654-4 x B110 and Tx205 x B110 produced 160.7 and 161.8 bu/a, same as DKC66-80, higher than Garst 8288, and lower than P31B13 (Table 1). P31B13 is a full-season, high yielding Bt-hybrid. It is recognized that the Bt-gene provides at least 5% yield advantage. The days to pollen shedding were 70.6 for Garst 8188, 73.7 for DKC66-80 and 69.7 for C3A654-4 x B110 (Table 2). A five-day difference in maturity may save one irrigation during late season.

Under drought conditions, the average grain yield of eight hybrids ranged from 56.6 bu/a (S1W x CML343) to 97.3 bu/a (P31B13) with a mean of 78.6 bu/a. C3A654 x B110 yielded lower than P31B13 and DKC66-80 but higher than Garst 8288, however, statistically its yield was not significantly different from those of the three checks (Table 1).

When combined with all environments (years, locations, and irrigations), the mean grain yield was 118 bu/a ranging from 101.2 bu/a (S1W x CML343) to 137.7 bu/a (P31B13). Early hybrid C3A654-4 x B110 yielded 123.5 bu/a, higher than Garst 8288 (115.5 bu/a), and close to DKC66-80 (127.4 bu/a) (Table 1). DKC66-80 was 5.2 days later than C3A654 x B110. These results indicate that new short-season hybrids can yield as well as full-season hybrids.

Forage Yield

Forage yield under well-watered conditions ranged from 20398.1 kg/a (S2B73 x NC300) to 24131.8 kg/a (SGP3-1 x B110) with a mean of 22,196 kg/a (or 24.42 short tons/a). Under drought conditions, the average forage yield was 15,682.8 kg/a; P31B13 (17,955.6 kg/a) and

C3A654-4 x B110 (16,989.6 kg/a) had the highest forage yields. When combined over eight environments (2 years, 2 locations, and 2 irrigation treatments), C3A654 x B110 had the highest forage yield 20,462.4 kg/a, and the yields of all TAES hybrids were generally not different from the commercial checks (Table 1).

The fact that C3A654-4 x B110 was five day earlier but produced the same grain yield and higher forage yield indicates that selection for shorter-season, stress-tolerant hybrids is a feasible approach to reduce irrigation without yield penalty. A hybrid that can flower and mature five days earlier may save one late season irrigation. Since corn producers in the Texas High Plains usually water about 10 times with a total of 25 acre-inches in the entire growing season, use of short-season and high yielding hybrids like C3A654 x B110 may save 10% of the total irrigation.

Effects of Irrigation Treatments on Grain Yield, Forage Yield, and Other Agronomic Traits

Grain yield, forage yield, and other agronomic traits responded significantly to irrigation treatments. The effect of year and irrigation interaction (YEAR*IRR) was significant for grain yield, forage yield, and plant height, but not for days to pollen shedding and ear height, indicating that in both years drought stress occurred at similar growth stages, and irrigation affected the grain yield, forage yield, and plant height at a different degree in 2005 and 2006 (Table 3). The effect of irrigation by hybrids interaction (IRR*ENO) was significant for grain yield, days to pollen shedding, and plant height, but not for forage yield and ear height, indicating that the eight hybrids responded to irrigation treatments differently in the first three traits but in the same way in forage yield and ear height.

As expected, drought stress reduced grain yield by 50.1% from 157.5 bu/a to 78.6 bu/a, reduced forage yield by 29.3% from 22,196.1 kg/a to 15,682.8 kg/a, delayed pollen shedding by 0.8 days, downsized plant height by 14% from 251.7 cm to 216.6 cm, and lowered ear height by 11.0% from 104.4 cm to 92.9 cm. This may have significant implication for water management of grain and silage corn production. When one needs reduce irrigation, silage field may be an advantageous choice since the same reduction of irrigation leads to lower percentage loss of forage yield. But this requires further economic analysis.

