EVALUATION OF TEXAS HIGH PLAINS COTTON-SORGHUM CROPPING SYSTEMS USING LIMITED IRRIGATION STRATEGIES

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Abstract

Due to the increasing demand and limited supply of groundwater from the Ogallala aquifer, water use efficiency and agricultural water savings policies are at the forefront in the Texas High Plains. The objective of this field experiment was to determine yield and seasonal irrigation water use efficiency (SIWUE) of continuous cotton and cotton/sorghum rotations while evaluating three "water saving" strategies with annual irrigation depths limited to less than 5 inches per year. The experiment was conducted from 2004 to 2007 at the Texas AgriLife Research Center at Halfway. The continuous cotton and the cotton/sorghum rotation treatments were composed of the cropping sequences CCC – continuous cotton, CCS – cotton followed by cotton and sorghum, CSC – cotton followed by sorghum and cotton, and SCC – sorghum followed by two years of cotton. The irrigation strategies were; T1 - water applied to insure crop establishment, no in-season irrigation, any remaining water up to the five inch limit is "saved"; T2 - five inches of annual irrigation applied only if soil water content at planting was greater than 50% of field capacity, otherwise, the water is "saved"; and T3 - five inches of annual irrigation regardless of initial soil water content. Over the 4-year period, the T1 treatment resulted in average annual cotton yields ranging from 674 to 719 lb lint/ac with total irrigations of 0.8 inches; T2 resulted in yields ranged from 905 to 951 lb lint/ac with irrigations of 3.04 to 3.35 inches; and T3 resulted in yields ranged from 1021 to1050 lb lint/ac with total annual irrigations of 4.53 to 5.22 inches. By evaluating treatments using gross return including residual water valued at $12/ac-in, water savings in the T1 treatment did not compensate for the increase in value from crop sales received by applying additional irrigation in the T2 and T3 treatments. The continuous cotton treatment resulted in higher gross returns within each strategy than did the cotton-sorghum rotation treatment. SIWUE of strategies T2 and T3 exceeded normal water use efficiency levels by 44 and 126%, respectively, over the 4-year test period. Additional economic evaluations will be made in the future.

Introduction

The demand for groundwater from the Ogallala continues to increase. Agricultural water policies related to actual water "savings" in contrast to simply improving water use efficiency are being openly discussed on the Texas High Plains. Although the value of water consumed in municipal and industrial settings is much higher than that in production agriculture, the economy of the irrigated plains regions of the US is heavily dependent on irrigated agriculture. Therefore, reducing the amount of Ogallala water used for agricultural production without substantial harm to regional economies will be a tremendous challenge.

Dryland production of cotton in the Southern High Plains has been economically feasible with approximately 1.8 million acres planted each year (TASS, 2005). On the more profitable 2.0 million irrigated acres, the ability to maintain economic production relied on drought tolerant crops like cotton and grain sorghum. Some of this irrigated crop area received as little as 25% of the full crop evapotranspiration (ET) rate. Both dryland and limited irrigated crop production has required full use of water resources with practices such as furrow diking and the use of regional specific varieties. In addition, irrigated crop rotations have also shown potential economic advantages (Segarra et al., 1991; Blackshear and Johnson, 2003) over continuous cotton production. Rotations have provided biodiversity (Francis and Clegg, 1990) and sustainability (Parr et al., 1990) particularly in semi-arid regions (Howell et al., 2004). Conservation tilled cotton in rotation with grains under furrow irrigation have also shown yield benefits on the High Plains (Keeling et al., 1989, Bordovsky et al., 1994). In addition, the Low Energy Precision Application (LEPA) irrigation method (Lyle and Bordovsky, 1981) has provided an economical, efficient irrigation delivery system that is critical in water short environments.

Research is currently being conducted by the Texas AgriLife Research and Extension Center at Halfway to develop viable long-term production alternatives that use very little supplemental irrigation. The goal of this research project is to develop crop production data for modeling and economic analysis of three irrigation strategies that limit supplemental irrigation to no more than 5 inches of depth. This report evaluates strategies using crop yield, gross return determined from combinations of crop yield at current market prices plus the value of water "saved", and seasonal irrigation water use efficiency. Although the level of agricultural production will be reduced compared to more traditional irrigation practices, proposed treatments may help free water for future uses without crippling the economies of West Texas communities.

