Cotton-Grain Sorghum Rotation under Extreme Deficit Irrigation Conditions

J. P. Bordovsky, J. T. Mustian, A. M. Cranmer, C. L. Emerson

Abstract. *There are over 1.0 million ha of cultivated land in the Southern High Plains of Texas, with about 40% in dryland production. Strategies that couple dryland production methods with very low levels of supplemental irrigation in contrast to current irrigated practices could stabilize crop output for an extended period at the expense of reduced agricultural productivity. An eight-year field experiment was conducted from 2001 to 2008 to develop cropping data for economic analysis. The principle goal was to compare a cotton (*Gossypium hirsute *L.) - sorghum [*Sorghum bicolor *(L.) Moench] (2:1) rotation system to a continuous cotton system, both efficiently irrigated at levels well below the evapotranspiration rate of these crops. Seasonal irrigation capacities were approximately 0%, 20%, and 40% of peak evapotranspiration rates. The rotation strategy from 2003 to 2005 allowed the movement of limited irrigation between crops based on relative water needs at critical growth periods, and from 2006 to 2008, based on water needs of the crop with the higher economic value. The results showed that in years of below average rain, cotton following sorghum resulted in 18% to 44% higher lint yields compared to continuous cotton. In years of average rain, cotton lint yields following grain sorghum were generally higher than those of continuous cotton, averaging 21%, with a portion of the increase due to higher irrigation. And, in years of above average rain, significant yield differences due to rotation were minimal, particularly at the highest irrigation capacity. Directing available irrigation to the crop of higher value (cotton) at the expense of the lower value crop (sorghum) appeared to be a major factor in elevating seasonal irrigation water use efficiency (0.448 to 0.513 kg lint m^{-3}) compared to irrigating the most water stressed crop (0.200 to 0.35 kg lint m^{-3}). Although cotton lint yield tended to be higher in the rotation than the continuous cotton treatments, the rotation resulted in significantly lower gross irrigation value than the continuous cotton cropping system in most years.*

Keywords. *Deficit irrigation, Cotton, Grain sorghum, Crop rotation.*

The competition for available water in Texas is increasing. In West Texas, the Llano Estacado Regional Planning Group projects water demand for residential, manufacturing, and livestock segments of the economy to escalate as population increases by 22% over the next 50 years (TWDB, 2010). This demand for water will be at the expense of irrigated agriculture although irrigated production is forecast to remain the cornerstone of the economy. The Ogallala Aquifer is the major water-bearing formation in the region with over 90% of the water currently used for irrigation. Recharge of the formation is minimal, estimated at less than 13 to 75 mm y^{-1} (TWDB, 2010). Therefore, non-irrigation demand will reduce availability for irrigation as groundwater supplies diminish. To maintain the agriculturally based economy, a principal strategy of the Llano Estacado Planning Group is to increase irrigation water use efficiency. This can only be achieved by taking full advantage of the region's climate, soils, and rain, and by distributing supplemental water with well-managed, efficient irrigation systems.

Dryland crop production has been economically viable on the Southern High Plains (SHP) as over 0.4 million ha of non-irrigated, row-crops are harvested each year (TASS, 2003). Two major economic problems with non-irrigated crop production include extreme year-to-year yield variability and low overall production, with yields averaging less than 25% of those from irrigated crops. On the 0.6 million irrigated ha of the SHP, production of drought tolerant crops such as cotton and grain sorghum is typical with irrigation plus rain providing 40% to 80% of crop evapotranspiration (ET). However, water demands on the aquifer could be reduced while helping stabilize crop output over dryland by combining the efficient use of very limited irrigation with dryland production strategies. This overall strategy requires the diligent use of both dryland production practices such as furrow diking, reduced and/or minimum tillage, precise plant populations and varieties, and crop rotations, as well as the use of very efficient irrigation delivery systems such as LEPA (Bordovsky et al., 1992).

The benefits of conservation-tilled cotton in rotation with grains on the SHP have been documented under furrow-irrigated conditions. Bordovsky et al. (1994) showed that a cotton-wheat (*Triticum aestivum* L.) rotation increased dryland and irrigated lint yields by 12.6% and 12.8%, respectively. No-till treatments significantly increased cotton yield (6.9% and 5.5% for dryland and irrigated, respectively) and enhanced seasonal soil water content. When no-till cultural practices were combined with planting into terminated wheat, increases in yields of 5% to 18% over

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The authors are **James P. Bordovsky, ASABE Member Engineer,** Senior Research Scientist, **Joseph T. Mustian,** Research Associate, **Andy M. Cranmer,** Farm Research Services Manager, and **Cora Lea Emerson,** Research Assistant, Texas AgriLife Research, Texas A&M University System, Lubbock-Halfway, Texas. **Corresponding author:** James P. Bordovsky, Texas AgriLife Research, Texas A&M University System, 823 West US Hwy 70, Plainview, TX 79072; phone 806-889-3315; e-mail: j-bordovsky@tamu.edu.

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conventionally planted cotton were observed in experiments at Lubbock and Halfway (Keeling et al., 1989). Potential economic advantages of rotations in irrigated production have also been investigated. Blackshear and Johnson (2003) performed an analysis of cotton yield in a cotton-grain sorghum rotation in the High Plains region indicating an increase in lint yield of 190 and 159 kg ha^{-1} following grain sorghum by one and two years, respectively. They indicated that as producers approached risk neutrality, all rotation strategies in their analysis were preferred to continuous cotton.

One of the advantages of crop rotations in areas of limited irrigation capacity is more flexible irrigation timing. In most crops, water stress at critical growth stages affects yields more adversely than at others. For example in grain sorghum, Newman (1966) reported that if only one summer irrigation is applied, maximum yield and water efficiency is achieved when the application is timed at the boot stage, or 40 to 50 days following planting. Eck and Musick (1979) and Musick (1984) found that good yield responses and efficient use of water were achieved with irrigations applied from mid-boot to flowering with much lower yield response and efficiency when water is applied only at the 6- to 8-leaf stage and the milk to soft dough stage. In cotton, yield reductions occur with reduced water availability at peak flowering compared to either earlier or later in the flowering period (Newman, 1966; Jordan, 1983). Although cotton can resume growth after a period of water stress, if water deficits develop during the peak reproductive period, the typically short South Plains growing season will reduce lint yield. The option of simultaneously producing two crops with different critical water need periods allows the option of directing limited irrigation water to the crop with the highest critical need.

The question to be answered is whether a crop rotation system will result in higher water value than a traditional continuous cotton production system under extremely deficit irrigation conditions on the Southern High Plains. The objective of this article is to document the results of a field experiment comparing two cropping systems, a cotton-sorghum rotation (ROT) and continuous cotton (ContCot), irrigated at two capacities significantly lower than the crop water demand. Preliminary economic comparisons are also presented.

Materials and Methods

The field experiment was conducted at the Texas AgriLife Research and Extension Center at Halfway, Texas (1071 m elev., 34° 11'N, 101° 56' W). The field is located adjacent to a playa in a transitional soil changing from a Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) at high elevations to an Olton loam (fine, mixed, thermic Aridic Paleustolls) at lower elevations. In 2001, a cotton-sorghum cropping system (ROT) was established on a 3.5-ha area under an 8-span center pivot with crops irrigated by LEPA using circular rows oriented perpendicular to the pivot lateral. The rotation was two years cotton followed by one year of grain sorghum. Rotation plots included: CCS – cotton followed by cotton and sorghum, CSC – cotton followed by sorghum and cotton, and SCC – sorghum followed by two years of cotton. Cotton production from individual treatments, as well as crop values from the combination of rotation treatments were compared to production from continuous cotton treatments (CCC) and values representing a continuous cotton cropping system (ContCot). Treatment areas were 12 1-m rows wide and arced 70° of the pivot circle. The 70° pivot arc was split into three smaller wedge-shaped areas where in-season irrigation capacity was limited to 0.0 mm d^{-1} (no seasonal irrigation), 1.7 mm d^{-1}, and 3.4-mm d^{-1} approximating 0%, 20%, and 40% of peak cotton ET, respectively. The four treatment plots were arranged in a complete randomized block design within four blocks along the length of the pivot lateral. This arrangement limited statistical comparisons of different irrigation capacities, but was required due to physical limitations of the irrigation system. The LEPA applicators were positioned every 2 m along the pivot lateral and dispensed water in alternate diked furrows at the ground surface. All applicators were equipped with flow valves that were either manually opened or closed as the pivot passed over plots depending on the treatment, pivot position, and irrigation protocol for that week.