Silage Quality

Silage quality traits varied among hybrids. The total digestible nutrients (TDN) was highest in Garst 8288 (75.33%), followed by C3A654-4 x B110, then P31B13 (CK2), Tx205 x B110, SGP3-1-1 x B110, DKC66-80, S2B73 x NC300, and S1W x CML343 (66.21). S1W x CML343 had the highest percentage of tropical germplasm among the eight hybrids and was the latest, and thus had the lowest grain yield and lowest starch content at harvest (Table 5).

Effect of Drought Stress on Silage Quality

Compared to well-watered treatments, silage from drought-stressed plants had 4.5% higher crude protein, 17.5% higher ADF, 15.1% higher NDF, 5.5% lower total digestible nutrients, 30.7% higher lignin contents, and 26.1% lower starch. Neutral detergent fiber (NDF) is a measure of hemicellulose, cellulose and lignin representing the fibrous bulk of the forage. These three components are classified as cell wall or structural carbohydrates. They give the plant rigidity enabling it to support itself as it grows, much like the skeleton in animals. Acid detergent fiber (ADF) is a measure of cellulose and lignin. Cellulose varies in digestibility and is negatively influenced by the lignin content. As lignin content increases, digestibility of the cellulose decreases. Both ADF and NDF is negatively correlated with intake and with overall digestibility. Total digestible nutrients (TDN) is the sum of the digestible protein, digestible nitrogen-free extract (NFE), digestible crude fiber and 2.25X the digestible fat. All key silage quality traits were significantly different between two irrigation treatments. Drought stress significantly reduced the silage quality.

Training of Students

The TWDB grant supported the research of Mr. Randall Montgomery for his M.S. degree in Crop Science at Texas Tech University. The grant was used to pay his graduate assistantship (stipend, tuitions, and fees). In addition, the TWDB grant paid wages of four undergraduate students from Texas Tech who were employed as part-time research assistants and gained research experience in plants breeding and genetics and water management.

Field Days

During crop growing seasons, we held field days at Etter, Halfway, and Kress to show the TWDB-supported research to producers and other stakeholders and to demonstrate how new multiple stress tolerant corn lines and hybrids could save water (see field day photos on page 11).

Other Progress Related To TWDN Grant

<u>Development of new stress tolerant lines and hybrids</u>: The research funded by the TWDB grant provided valuable information on grain and biomass production with limited irrigation. We have also developed new drought and heat tolerant germplasm, new brown-midrib lines and hybrids, and identified new hybrids (such as DK888:N11a-5 x B110, C2A554 x B110) for grain

Corn field day at Etter on August 9, 2006.

Corn field day at Kress on September 15, 2006.

Corn field day at Halfway on August 19, 2005.

and silage production. Combined over five environments, S2B73BC x NC300 and S1W x CML343 had 87% and 72% less aflatoxin than the average of four check hybrids (2194 ppb),while WA22W x S1W, Tx202 x CML343, and CUBA117:S15-1A-1 x Tx205 had 62%, 51%, and 51% less aflatoxin than the check means, respectively. S2B73Bc x NC300 and S1WC3 produced 50% to73% more biomass compared to the average of four commercial hybrids in an on-farm study near Kress (Fig. 1). S1WC3 had less CEW damage without insecticide treatment than commercial hybrids that were sprayed weekly with 5 applications (data not shown). It should be noted that these new hybrids have better stress tolerance and acceptable yield, but they cannot beat the commercial hybrids by major companies in every trait examined. They may be used directly to produce commercial hybrids as well as in further breeding efforts by seed companies. Improved grain quality is an important aspect of water conservation. With tropical germplasm, these hybrids produce strong plants with above average height and a ‘stay green’ trait. The results show that these new multiple stress-tolerant hybrids can save a significant amount of water, reduce mycotoxin contaminations, and produce high quality grain or silage with less water.

<u>Leverage funds</u>: The TWDB-funded research significantly enhanced silage corn research in Texas. Because of the progress from the TWDB funded project, we have obtained funding from TAES, Texas Corn Producers Board and a seed company (a total of $100,000) for purchasing a silage chopper. With the silage chopper and experience from the TWDB project, we initiated a state silage corn performance test at Etter in 2007 for the first time in history. The test compared 26 commercial silage corn hybrids and the results have been posted at the TAES Lubbock website (http://lubbock.tamu.edu) and the Texas A&M Soil and Crop Science department

website (http://varietytesting.tamu.edu). These results will help producers, extension specialists and consultants select commercial hybrids best suited to the Texas High Plains.