Materials and Methods

A field experiment was conducted at the Texas AgriLife Research and Extension Center at Halfway, TX (1070 m elev., 34^0 11'N, 101^0 56' W) from 2004 to 2007. The research site was located adjacent to a playa in a transitional soil changing from a Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) at higher elevations to an Olton loam (fine, mixed, thermic Aridic Paleustolls) at lower elevations. A 22-acre area under an 820-ft center pivot where continuous cotton and cotton/sorghum rotations had been established was divided into nine wedges (representing three irrigation strategies x three replicates). The crop response from irrigation strategy treatments was heavily dependent on pre-plant soil water conditions. The strategy treatments were:

1) **Pre-plant only (T1)**. Plant on rainfall; if no timely rain, plant dry and irrigate to establish crop; "save" remaining water.
2) **If early soil moisture conditions are favorable, invest in seasonal irrigation (T2)**. If available soil water at planting was >50% of field capacity, irrigation was provided to establish a stand in a timely fashion; if available soil water was < 50% of field capacity, planting occurred following rainfall. If a crop was established, the remaining water was used for irrigations at critical reproductive periods, otherwise, production for the year was terminated and the allocated irrigation water was "saved".
3) **Use water to establish crop and provide some seasonal irrigation (T3)**. If necessary, the crop was irrigated for establishment, followed by timely irrigation with remaining available water. No water was "saved" with this treatment.

"Saved" water refers to the portion of the 5 inches of irrigation depth per year that was not used for crop production in a treatment year and could be transferred to other crops or "credited" for use in future years. The 5-inch maximum irrigation depth was an arbitrary irrigation level chosen to represent twice the upper estimated natural recharge rate of the Ogallala aquifer (Dutton, 2007). Continuous cotton and cotton/sorghum rotations with four replicates were maintained within each of the nine wedged-shaped areas. Rotation plots, or sequences, included: CCC - continuous cotton, CCS - cotton followed by cotton, then sorghum, CSC - cotton followed by sorghum, then cotton, and SCC - sorghum followed by two years of cotton.

The treatment factors in this experiment were 1) irrigation strategy and 2) crop rotation treatments within each strategy (Figure 1). The experimental design was a split plot. Each whole block covered approximately 48^0 of the pivot arc with each of the three strategy treatments occupying 16^0 of this arc. Within each strategy treatment area, crop rotation treatments were continued in previously established plots, each of these treatment areas were 12 rows wide by 16^0 with four replications. Conservation tillage methods were used. Row direction was perpendicular to the pivot lateral.