The experiment was initiated in 2001 and required three years for completion of the first rotation cycle. Cotton had been grown in the test area for three years prior to this experiment. The cultural practices and irrigation sequences for 2001 and 2002 were the same as those described below for 2003 to 2005.

Irrigation Strategies

Pre-Plant Irrigations

The emphasis of this experiment was to identify strategies to achieve high water value through crop production. Although filling the soil profile prior to planting is a common practice, studies in the Texas High Plains have documented over 50% reduction in water productivity when comparing application at pre-plant to application at critical growth stages (Allen and Musick, 1986 and Bordovsky and Porter, 2003). Therefore, after 2003, pre-plant irrigations were only applied to establish crops and not to store water. These irrigations averaged 33 mm y^{-1} in seasonally irrigated treatments from 2003 to 2008.

In-Season Irrigations 2003-2005

In an effort to minimize cotton and grain sorghum stresses with the available irrigation capacities, an in-season irrigation plan was established for the ROT cropping system. The planned weekly irrigation depths for each treatment are given in table 1 along with optional schedules that adhered to irrigation capacity limitations. Early planted sorghum was initially irrigated with water available for sorghum plus that available for cotton. This was to supply water during early rapid develop of sorghum and build profile water at a time when cotton transpiration is very low and any irrigation could aggravate cotton seedling diseases. By early to mid-July, the irrigation protocol provided diversion of water from sorghum to cotton. Additional sorghum irrigations were applied at early dough stage depending upon rain and irrigation capacity. Water was provided to cotton at squaring and from peak bloom to the first week in September. Within rotation plots, the total weekly irrigation volume of combined cotton and sorghum plots was limited by irrigation capacity, either 1.7 or 3.4 mm d^{-1}, and the total irrigated area of the plots.

Table 1. Planned and optional weekly irrigation amounts (mm) in the continuous cotton and cotton-sorghum rotation cropping system treatments from 2001-2005.

Week No.[a]	Distribution Option	1.7 mm d^{-1}				3.4 mm d^{-1}			
		CCC	CCS	CSC	SCC	CCC	CCS	CSC	SCC
1	A				35				35
2	A	24			35	24			71
3	A				35	24			71
4	A	24			35	24	24	24	24
5	A		18	18		24	24	24	24
6	A	24	18	18		24	24	24	24
7	A				35	24	24	24	24
8	A	24			35	24	24	24	24
9	A	12	18	18		24	24	24	24
10	A	12	18	18		24	36	36	
11	A	12	18	18		24	36	36	
12	A	12	18	18		24	36	36	
13	A	12	18	18		24	36	36	
14	A	12	18	18		24	36	36	
Optional weekly irrigation distributions	B		0	0	35		0	0	73
	C		8	8	20		10	10	51
	D		12	12	12		18	18	35
	E		18	18	0		24	24	24
	F						28	28	15
	G						36	36	0

[a] Distributions in weeks 5 to 9 were based on rainfall and relative crop need at both irrigation capacities.

Continuous cotton treatments, by contrast, were irrigated at uniform rates throughout the irrigation period. Irrigations were typically applied one to three times per week depending on the weekly requirement. Irrigation depths during each application were no more than 12 mm per application.

In-Season Irrigations 2006-2008

Although there are yield benefits of cotton in rotation with sorghum, differences in relative crop value can offset these benefits in a rotation system. Differences in gross revenues for cotton and grain sorghum have traditionally favored cotton production in the SHP. The irrigation strategy for the rotation treatments was modified in 2006 through 2008 to reflect this. Once both crops were established, cotton was irrigated beginning at the squaring growth stage at the expense of grain sorghum until weekly irrigation plus effective rain reached approximately 80% of the estimated cotton ET. Any residual irrigation volume was applied to grain sorghum. This strategy resulted in near dryland production of sorghum at the 1.7-mm d^{-1} capacity and only very moderate irrigation of sorghum at 3.4 mm d^{-1} except when seasonal rainfall was above average. The hypothesis was that the potential increase in cotton yield achieved by rotating with sorghum plus the increase in irrigation capacity at the expense of sorghum would more than offset the value lost by lowering sorghum yield. As from 2003 to 2005, continuous cotton treatments were irrigated with uniform weekly quantities throughout the irrigation period at capacities of 1.7 or 3.4 mm d^{-1}.

Cultural Practices

One of the overall production guidelines was to minimize soil surface evaporation and runoff using available cultural practices in all test areas. The previous year's seedbeds were reshaped to initiate the cultural practices in most of the eight test years. Phosphorous and nitrogen were banded using a minimum till coulter/chisel applicator. Furrow diking of non-traffic furrows reduced rain runoff and held irrigation applications until infiltration occurred. Shredding and pulling stalks with furrow dikes in place left residue on the soil surface for up to two years. However, tillage practices, seed variety and hybrids, and nutrient requirements differed among treatment plots and years based on crop, irrigation level, and available seed technology. For example, continuous cotton plots often required additional tillage to control blowing sand compared to plots with sorghum residue. Nutrient requirements based on pre-plant soil sampling were different due to crop history and anticipated yield within a seasonal irrigation capacity. Crop seed planted in 2006 and beyond were changed from previous years due to newer hybrids and varieties that showed improved yield response to limited water and traits that allowed the use of contact herbicides later in the growing season. Specific tillage and herbicide applications from 2003 to 2008 are given in table 2. Planting information and nutrient application amounts are given in table 3.

Soil Water Monitoring

Differences in volumetric soil water content due to cultural practices or rotation within each irrigation capacity were estimated using neutron attenuation methods. Fifty-mm diameter aluminum access tubes were installed in each replicate of each treatment to the depth of 1.5 m in the center of seedbeds. Installations occurred following crop establishment from 2005 through 2008 with soil water measurements made every 0.3 m of depth starting at

Table 2. Tillage and herbicide applications of ContCot and ROT cropping system treatments at Texas AgriLife Research, Halfway, Tex., 2003-2008.