Future Work

Our goal is to increase water use efficiency by developing multiple stress-tolerant corn to produce high quantity and quality corn for food, feed and silage to meet the needs of an increasing animal industry while reducing demand on irrigation water. This study was conducted on the High Plains, but its products (new corn lines and hybrids and water use information) can benefit the entire state. The study showed significant genetic variation in grain and forage yield and silage quality in corn. Reduced irrigation significantly reduces yield and quality. Our inbred line Tx205 has been licensed to 15 seed companies. Other lines used in this study will soon be released. The results can help to develop new water and crop management strategies for new corn germplasm. It should be emphasized that we mean "high water use efficiency" by the traditional high biomass as well as by the high grain quality (less insect feeding damage and lower aflatoxin). Based on our findings, we believe that the new corn germplasm and accompanying strategies for watering and crop management can save 10% of the irrigation needed to produce equal amounts of grain and reduce the aflatoxin level by 70%. A sustainable corn production adds a viable crop rotation option for cotton production. The economic impact would be enormous.

Our current and future efforts are to continue the development of drought tolerant corn suitable for feed, food, silage and feedstock production in Texas and the southern U.S., to assess full and limited irrigation corn production functions, to conduct an economic analysis of using corn for bioengery production under limited irrigation, and to formulate the best agronomic systems (including hybrids, irrigation, and other factors) for corn bioenergy production.

In the meantime, we will continue testing commercial hybrids for the silage yield and quality and identifying the most suitable hybrids for the Texas High Plains. However, our current resources are only for evaluating hybrids for one irrigation treatment (hence, well-watered treatment). We believe that comparison of available commercial hybrids at 75% of current irrigation levels by producers should be conducted to meet the demand for silage corn and the need for conserving the precious Ogallala Aquifer water. We wish that such resource were available for this work because of its immediate and direct impact on water conservation.

Acknowledgements

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Table 1. Average grain yield of eight hybrids under well watered (WW) and drought (DRT) conditions at Etter and Halfway, Texas in 2005 and 2006. The grain and forage yields were adjusted to a standard 15.5% and 65%, respectively.

	Grain yield (bu/a)						Forage yield (kg/a)					
Hybrids	WW		DRT		Total		WW		DRT		Total	
C3A654-4 x B110	160.7	bc	86.4	ab	123.5	bc	23935.1	a	16989.6	a	20462.4	a
S2B73 x NC300	141.0	d	77.4	bc	109.2	de	20398.1	b	15247.4	ab	17822.7	bc
SGP3-1-1 x B110	155.1	bcd	75.1	bc	115.1	cd	24131.8	a	15629.7	ab	19880.8	ab
S1W x CML343	145.6	cd	56.8	d	101.2	e	20680.9	b	13325.4	b	17003.1	c
Tx205 x B110	161.8	b	67.6	cd	114.7	cd	21678.9	ab	15962.2	ab	18820.6	abc
Garst 8288 (CK1)	155.4	bcd	75.0	bc	115.2	cd	21380.8	ab	15220.6	ab	18300.7	bc
P31B13 (CK2)	178.2	a	97.3	a	137.7	a	22956.4	ab	17955.6	a	20456.0	a
DKC66-80 (CK3)	161.5	b	93.2	a	127.4	b	22407.0	ab	15131.8	ab	18769.4	abc
Test mean	157.4		78.6		118.0		22196.1		15682.8		18939.5	
CV%	12.1		18.4		14.3		17.3		22.6		19.5	

Means in a column with the same letter are not significantly different at 5% level.

Table 2. Means of days to pollen shedding, plant and ear height of eight hybrids under well-watered (WW) and drought (DRT) conditions at Etter and Halfway in 2005 and 2206.