Year	Input	Operation	Date	CCC	CCS	CSC	SCC
2003	Tillage	Shred stalks	18-Jan	X		X	X
		Shred stalks	18-Mar		X		
		Dike	18-Mar		X		
		Stalk puller	19-Mar		X		
		Rotary hoe	24-May	X		X	
		Rotary hoe	31-May	X		X	
		Sweep cultivator	2-Jun				X
		Rotary hoe	3-Jun	X		X	
		Rotary hoe	7-Jun	X		X	
		Sweep cultivator	9-Jun				X
		Barring off disc/cultivator	10-Jun				X
		Dike	10-Jun				X
		Dike	18-Jun	X		X	
		Rotary hoe	23-Jun	X		X	
		Rotary hoe	25-Jun	X		X	
		Sweep cultivator	30-Jun	X	X	X	
		Barring off disc/cultivator	1-Jul	X		X	
		Dike	2-Jul	X	X	X	
	Herbicide	Glyphosate broadcast (mL m^{-2})	28-Mar	0.190		0.190	0.190
		Pendimethalin broadcast (mL m^{-2})	5-Apr	0.175		0.175	
		Paraquat dichloride broadcast (mL m^{-2})	1-May				0.117
		Paraquat dichloride broadcast (mL m^{-2})	7-May	0.117	0.117	0.117	
		Prometryn non-incorporated (mL m^{-2})	14-May	0.117	0.117	0.117	
		Atrazine non-incorporated (mL m^{-2})	15-May				0.117
		Glyphosate broadcast (mL m^{-2})	11-Jun	0.146	0.146	0.146	
		Pendimethalin directed (mL m^{-2})	11-Jun				0.175
		Glyphosate directed (mL m^{-2})	15-Aug	0.146	0.146	0.146	
2004	Tillage	Dike	23-Mar	X	X	X	X
		Shred stalks	24-Mar	X	X	X	X
		Dike	19-May	X	X	X	X
		Rotary hoe	26-May	X		X	X
		Rotary hoe	7-Jun	X		X	X
		Rolling cultivator	7-Jul	X	X	X	X
		Dike	7-Jul	X	X	X	X
	Herbicide	Paraquat dichloride (mL m^{-2})	1-Apr	0.234	0.234	0.234	0.234
		Pendimethalin broadcast (mL m^{-2})	15-Apr	0.234	0.234	0.234	
		Glyphosate broadcast (mL m^{-2})	21-Apr		0.175		0.175
		Atrazine non-incorporated (mL m^{-2})	1-Jun				0.175
		Glyphosate, shielded (mL m^{-2})	7-Jun	0.161	0.161	0.161	
		Glyphosate, shielded (mL m^{-2})	12-Jul	0.161	0.161	0.161	
2005	Tillage	Disk bedder	14-Mar				X
		Rolling cultivator	14-Mar				X
		Dike	24-Mar	X	X	X	X
		Shred stalks	30-Mar	X	X	X	X
		Stalk puller	31-Mar	X	X	X	X
		Dike	10-May	X		X	X
		Rolling cultivator	20-Jun	X	X	X	X
		Dike	20-Jun	X	X	X	X
	Herbicide	Paraquat dichloride broadcast (mL m^{-2})	21-Mar	0.256	0.256	0.256	
		Pendimethalin broadcast (mL m^{-2})	10-Apr	0.234	0.234	0.234	
		Glyphosate broadcast (mL m^{-2})	6-May	0.234	0.234	0.234	0.234
		Atrazine & S-metolachlor (mL m^{-2})	18-May				0.175 & 0.153
		Glyphosate, shielded (mL m^{-2})	7-Jun	0.234	0.234	0.234	
		Bromoxynil octanoate (mL m^{-2})	15-Jun				0.117
		Glyphosate, shielded & Pendimethalin (mL m^{-2})	20-Jul	0.234 & 0.117	0.234 & 0.117	0.234 & 0.117	

Table 2 (cont.) Tillage and herbicide applications of ContCot and ROT cropping system treatments at Texas AgriLife Research, Halfway, Tex., 2003-2008.

Year	Input	Operation	Date	CCC	CCS	CSC	SCC
2006	Tillage	Shred stalks	1-Mar				X
		Disk	3-Mar				X
		List w/RTK-GPS	3-Mar				X
		Rolling cultivator	12-Apr	X	X	X	
		Dike	21-Apr	X	X	X	
		Shred stalks	23-Apr	X	X	X	
		Stalk puller	24-Apr	X	X	X	
		Rotary hoe	26-May	X		X	X
	Herbicide	Paraquat dichloride broadcast (mL m^{-2})	27-Mar	0.117	0.117	0.117	
		Pendimethalin 3.3 EC broadcast (mL m^{-2})	12-Apr	0.351	0.351	0.351	
		Glyphosate broadcast (mL m^{-2})	10-May				0.234
		Atrazine & S-metolachlor (mL m^{-2})	16-May				0.175 & 0.117
		Glyphosate (mL m^{-2})	6-Jun	0.161	0.161	0.161	
		Bromoxynil octanoate & S-metolachlor (mL m^{-2})	22-Jun				0.117 & 0.161
		Glyphosate & Diuron 4L (mL m^{-2})	6-Jul	0.161 & 0.175	0.161 & 0.175	0.161 & 0.175	
2007	Tillage	Shred stalks	6-Dec	X	X	X	
		Disk	18-Dec	X	X	X	
		List w/RTK-GPS	18-Dec	X	X	X	
		Rolling cultivator	4-Apr	X	X	X	
		Dike	11-Apr	X	X	X	X
		Shred stalks	13-Apr				X
		Stalk puller	13-Apr				X
		Rotary hoe	23-May	X		X	X
		Rotary hoe	5-Jun	X		X	X
	Herbicide	Paraquat dichloride broadcast (mL m^{-2})	22-Feb				0.117
		Pendimethalin 3.3 EC broadcast (mL m^{-2})	4-Apr	0.175	0.175	0.175	
		Glyphosate broadcast (mL m^{-2})	3-May				0.161
		Atrazine & S-metolachlor (mL m^{-2})	17-May				0.175 & 0.117
		Prometryn & Glyphosate, shielded (mL m^{-2})	22-May	0.175 & 0.205	0.175 & 0.205	0.175 & 0.205	
2008	Tillage	Rolling cultivator	25-Mar	X	X	X	
		Dike	26-Mar	X	X	X	X
		Shred stalks	27-Mar	X	X	X	X
		Stalk puller	28-Mar	X	X	X	X
	Herbicide	Paraquat dichloride broadcast (mL m^{-2})	19-Mar	0.117	0.117	0.117	0.117
		Pendimethalin 3.3 EC broadcast (mL m^{-2})	25-Mar	0.175	0.175	0.175	
		Glyphosate broadcast (mL m^{-2})	13-May	0.205	0.205	0.205	0.205
		Atrazine & S-metolachlor (mL m^{-2})	19-May				0.175 & 0.117
		Diuron (mL m^{-2})	21-May	0.117	0.117	0.117	
		Glyphosate (mL m^{-2})	17-Jun	0.205	0.205	0.205	
		Bromoxynil octanoate & S-metolachlor (mL m^{-2})	30-Jun				0.117 & 0.153

approximately 0.15 m below the furrow elevation. Volumetric soil water was determined periodically during the growing season using measurements from a depth probe (Model 503 DR Hydroprobe, Campbell Pacific, Inc., Logan, Utah).

Harvest

From 2001 to 2007, burr cotton from 4-m^2 areas at three random locations in each plot were hand harvested and weighed to determine burr cotton yield. In 2008, a modified cotton stripper with weighing system was used to harvest approximately 62 m^2 from the centers of each cotton plot to determine burr cotton yield. Subsamples from harvested areas were weighed and gin using a small plot gin at the Texas AgriLife Research and Extension Center in Lubbock to determine lint and seed yield percentages. A lint sample was obtained during ginning for a HVI analysis performed by the Fiber and Biopolymer Research Institute at Texas Tech University in Lubbock to determine lint quality and value for each respective plot.

In each year of the experiment, grain sorghum was hand harvested from three 4-m^2 areas in each plot, seed was separated using a grain plot combine (ALMACO, Nevada, Iowa), and grain moisture measured. All grain sorghum yields were adjusted to 13% moisture content.

Data Analysis

Crop yield, water use efficiency, and water value were determined and averaged by treatment. Analysis of variance (AOV) of these parameters was conducted using the MIXED

Table 3. Agronomic data from cropping systems experiments at Texas AgriLife Research, Halfway, Tex., 2001-2008.