	Days to pollen shedding						Plant height (cm)						Ear height (cm)					
Hybrids	WW		DRT		Total		WW		DRT		Total		WW		DRT		Total	
C3A654-4 x B110	69.7	e	69.6	e	69.6	e	220.9	d	196.0	e	208.5	e	86.8	d	83.0	e	84.9	f
S2B73 x NC300	73.8	b	75.0	b	74.4	b	266.9	a	234.2	a	250.5	a	113.4	a	102.8	a	108.1	a
SGP3-1-1 x B110	71.8	cd	71.6	d	71.7	d	260.4	ab	224.2	ab	242.3	bc	106.3	ab	95.0	abc	100.7	bcd
S1W x CML343	80.5	a	83.3	a	81.9	a	261.2	ab	207.2	d	234.2	cd	115.5	a	93.0	bcd	104.3	abc
Tx205 x B110	72.3	c	73.2	c	72.7	c	247.7	c	212.1	cd	229.9	d	105.9	ab	92.3	cde	99.1	cd
Garst 8288 (CK1)	70.6	de	70.3	e	70.4	e	260.6	ab	224.3	ab	242.5	ab	94.1	cd	85.3	de	89.7	ef
P31B13 (CK2)	74.3	b	75.1	b	74.7	b	244.1	c	215.1	bcd	229.6	d	110.5	ab	101.8	ab	106.2	ab
DKC66-80 (CK3)	73.7	b	74.8	b	74.2	b	251.9	bc	219.7	bc	235.8	bcd	102.5	bc	89.8	cde	96.1	de
Mean	73.3		74.1		73.7		251.7		216.6		234.2		104.4		92.9		98.6	
CV%	2.2		2.2		2.2		6.2		6.1		6.1		11.7		12.2		11.9	

Means in a column with the same letter are not significantly different at 5% level.

Table 3. Combined analysis of variance of hybrids over two years, two locations and two irrigation treatments on grain yield (bu/a), forage yield (kg/a), days to pollen shedding, plant height (cm), and ear height (cm). Values in the table are mean squares.

Source of variation	df		Grain yield		Forage yield		Days to pollen		Plant height		Ear herght	
YEAR	Y-1	1	5125.5	*	684141730	***	18.8	*	20.0	ns	1.0	ns
LOC	L-1	1	27508.7	***	683350606	***	2775.5	***	2338.0	*	5271.0	***
IRR	I-1	1	298332.9	***	2036333714	***	28.5	*	59220.8	***	6348.0	***
REP(YEAR*LOC*IRR)	Y*L*I*(R-1)	16	952.1	***	25609359	*	3.8	***	368.2	*	235.8	ns
ENO	G-1	7	3069.2	***	37551471	*	345.7	***	3791.6	***	1570.2	***
YEAR*LOC	(Y-1)*(L-1)	1	10988.4	***	736912924	***	114.1	***	13400.1	***	3267.0	**
YEAR*IRR	(Y-1)*(I-1)	1	49049.8	***	330034502	*	0.3	ns	3978.5	**	275.5	ns
YEAR*LOC*IRR	(Y-1)*(L-1)*(I-1)	1	17403.7	***	28145804	ns	56.3	***	1752.1	***	1680.3	***
LOC*IRR	(L-1)*(I-1)	1	197.5	ns	114870937	*	46.0	**	500.5	ns	1887.5	*
YEAR*ENO	(Y-1)(G-1)	7	690.6	*	50753648	**	8.9	**	285.4	ns	199.6	ns
LOC*ENO	(L-1)(G-1)	7	2129.3	***	38474099	*	9.8	**	200.2	ns	183.1	ns
IRR*ENO	(I-1)*(G-1)	7	604.3	*	8859405	ns	6.2	*	441.1	*	174.7	ns
YEAR*LOC*ENO	(Y-1)*(L-1)*(G-1)	7	510.1	ns	51051852	*	23.2	***	168.1	ns	459.5	*
YEAR*IRR*ENO	(Y-1)*(I-1)*(G-1)	7	143.3	ns	18395457	ns	1.8	ns	139.3	ns	67.0	ns
LOC*IRR*ENO	(L-1)*(I-1)*(G-1)	7	994.1	***	8149506	ns	2.4	ns	510.8	*	35.7	ns
YEAR*LOC*IRR*ENO	(Y-1)*(L-1)*(I-1)*(G-1)	7	387.1	ns	5689166	ns	4.0	ns	104.2	ns	146.5	ns
Error	Y*L*I*(R-1)*(G-1)	112										
Total	Y*L*I*R*G-1	191										

*, **, *** significant at 0.05, 0.01, and 0.001 levels, respectively. Ns = non-significant at 0.05 level.
YEAR = Years, LOC = locations, IRR = irrigation treatments, REP = replications, ENO = hybrids.