	Crop		Irr. Cap. ($mm\ d^{-1}$)	Year 2001	2002	2003	2004	2005	2006	2007	2008
Planting	Sorghum	Planting Date		18-May	14-May	14-May	19-May	18-May	16-May	17-May	19-May
		Variety[a]		GA 1506	GA 1506	GA 1506	GA 1506	GA 1506	GA 3545	GA 3545	GA 3545
		Seeding rate (1000 seed/ha^{-1})[b]		64 to 110	64 to 110	64 to 110	64 to 110	64 to 110	64 to 110	64 to 110	64 to 110
	Cotton	Planting date		20-May	14-May	15-May	19-May	17-May	15-May	16-May	19-May
		Variety		PM 2325 RR	PM 2325 RR	PM 2325 RR	PM 2325 RR	PM 2325 RR	FM 989B2R	FM 989B2R	FM 989B2R
		Seeding rate (1000 seed/ha^{-1})		150	150	150	150	130	120	130	114
Nutrients[c]	Sorghum	Phosphorous (kg ha^{-1})	0	45	30	34	0	0	0	0	0
			1.7	45	65	45	0	62	45	38	0
			3.4	45	95	45	22	0	78	38	56
		Nitrogen (kg ha^{-1})	0	56	31	45	41	34	78	0	39
			1.7	112	64	101	41	34	112	101	67
			3.4	112	112	146	90	101	134	101	112
	Cotton	Phosphorous (kg ha^{-1})	0	45	30	34	0	0	0	0	0
			1.7	45	65	45	0	0	45	38	0
			3.4	45	95	50	22	62	78	38	78
		Nitrogen (kg ha^{-1})	0	56	56	45	0	34	78	56	39
			1.7	112	56	101	76	67	112	101	101
			3.4	112	95	147	90	67	134	157	157

[a] GA - Golden Acres Brand Seed, PM - Paymaster Brand Seed., FM - FiberMax Brand Seed.
[b] Seeding rate range from 0 to 3.7 mm d^{-1} irrigation levels.
[c] N and P were applied as either 10-34-0 or 32-0-0.

procedure in SAS® (Littell et al., 2006). The AOV's were separately conducted under each irrigation capacity. Means separation analysis was conducted using the Duncan's Multiple Range Test.

Results and Discussion

Weather Effects

Timing and quantity of rain have a significant impact on crop production in limited irrigated areas. Figure 1 shows monthly rain depths from 2003 to 2008 at the research center at Halfway. With average annual rainfall at 460 mm y^{-1}, rain was below average in 2003 (303 mm) and 2008 (376 mm), was close to average in 2005 (448 mm), 2006 (455 mm), and above average in 2004 (876 mm) and 2007 (559 mm). The distribution of rain differed from year to year with the poorest distribution in 2003 where approximately 50% of the 2003 annual total occurred in June. Heavy rain, hail, and high winds in June drastically reduced cotton plant populations and increased susceptibility of remaining plants to the seedling diseases rhizoctonia, pythium, and thielaviopsis that slowed growth. The most timely rain distribution was in 2005 when the pattern of increasing monthly rains proportionally matching that of crop water demand during the months of May to August. The 2004 crop year was the second wettest on record at the research location and the area.

The time period for full maturity of cotton plants in the SHP is limited due to elevation and latitude. Cumulative growing-degree days ($dd_{15.6c}$) are typically used as an indicator of physiological development of cotton (Stapleton, 1970) particularly in thermally limited areas. Monthly growing-degree days from 2003 to 2008 are given in figure 1. The lowest annual $dd_{15.6c}$ occurred in 2004 (1030 $dd_{15.6c}$), the year of highest rain; the highest $dd_{15.6c}$ occurred in 2006 (1228 $dd_{15.6c}$) when rain from May to August totaled only 166 mm. Although cumulative growing-degree days can be irrelevant when cotton plants lack sufficient water to meet transpiration needs, late season energy received by cotton plants is thought to have greatly contributed to final cotton yield in 2005 and 2007. Total $dd_{15.6c}$'s in September and October were 234 and 255 in the two respective years compared to the long-term average of 190 $dd_{15.6c}$'s for the two months.

The estimated crop water demand or ET from planting is also given in figure 1. These values were determined using reference ET (ET_o) values from the Texas High Plains Evapotranspiration Network (Porter et al., 2005) and locally derived crop coefficients. Of the six years considered, the highest demand occurred in 2006 (723 mm) and the lowest in 2007 (582 mm).

Irrigation

Seasonal irrigations were typically initiated the first week of June and were terminated the last week in August. Because weekly irrigation volumes were low at both capacities, irrigations occurred every week even when crop water demand was zero unless heavy rain physically prevented them or the estimate available soil water content of the profile was near 100%. Some irrigations were eliminated in treatments in 2003 (extremely wet June), and in the higher than average rain years of 2004 and 2007. Annual irrigation depths by treatment from 2001 to 2008 are given in table 4.

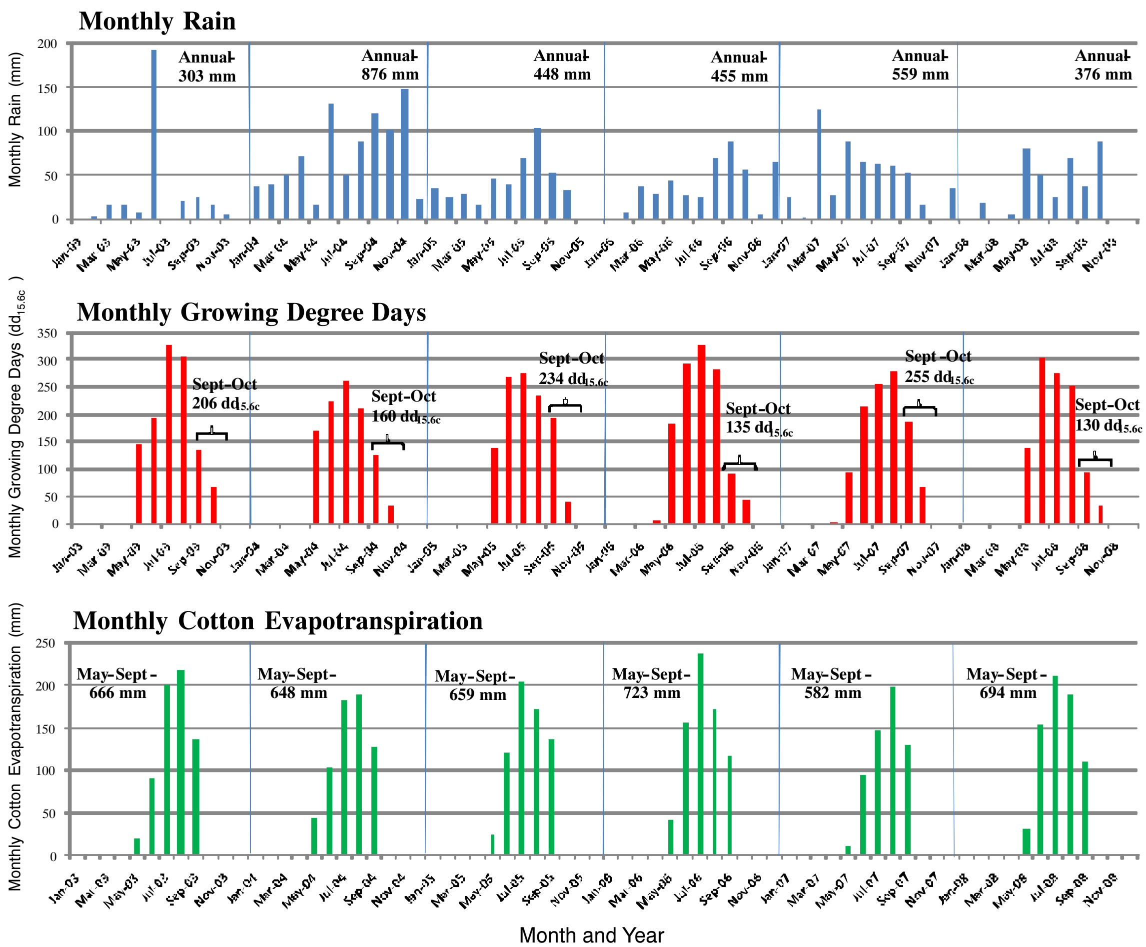

Figure 1. Monthly rain, growing degree days, and ET from cropping system experiments at Texas AgriLife Research, Halfway, Tex., 2003-2008.