Table 4. Average effect of drought stress on grain yield, forage yield, days to pollen shedding, plant height, and ear height at Etter and Halfway, Texas in 2005 and 2006.

Traits	WW		DRT		(DRT - WW)/WW*100
Grain yield (bu/a)	157.4	a	78.6	b	-50.1
Forage yield (kg/a)	22196.1	a	15682.8	b	-29.3
Days to pollen shedding	73.3	a	74.1	b	1.1
PHT	251.7	a	216.6	b	-14.0
EHT	104.4	a	92.9	b	-11.0

Means in a row with the same letter are not significantly different at 5% level.

Table 5. Silage quality of eight hybrids under well-watered (WW) and drought (DRT) conditions at Etter and Halfway, Texas in 2005 and 2006.

Hybrids	CP			ADF			NDF			TDN			Lignin			Starch		
	WW	DRT	TOTAL	WW	DRT	TOTAL	WW	DRT	TOTAL	WW	DRT	TOTAL	WW	DRT	TOTAL	WW	DRT	TOTAL
C3A654-4 x B110	8.01	8.46	8.23	18.96	22.41	20.68	34.36	39.67	37.01	75.42	71.83	73.63	2.94	3.11	3.03	41.93	33.62	37.78
S2B73 x NC300	7.82	8.36	8.09	24.77	27.31	26.04	42.88	46.37	44.63	68.83	67.00	67.92	3.80	4.03	3.91	29.48	20.63	25.05
SGP3-1-1 x B110	8.33	8.38	8.35	19.78	23.60	21.69	36.30	41.68	38.99	74.75	69.75	72.25	2.78	3.77	3.28	38.36	28.97	33.66
S1W x CML343	7.83	8.28	8.05	27.06	31.43	29.25	45.98	52.78	49.38	68.25	64.17	66.21	3.88	4.27	4.08	25.77	15.37	20.57
Tx205 x B110	7.85	8.65	8.25	19.34	24.25	21.80	34.78	42.08	38.43	75.00	69.58	72.29	2.77	3.63	3.20	40.78	27.24	34.01
Garst 8288 (CK1)	8.28	8.35	8.31	16.47	20.03	18.25	29.93	35.51	32.72	77.50	73.17	75.33	2.57	3.21	2.89	44.83	35.73	40.28
P31B13 (CK2)	8.34	8.66	8.50	18.53	22.48	20.50	33.43	39.75	36.59	75.08	70.58	72.83	2.88	6.88	4.88	40.33	29.86	35.09
DKC66-80 (CK3)	8.23	8.42	8.32	20.84	23.17	22.00	36.42	40.75	38.58	73.67	70.33	72.00	3.29	3.68	3.48	36.74	28.83	32.79
Mean	8.08	8.44	8.26	20.72	24.33	22.53	36.76	42.32	39.54	73.56	69.55	71.56	3.11	4.07	3.59	37.28	27.53	32.40
CV%	5.08	4.71	4.89	12.00	11.91	11.99	9.41	9.81	9.67	3.03	3.27	3.15	13.02	96.78	77.94	12.36	20.28	15.80
LSD 0.05	0.34	ns	0.23	2.03	2.37	1.55	2.83	3.40	2.19	1.83	1.86	1.29	0.33	ns	ns	3.77	4.57	2.93

Table 6. Combined analysis of variance of hybrids over two years, two locations and two irrigation treatments on silage quality traits. Values in the table are mean squares.

Source	df		CP		ADF		NDF		TDN		Lignin		Starch	
YEAR	Y-1	1	0.0	ns	13.0	ns	100.8	*	89.4	*	3.0	ns	26.0	ns
LOC	L-1	1	17.6	***	1.2	ns	35.8	ns	259.0	***	3.9	ns	73.5	ns
IRR	I-1	1	6.2	***	628.2	***	1484.6	***	772.0	***	43.8	*	4559.1	***
REP(YEAR*LOC*IRR)	Y*L*I*(R-1)	16	0.3	*	10.2	ns	14.5	ns	6.6	ns	9.4	ns	31.5	ns
ENO	G-1	7	0.5	*	290.7	***	640.3	***	216.8	***	10.5	ns	1016.7	***
YEAR*LOC	(Y-1)*(L-1)	1	15.2	***	0.1	ns	5.9	ns	125.1	***	6.0	ns	30.2	ns
YEAR*IRR	(Y-1)*(I-1)	1	0.0	ns	84.9	*	61.8	ns	71.3	*	0.2	ns	359.2	*
YEAR*LOC*IRR	(Y-1)*(L-1)*(I-1)	1	0.0	ns	10.0	ns	0.5	ns	0.3	ns	12.0	ns	1.1	ns
LOC*IRR	(L-1)*(I-1)	1	2.0	*	44.2	ns	71.7	*	84.0	*	14.0	ns	332.9	***
YEAR*ENO	(Y-1)(G-1)	7	0.2	ns	23.9	*	51.9	*	19.9	***	7.9	ns	98.0	*
LOC*ENO	(L-1)(G-1)	7	0.1	ns	8.4	ns	23.3	ns	6.6	ns	6.9	ns	39.1	ns
IRR*ENO	(I-1)*(G-1)	7	0.4	*	4.5	ns	9.5	ns	7.4	ns	9.5	ns	18.9	ns
YEAR*LOC*ENO	(Y-1)*(L-1)*(G-1)	7	0.2	ns	19.9	*	46.5	*	14.0	*	7.9	ns	78.0	*
YEAR*IRR*ENO	(Y-1)*(I-1)*(G-1)	7	0.2	ns	12.2	ns	10.2	ns	5.5	ns	7.7	ns	31.1	ns
LOC*IRR*ENO	(L-1)*(I-1)*(G-1)	7	0.3	*	8.0	ns	14.5	ns	8.7	ns	8.0	ns	46.2	ns
YEAR*LOC*IRR*ENO	(Y-1)*(L-1)*(I-1)*(G-1)	7	0.2	ns	8.5	ns	11.3	ns	7.9	ns	7.6	ns	20.2	ns
Error	Y*L*I*(R-1)*(G-1)	112												
Total	Y*L*I*R*G-1	191												

*, **, *** significant at 0.05, 0.01, and 0.001 levels, respectively. Ns = non-significant at 0.05 level.
YEAR = Years, LOC = locations, IRR = irrigation treatments, REP = replications, ENO = hybrids.

Table 7. Comparison of silage quality between two irrigation treatments (means over two years and two locations) and between Etter and Halfway under well-watered (WW) and drought (DRT) conditions in 2005 and 2006.