An example of actual irrigation application in cotton and grain sorghum treatments used through 2005 at 1.7 and 3.4 mm d^{-1} is shown in figure 2. The CCS and CSC irrigation applications were identical in all years, therefore, irrigation amounts from the CSC treatments are not shown. The slopes of lines through data points indicate irrigation rates and show periods where water was applied to sorghum, cotton, or both in the rotation system. Uniform rates of cotton irrigation throughout the growing season in the CCC treatments are also shown. According to the irrigation protocol, cotton in the CCS treatments received less cumulative irrigation up to the critical peak blooming period (24 Jul to 7 Aug) than did the

Table 4. Pre-plant, at-plant, and seasonal irrigation amounts (mm) by year and cropping system treatments, 2001-2008.

Irr. Cap. (mm d^{-1})	Irr. Time	Plot Treatment	2001	2002	2003	2004	2005	Avg 2003-2005	2006	2007	2008	Avg 2006-2008
0	Pre-plant	All	76	6	29	0	0	*10*	49	0	66	*38*
	At-plant	All	0	0	0	36	18	*18*	10	0	8	*6*
	In season	All	0	0	0	0	0	*0*	0	0	0	*0*
1.7	Pre-plant	All	76	65	83	0	0	*28*	49	0	66	*38*
	At-plant	All	0	0	0	36	18	*18*	10	0	8	*6*
	In season	CCC	163	159	114	156	124	*131*	153	101	179	*144*
		CCS	152	143	97	118	133	*116*	215	134	197	*182*
		CSC	152	143	97	118	133	*116*	215	134	197	*182*
		SCC	157	197	198	208	126	*178*	0	108	112	*73*
3.4	Pre-plant	All	76	99	82	0	0	*27*	49	0	66	*38*
	At-plant	All	0	0	0	36	18	*18*	10	0	8	*6*
	In season	CCC	284	324	213	275	245	*245*	285	196	275	*252*
		CCS	274	316	173	227	249	*216*	366	241	302	*303*
		CSC	279	316	173	227	249	*216*	366	241	302	*303*
		SCC	340	326	378	313	180	*290*	116	124	243	*161*

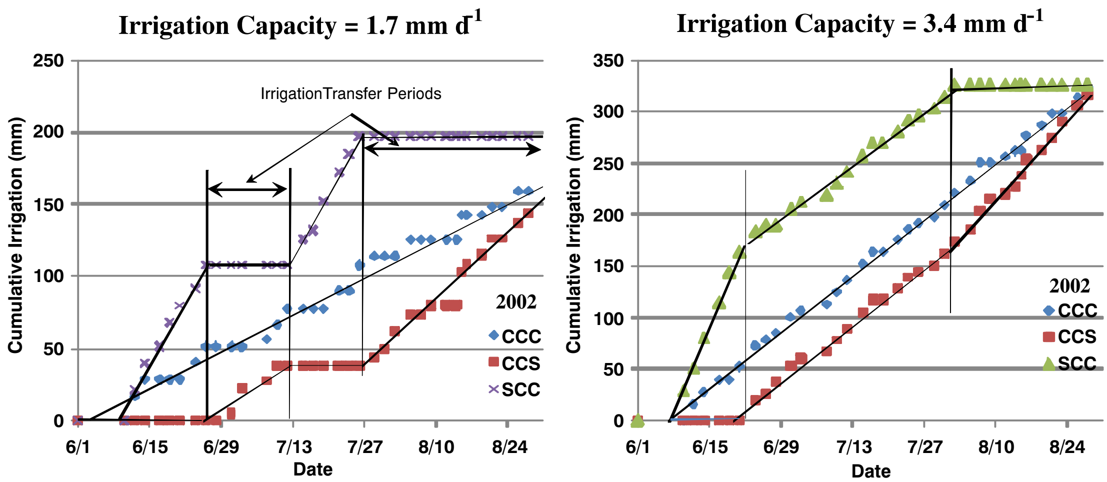

Figure 2. An example of cumulative irrigation in treatment areas of the cropping systems experiment at Texas AgriLife Research, Halfway, Tex., 2002.

CCC treatments. Part of the strategy was that the higher irrigation rates at peak bloom and later in the growing season would compensate for the lower cumulative irrigation total up to that point.

In-season irrigation strategy changed in 2006 as described earlier. Irrigation amounts are given in table 4. The major difference in irrigation distribution from the 2006-2008 period and that of the three previous years can be seen in the in-season irrigation averages among treatments. In the later years continuous cotton received an average of 144- and 252-mm seasonal irrigation at the 1.7- and 3.4-mm d^{-1} irrigation levels while the rotation cotton received 26% and 20% more water (182 and 303 mm, respectively). In contrast, from 2003 to 2005, continuous cotton received an average of 131- and 245-mm seasonal irrigation at the 1.7- and 3.4-mm d^{-1} irrigation levels while the rotation cotton received 11% and 12% less water (116 and 216 mm, respectively). Irrigation quantity available to grain sorghum was inversely proportional to that applied to cotton in the rotation treatments due to irrigation capacity limits.

Volumetric Water Content

Seasonal volumetric soil water content (VWC) in the 1.4-m soil profile of cropping system treatments from 2005 to 2008 are shown in figure 3. The VWC in the cotton treatments following sorghum (CCS) showed no consistent increase over measured VWC in the continuous cotton treatments (CCC) except in 2008. As expected, within a given year, the VWC generally started and ended the growing season at slightly higher levels in treatments having higher irrigation capacity. For example, in 2006, the VWCs on day 159 of the CCS treatments were 0.254, 0.267, and 0.283 mm mm^{-1} at respective irrigation capacities of 0.0, 1.7, and 3.4 mm d^{-1}. Also, following the change in irrigation strategy in 2006, VWCs in the sorghum treatment plots were generally less than those in cotton plots.

Cotton Production

Yield

Cotton lint yield by treatment from 2003 through 2008 are given in table 5. Variations in climatic conditions over the period directly affected treatment responses. Following the harsh June weather in 2003, irrigated cotton benefited from 60 days of hot, dry weather producing reasonable cotton yields. Irrigated cotton treatments following sorghum resulted in yields up to 27% higher than those from corresponding continuous cotton treatments (1083 vs. 855 kg ha^{-1} in CCS and CCC treatments, respectively, at the 3.4-mm d^{-1} capacity) The crops in 2008 also received below average rainfall with cotton yields from CCS treatments up to 44% higher than CCC treatments (1056 vs. 734 kg ha^{-1} in respective treatments at the 1.7-mm d^{-1} capacity). A portion of this yield increase is attributed to 10.1% higher seasonal irrigation in the CCS than the CCC treatments (table 4).

The 2004 growing season, with above average rainfall, resulted in particularly high lint yield in the non-seasonally irrigated (0.0 mm d^{-1}) treatments and appeared to have eliminated significant yield differences due to rotation at the 1.7- and 3.4-mm d^{-1} capacities. Above average rains also fell in 2007. Lint yields were high at all irrigation capacities with the CCS treatment producing 14% and 15% more cotton lint at 0.0- and 1.7-mm d^{-1} capacities, respectively, than the CCC treatment. Again, due to irrigation strategy, CCS received 33% more irrigation than CCC at the 1.7-mm d^{-1} capacity (134 vs. 101 mm, respectively), therefore, yield increase likely was not solely due to rotation effects. No significant yield differences at the 3.4 mm d^{-1} was observed and is attributed to seasonal rain in 2007.

The annual rainfall amounts and patterns in 2005 and 2006 were very near to the long term average. Cotton lint yields were high in 2005 due in part to residual soil water from the previous year, the timely rain in the summer of 2005, and the long growing season (growing degree day of 234 $dd_{15.6c}$ in September and October). At 0.0- and 1.7-mm d^{-1} capacities, cotton following sorghum produced significantly higher lint yield, 6% and 15%, respectively, than continuous cotton. The 2006 crop year was hot and dry until rain occurred in August. For the year at the 0-, 1.7-, and 3.4-mm d^{-1} capacities, the CCS treatment significantly increased yield over the CCC treatment by 45, 390, and 334 kg ha^{-1}. However, much of the increase was attributable to higher irrigation quantities in the CCS than the CCC plots at 0, 62, and 81 mm at the respective irrigation capacities.

When considering the average lint yields of years 2003 to 2005, there were no significant differences (α = 0.05) in cotton lint yield due to rotation with sorghum within

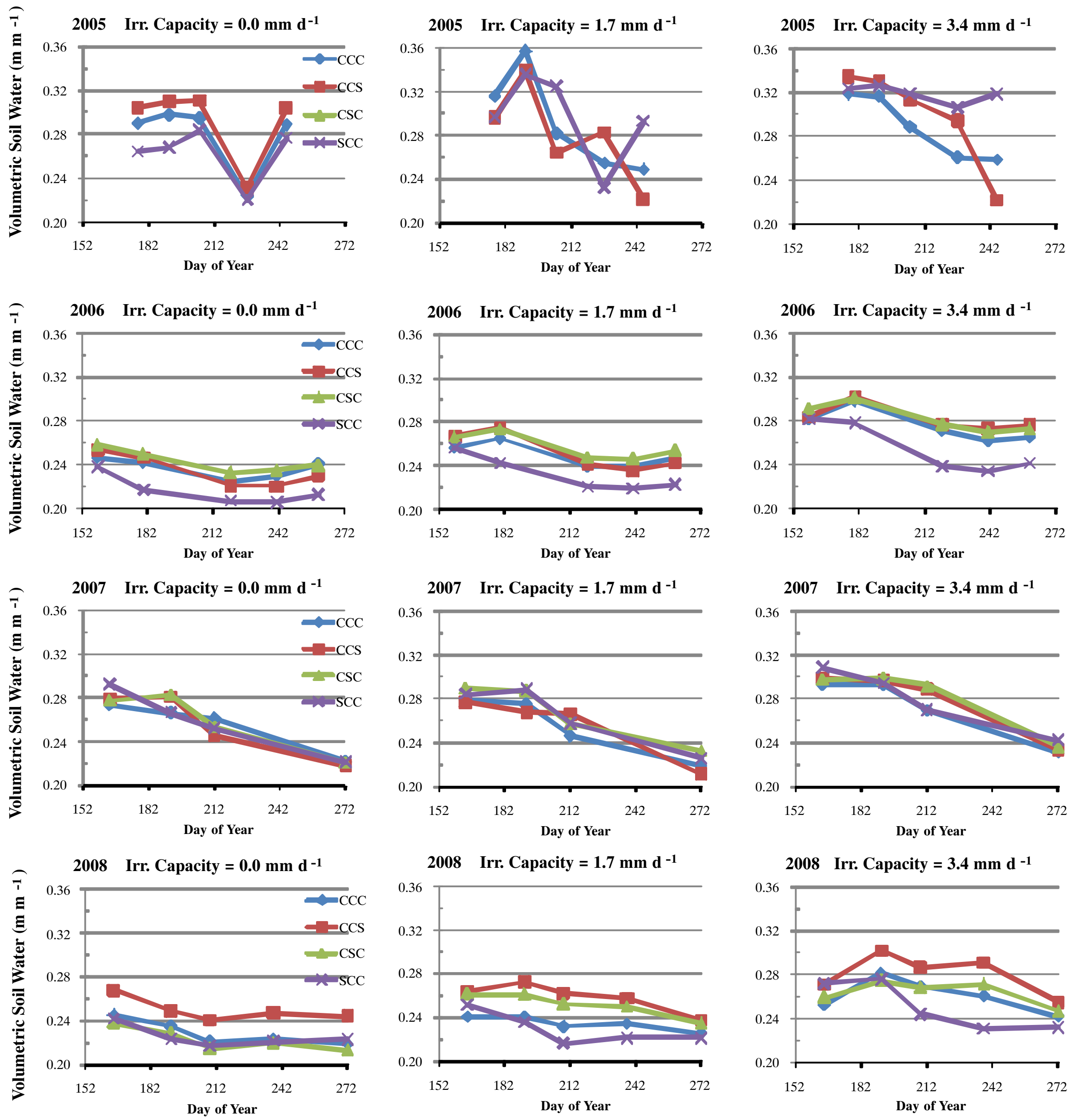

Figure 3. Seasonal volumetric soil water content from cropping system treatments at Texas AgriLife Research, Halfway, Tex., 2005-2008.

irrigation capacity. From 2006 to 2008, where water was used to meet the needs of cotton before grain sorghum, the cotton treatments with sorghum resulted in significant increases in lint yield of 31% and 10.6% at seasonal irrigation capacities of 1.7 and 3.4 mm d^{-1}. These relative yield increases were primarily attributed to higher irrigation quantities applied, 26% and 20% more in the rotation than continuous cotton treatments at the two respective irrigation capacities.

The benefits of having sorghum in rotation with cotton were most evident in adverse weather year of 2003. This was due to sorghum residue providing protection to cotton plants from blowing sand and a probable reduction in the occurrence of cotton diseases. Further direct benefits to cotton are realized in the reduction in the number of field operations required to reduce blowing sand compared to continuous cotton (table 2).

Water Use Efficiency

The calculation of water use efficiency (WUE) normalizes the effect of different irrigation amounts on comparable treatments providing a better picture of treatment effects. In years that the seasonal soil water was measured, WUE estimates were calculated for each treatment replicate by dividing lint yield by the water use of the treatment during the period from planting until 30 September. Total water use was estimated by adding seasonal irrigation, effective rain, and changes in profile water. Effective rain quantities were determined by daily rainfall measurement at the Halfway research site reduced by runoff. Runoff was estimated using USDA-SCS runoff curve number method (USDA-SCS, 1985). The change in profile water over the consumptive period was estimated using VWC measurements from 2005 through 2008. Average WUEs by treatment are given in table 5.

Table 5. Cotton lint yield, loan value, water use efficiency (WUE), and seasonal irrigation water use efficiency (SIWUE) by year and crop sequence, Halfway, 2003-2008.