Traits	WW		DRT		(DRT-WW)/WW*100	Etter		Halfway	
CP	8.08	a	8.44	b	4.5	8.57	a	7.96	b
AP	7.52	a	7.81	b	3.9	7.96	a	7.37	b
ADICP	0.56	a	0.63	b	12.6	0.60	a	0.59	a
ADJCP	8.08	a	8.44	b	4.5	8.57	a	7.96	b
SPCP	30.66	a	37.90	b	23.6	35.45	a	33.10	b
NPCD	56.01	a	60.61	b	8.2	59.34	a	57.28	b
NDICP	1.33	a	1.43	b	7.9	1.43	a	1.33	b
ADF	20.72	a	24.33	b	17.5	22.45	a	22.60	a
NDF	36.76	a	42.32	b	15.1	39.97	a	39.11	a
TDN	73.56	a	69.55	b	-5.5	70.40	a	72.72	b
LIGNIN	3.11	a	4.07	b	30.7	3.74	a	3.45	a
NFC	49.17	a	42.88	b	-12.8	45.35	a	46.70	b
NSC	47.15	a	40.65	b	-13.8	43.27	a	44.53	b
STARCH	37.28	a	27.53	b	-26.1	31.78	a	33.02	a
SUGAR	9.88	a	13.12	b	32.7	11.49	a	11.51	a
CFAT	2.92	a	2.46	b	-15.5	2.68	a	2.70	a
ASH	4.41	a	5.33	b	20.9	4.86	a	4.87	a
NEL	0.78	a	0.71	b	-8.0	0.73	a	0.76	b
NEM	0.78	a	0.71	b	-8.7	0.73	a	0.76	b
NEG	0.50	a	0.44	b	-12.0	0.45	a	0.49	b
Cal	0.18	a	0.25	b	37.2	0.21	a	0.21	a
PHOS	0.22	a	0.25	b	10.9	0.24	a	0.22	b
MAGN	0.14	a	0.18	b	28.6	0.16	a	0.15	b
POT	1.11	a	1.27	b	14.8	1.23	a	1.15	b
SUL	0.09	a	0.09	b	6.6	0.09	a	0.09	b
CHL	0.35	a	0.46	b	29.7	0.42	a	0.39	b
SSNEL	0.74	a	0.68	b	-7.8	0.70	a	0.73	b
SSPNEL	0.77	a	0.69	b	-9.4	0.72	a	0.74	b
LYSINE	0.40	a	0.21	a	-46.9	0.41	a	0.20	a
METHI	0.12	a	0.13	a	4.4	0.13	a	0.12	a

Means in one row with the same letter for WW and DRT and for Etter and Halfway are not significantly different at 0.05 level.

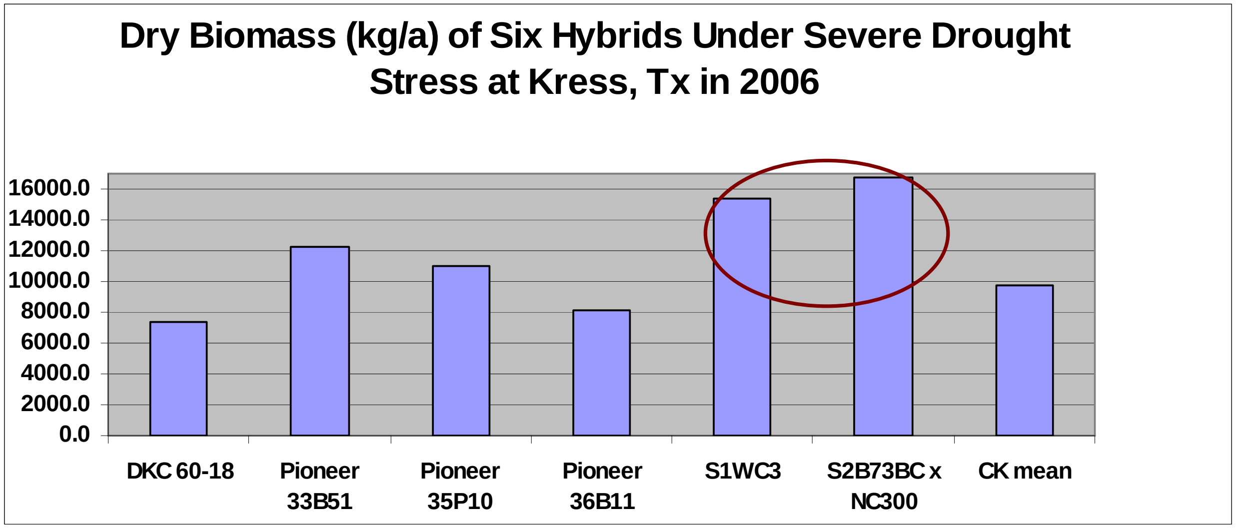

Fig. 1. The dry biomass of two TAES hybrids (S1W x CML343 and S2B73BC x NC300) and four commercial hybrids in an on-farm study at Kress, Texas in 2006. The field received an estimated total of 7 acre-inches of water from two irrigations in every other row plus less than 3-inches of rain during the growing season. TAES hybrids S1W x CML343 and S2B73BC x NC300 produced 26% and 38% more dry biomass than the best check hybrid Pioneer 33B15.