Parameter	Irr. Cap. (mm d^{-1})	Crop Sequence	2003[c]	2004	2005	Avg. 2003-2005	2006	2007	2008	Avg. 2006-2008	Avg. 2003-2008[d]
Yield (kg ha^{-1})	0	CCC	330 a	622 ab	1144 b	*699 a*	130 b	476 b	102 a	*236 b*	*467*
		CCS	318 a	668 a	1210 a	*732 a*	175 a	541 a	134 a	*284 a*	*508*
		CSC	323 a	577 b	1173 ab	*691 a*	145 ab	456 b	65 b	*222 b*	*457*
	1.7	CCC	667 c	978 a	1500 b	*1048 a*	806 b	1075 b	734 c	*872 b*	*960*
		CCS	790 a	967 a	1728 a	*1162 a*	1196 a	1226 a	1056 a	*1159 a*	*1161*
		CSC	708 b	971 a	1434 b	*1037 a*	1132 a	1302 a	952 b	*1129 a*	*1083*
	3.4	CCC	855 b	1085 a	1720 a	*1220 a*	1541 b	1640 a	1167 b	*1449 b*	*1335*
		CCS	1083 a	1050 a	1677 a	*1270 a*	1875 a	1618 a	1295 a	*1596 a*	*1433*
		CSC	1012 a	1082 a	1713 a	*1269 a*	1815 a	1696 a	1312 a	*1608 a*	*1438*
Loan value ($ kg^{-1})	0	CCC	1.193	1.127	1.261	*1.194*	1.140	1.100	1.144	*1.128*	*1.161*
		CCS	1.047	1.052	1.215	*1.105*	1.186	1.114	1.158	*1.152*	*1.129*
		CSC	1.103	1.094	1.257	*1.151*	1.166	1.096	1.105	*1.122*	*1.137*
	1.7	CCC	1.195	1.131	1.272	*1.200*	1.250	1.239	1.230	*1.240*	*1.220*
		CCS	1.166	1.164	1.270	*1.200*	1.263	1.274	1.164	*1.234*	*1.217*
		CSC	1.166	1.127	1.274	*1.189*	1.250	1.266	1.173	*1.230*	*1.209*
	3.4	CCC	1.195	1.142	1.261	*1.200*	1.286	1.263	1.158	*1.236*	*1.218*
		CCS	1.197	1.144	1.279	*1.207*	1.266	1.204	1.120	*1.197*	*1.202*
		CSC	1.213	1.169	1.257	*1.213*	1.257	1.255	1.122	*1.211*	*1.212*
WUE (kg lint m^{-3})[a]	0	CCC			0.317 a		0.045 a	0.130 a	0.040 b	*0.072 b*	*0.133*
		CCS			0.335 b		0.061 a	0.148 a	0.053 a	*0.087 a*	*0.149*
		CSC			0.325 ab		0.051 a	0.125 a	0.026 c	*0.067 b*	*0.132*
	1.7	CCC			0.301 b		0.190 b	0.237 a	0.175 c	*0.200 b*	*0.226*
		CCS			0.341 a		0.246 a	0.252 ab	0.227 a	*0.242 a*	*0.266*
		CSC			0.283 c		0.233 a	0.267 a	0.205 b	*0.235 a*	*0.247*
	3.4	CCC			0.257 a		0.277 b	0.292 a	0.220 b	*0.263 a*	*0.261*
		CCS			0.249 a		0.294 a	0.267 b	0.233 ab	*0.264 a*	*0.260*
		CSC			0.254 a		0.285 ab	0.279 ab	0.236 a	*0.267 a*	*0.264*
SIWUE (kg lint m^{-3})[b]	1.7	CCC	0.201 b	0.229 b	0.288 b	*0.239 b*	0.442 a	0.594 ab	0.354 b	*0.463 a*	*0.351*
		CCS	0.307 a	0.293 a	0.439 a	*0.346 a*	0.497 a	0.558 b	0.483 a	*0.513 a*	*0.429*
		CSC	0.252 a	0.296 a	0.217 c	*0.255 b*	0.467 a	0.615 a	0.431 a	*0.504 a*	*0.380*
	3.4	CCC	0.197 b	0.168 a	0.235 a	*0.200 a*	0.495 a	0.594 a	0.387 a	*0.492 a*	*0.346*
		CCS	0.333 a	0.188 a	0.214 a	*0.245 a*	0.477 ab	0.474 b	0.395 a	*0.448 b*	*0.347*
		CSC	0.302 a	0.203 a	0.228 a	*0.244 a*	0.460 b	0.506 b	0.401 a	*0.456 b*	*0.350*

[a] WUE = lint yield / (seasonal irrigation + effective rain + change in profile water). Measurements of volumetric water content were not made in 2003 and 2004.
[b] SIWUE = (lint yield - non-irrigated lint yield) / seasonal irrigation
[c] Column means within a parameter and irrigation capacity followed by the same letter are not significantly different (α = 0.05, Duncan).
[d] WUE averages are for years 2005-2008.

WUE for treatments by year generally followed the trends seen in cotton lint yields. When considering averages for year 2005, the cotton treatments following sorghum (CCS) resulted in a 13% (0.341 vs. 0.301 kg m^{-3}) and -3% (0.249 vs. 0.257 kg m^{-3}) increase in WUE over continuous cotton (CCC) at the 1.7- and 3.4-mm d^{-1} irrigation capacities, respectively. For the years from 2006 to 2008, the cotton treatments following sorghum (CCS) resulted in a 21% (0.242 vs. 0.200 kg m^{-3}) and 0% (0.263 vs. 0.264 kg m^{-3}) increase in WUE over continuous cotton (CCC) at the 1.7- and 3.4-mm d^{-1} irrigation capacities.

Seasonal Irrigation Water Use Efficiency

Seasonal irrigation water use efficiency (SIWUE) is the quantity of cotton lint produced from each unit of seasonal irrigation applied and is also given in table 5. SIWUE is determined by subtracting the non-seasonally irrigated yields (yield of 0.0 mm d^{-1}) from corresponding seasonally irrigated yields and dividing by the seasonal irrigation quantity. Overall, the average SIWUE's were much higher from 2006 to 2008 than those from 2003 to 2005 (0.479 vs. 0.255 kg m^{-3}, respectively). This may partially be due to the forced change in cotton variety. The variety used through 2005 was no longer commercially available and was replaced with one having similar yield characteristics over a range of irrigation levels. When considering SIWUE averages for years 2003-2005, the cotton treatments following sorghum (CCS) resulted in a 44% (0.346 vs. 0.239 kg m^{-3}) and 23% (0.245 vs. 0.200 kg m^{-3}) increases in SIWUE over continuous cotton (CCC) at the 1.7- and 3.4-mm d^{-1} irrigation capacities, respectively. For the years from 2006 to 2008, CCS resulted in an 11% (0.513 vs. 0.463 kg m^{-3}) increase and a 9% (0.448

vs. 0.492 kg m^{-3}) *decrease* in SIWUE over CCC at the 1.7- and 3.4-mm d^{-1} irrigation capacities, respectfully. In general, SIWUE was greater at the 1.7-mm d^{-1} than the 3.4-mm d^{-1} irrigation capacity indicating the highest in-season water use efficiency tends to occur where irrigation is very limited and cotton is in rotation with sorghum compared to a continuous cotton production system.

Grain Sorghum Production

Grain sorghum yield by year and treatment is given in table 6. Grain yields were much higher in the 2003 to 2005 period than the 2006 to 2008 period (4567 kg ha^{-1} compared to 2330 kg ha^{-1}, respectively) due to the change in irrigation strategy directing more irrigation to cotton from 2006 to 2008. No grain was harvested in the 0.0-mm d^{-1} irrigation capacity treatments in 2003, 2006, and 2008 due to insufficient rain; or at the 1.7-mm d^{-1} capacity in 2006 due to low rain and lack of irrigation opportunity. However, sufficient plant growth occurred in these years to provide residue for the following cotton crop. From 2003 to 2005, grain sorghum yields were reasonable relative to the irrigation available. From 2006 to 2008, grain yields were heavily dependent on seasonal rain quantity and timing. Average grain prices, grain values, WUE, and SIWUE are also contained in table 6.

Comparison of Cropping Systems

Gross Seasonal Irrigation Value

Determining meaningful water value is difficult and can be very arbitrary. One of the reasons for conducting this field experiment was to provide data for economic models that would illustrate how irrigation decisions and strategies affect water value. One preliminary analysis was conducted by Pate et al. (2010) and concluded that continuous cotton production was economically preferred production system compared to the cotton-sorghum rotation. Additional evaluations of water value based on *net* rather than *gross* returns is beyond the scope of this article, however a simple evaluation of gross returns provides some general insights.

The gross seasonal irrigation value (IRRVAL) was determined for the ROT and ContCot cropping systems. The IRRVAL for the ROT system was determined each year by averaging the gross production values of the three irrigated rotation crops, (lint value from CCS, lint value from CSC, and grain value from SCC); reducing this amount by the gross return of the best non-irrigated alternative (lint value of CCC treatments at 0.0-mm d^{-1} capacity), and dividing this by the average seasonal irrigation depth from CCS, CSC, and SCC treatments at each irrigation capacity. This value represented the gross value of seasonal irrigation sold as lint cotton covering 66.6% and sorghum grain covering 33.3% of an area for a given year. Cotton value was determined for each treatment and replicate by multiplying lint yield by cotton lint loan price from that replicate (table 5). Grain value was determined by multiplying grain yield of each replicate by the average annual grain sorghum price for the particular year (NASS, 2009, table 6). The gross seasonal irrigation value for ContCot was similarly determined using cotton lint yield from the CCC treatments and seasonal irrigation amounts.

The IRRVALs of the two systems are given in table 7 by year and irrigation capacity. The IRRVAL from 2003 to 2005, where irrigations were applied to both crops at critical periods, ranged from \$0.06 m^{-3} to \$0.38 m^{-3} and was much lower than the IRRVAL from 2006 to 2008, where irrigations favored cotton production over sorghum, which ranged in value from \$0.42 m^{-3} to \$0.80 m^{-3}. This very large increase in value is attributed to focusing the limited irrigation to the crop of higher value as well as changing to more productive crop varieties.

Although cotton lint yield tended to be significantly higher when following grain sorghum, the ROT cropping system resulted in significantly lower IRRVAL than did the ContCot system in most years and at both irrigation capacities. The exception was the 1.7 mm d^{-1} irrigation capacity in 2006 to 2008, where average IRRVAL was \$0.60 m^{-3} for ContCot and \$0.54 m^{-3} for ROT cropping systems. Over the 6 year period, cotton rotation with sorghum resulted in lower gross water value than continuous cotton production.

Table 6. Grain sorghum yield, grain price, grain value, and water use efficiency by year from crop rotation treatments with cotton at Texas AgriLife Research, Halfway, Tex., 2003-2008.

Parameter	Irr. Cap. (mm d^{-1})	2003	2004	2005	Avg. 2003-2005	Avg.	2006	2007	2008	Avg. 2006-2008	Avg.
Yield (kg ha^{-1})	0	0	1126	4112	*1746*		0	1951	0	*650*	
	1.7	3338	6116	6171	*5208*		0	3835	829	*1555*	
	3.4	6346	6687	7207	*6746*	*4567*	2835	5564	5955	*4784*	*2330*
Avg. grain prices (\$ kg^{-1})	0	0.091	0.088	0.086	*0.088*		0.116	0.146	0.161	*0.141*	
	1.7	0.091	0.088	0.086	*0.088*		0.116	0.146	0.161	*0.141*	
	3.4	0.091	0.088	0.086	*0.088*		0.116	0.146	0.161	*0.141*	
Avg. grain value (\$ ha^{-1})	0	0	99	353	*151*		0	284	0	*95*	
	1.7	304	538	529	*457*		0	558	134	*231*	
	3.4	578	588	618	*595*	*401*	328	810	959	*699*	*341*
WUE (kg grain m^{-3})	0			1.225			0.000	0.515	0.000	*0.172*	
	1.7			1.266			0.000	0.831	0.259	*0.363*	
	3.4			1.461		*1.317*	0.666	1.135	1.317	*1.039*	*0.525*
SIWUE (kg grain m^{-3})	1.7	1.328	2.396	1.627	*1.784*		0.000	1.746	0.740	*0.829*	
	3.4	1.470	1.778	1.718	*1.656*	*1.720*	2.441	2.908	2.447	*2.599*	*1.489*

Table 7. Gross seasonal irrigation value (IRRVAL) of cropping system treatments by year ($ m^{-3}) at Texas AgriLife Research, Halfway, Tex., 2003-2008.

Irr. Cap. (mm d^{-1})	Cropping System	2003	2004	2005	Average of 2003-2005	2006	2007	2008	Average of 2006-2008
1.7	ContCot	0.35 a	0.26 a	0.38 a	*0.33 a*	0.56 a	0.80 a	0.44 a	*0.60 a*
	ROT	0.22 b	0.15 b	0.06 b	*0.14 b*	0.58 a	0.61 b	0.43 a	*0.54 a*
	Avg.	0.29	0.21	0.22	*0.24*	0.57	0.71	0.43	*0.57*
3.4	ContCot	0.30 a	0.20 a	0.30 a	*0.26 a*	0.64 a	0.79 a	0.45 a	*0.63 a*
	ROT	0.26 a	0.12 b	0.09 b	*0.16 b*	0.54 b	0.57 b	0.42 a	*0.51 b*
	Avg.	0.28	0.16	0.19	*0.21*	0.59	0.68	0.43	*0.57*

[a] Pairs of means within irrigation capacity treatments by year followed by the same letter are not significantly different ($\alpha = 0.5$, Duncan).

Grain Price Evaluation

The average annual price of grain sorghum used for this analysis increased from \$0.091 kg^{-1} in 2003 to \$0.161 kg^{-1} in 2008 (table 4). Since the IRRVAL was heavily dependent on sorghum grain price, a simple sensitivity analysis was conducted to determine the sorghum price required for IRRVAL of the ROT system to equal or exceed that of the ContCot system. Figure 4 shows the effect of grain sorghum price on IRRVAL of the 2:1 cotton-grain sorghum rotation compared to continuous cotton with cotton lint valued at \$1.32 kg^{-1} based on 2006 to 2008 crop yields. The figure shows that the grain price would have to double the average 2006 to 2008 price of \$0.14 kg^{-1}, or reach \$0.28 kg^{-1} for the ROT cropping system to achieve comparable irrigation value as the ContCot system.

Conclusions

The results documented the effect of crop rotation and irrigation strategy on cotton yield in a cotton-sorghum rotation where irrigation quantities were very limited. Annual rainfall had a critical effect on the results. In the below average rain years of 2003 and 2008, cotton following sorghum had significantly higher yields ranging from 18% to 44% compared to continuous cotton. Most of the yield increase was attributed to rotation effects. In years of above average rain, 2004 and 2007, rain events minimized significant yield differences due to rotation, particularly at the 3.4-mm d^{-1} irrigation capacity. In years of average rain, 2005 and 2006, lint yields following grain sorghum were generally higher than those of continuous cotton, but increases averaged only 21% with these increases also affected by increases in irrigation levels. Water use efficiencies generally mirrored lint yield results.

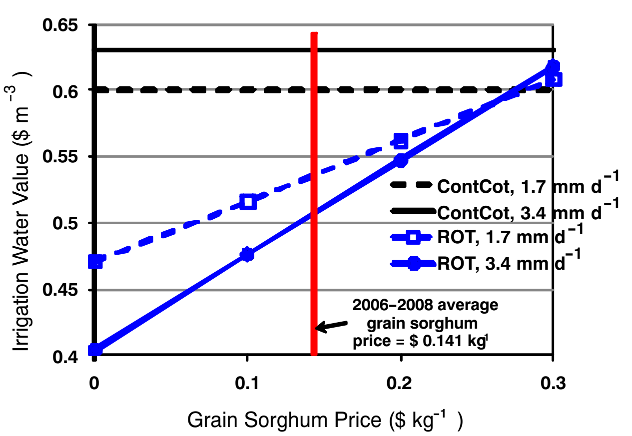

Figure 4. Comparison of gross irrigation water value based on average lint and grain yields from 2006 to 2008 and cotton lint price of \$1.32 kg^{-1} at 1.7- and 3.4-mm d^{-1} irrigation capacities from rotation and continuous cotton cropping systems at Texas AgriLife Research, Halfway, Tex.

In terms of distributing very limited water resources in a crop rotation system based on critical growth periods of both crops or based on the crop with higher value, the latter strategy along with a change in variety resulted in much higher seasonal irrigation water use efficiency for cotton. When water was distributed base on crop need, from 2003 to 2005, the average SIWUE ranged from 0.200 to 0.346 kg lint m^{-3} compared to 2006 to 2008 where the average SIWUE ranged from 0.448 to 0.513 kg lint m^{-3}.

Although cotton lint yield tended to be higher in the ROT versus the ContCot cropping system, the ROT system resulted in significantly lower gross irrigation value than ContCot system in most years at both 1.7- and 3.4-mm d^{-1} capacities. This was based on commodity prices during respective test years. A simple economic analysis indicated that sorghum grain price would have to double the 2008 price, or reach \$0.28 kg^{-1} for the ROT cropping system to achieve comparable irrigation value as the ContCot system.

Under very limited irrigated conditions, the major drawbacks to this rotation were the low grain value compared to that of cotton and the higher water requirement to initiate a minimum grain production relative to cotton. Data from this experiment will be used for modeling and further economic evaluations.

Acknowledgments

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