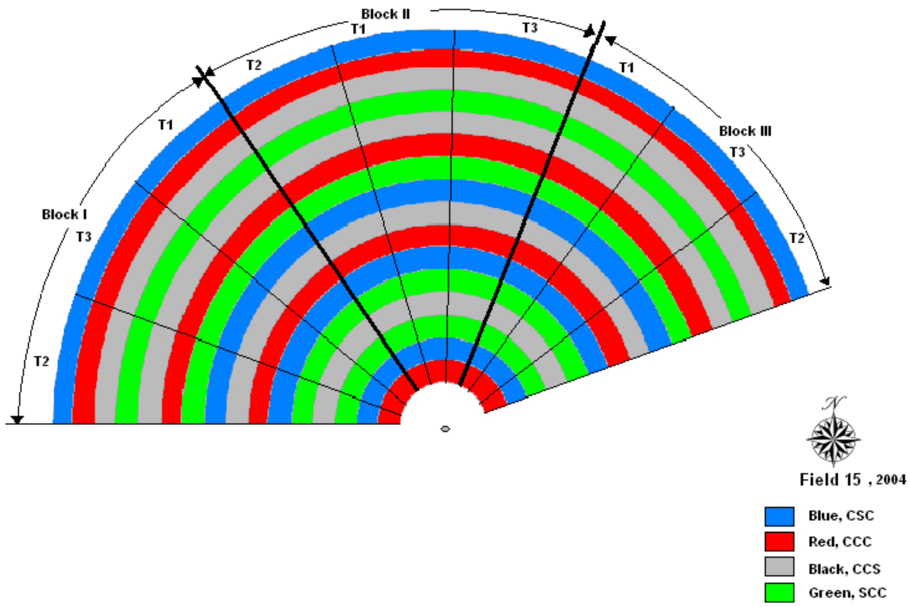

Figure 1. Field layout of irrigation strategy and cropping sequence plots in a 22-acre area at the Texas AgriLife Research Center at Halfway, 2004.

Agronomic information over the four-year period is given in Table 1. Paymaster 2326RR (2004) and Fibermax 989 BR (2005 to 2007) and Golden Acres 3545 were proven cotton varieties and grain sorghum hybrid, respectively, that had performed well over a wide range of irrigation levels in small plot tests on the THP. Phosphorus and nitrogen applications were based on annual soil tests with nutrients added to provide yield goals of 800 lbs lint/ac for cotton and 4500 lbs grain/ac for sorghum. Additional operations included stalk pulling, furrow diking, stalk shredding and use of a rotary hoe to keep seedling plants from wind damage. A minimum tillage system was used to enhance soil moisture conservation of all plots. Herbicides and nutrients were applied by traditional ground application methods or with the pivot during the season. Insect pests were controlled by applying chemicals aerially or with ground equipment when appropriate pest threshold levels were exceeded.

Irrigations were applied with the LEPA method. Each pivot water applicator was spaced 6.7 ft apart in alternate diked furrows and was equipped with manual, color-coded valves. The valves provided operator control of water to specific plots at appropriate times. The actual pre-plant, seasonal, and total irrigation amounts for each of the three irrigation strategies, the four crop rotation sequences, and the four test years are given in Table 2.

Crop samples were hand harvested from 86 ft^2 areas in each plot from 2004 to 2006 and 43 ft^2 in 2007. Cotton samples were ginned with a small plot gin at the Texas AgriLife Research and Extension Center in Lubbock to determine lint weight and yield per unit area of each treatment. Lint values were determined from fiber quality analysis performed at the International Textile Research Center at Texas Tech. Grain sorghum weights were determined following grain thrashing with small-scale plot equipment and adjusting grain weights to 13% moisture content. Grain sorghum crop values were calculated from annual average grain prices from 2004 through August 2007 (NASS, 2007). Crop yield, gross economic return from crop yields and "saved" water, and seasonal irrigation water use efficiency (SIWUE) for each irrigation strategy and rotation treatment were determined.

Table 1. Planting, nutrient, rainfall, and harvest data for irrigation strategy and crop rotation experiments, Texas AgriLife Research at Halfway, 2004-2007.

	Irrigation Strategy	Crop Sequence	Year 2004	2005	2006	2007	100-yr Plainview Avg.
Planting							
Cotton Variety	All	All	PM2326RR	FM989BR	FM989BR	FM989BR	
Planting Date	All	All	12-May	17-May	15-May	16-May	
Target Population (ppa)	All	All	56,400	59,280	49,700	52,700	
Sorghum Hybrid	All	SCC	GA 3545	GA 3545	GA 3545	GA 3545	
Planting Date	All	SCC	12-May	18-May	16-May	17-May	
Target Population (ppa)	All	SCC	20,250	26,100	26,000	26,000	
Nitrogen Fertilizer (lb/ac)	T1	CCC	37	30	70	10	
		CSC	55	30	70	10	
		CCS	86	30	70	10	
		SCC	55	30	70	0	
	T2	CCC	37	60	0	50	
		CSC	55	60	0	50	
		CCS	86	60	0	50	
		SCC	55	60	0	40	
	T3	CCC	37	60	70	90	
		CSC	55	60	70	90	
		CCS	86	60	70	90	
		SCC	55	60	70	40	
Phosphorus Fertilizer (lb/ac)	T1	CCC	20	55	0	34	
		CSC	60	55	0	34	
		CCS	40	55	0	34	
		SCC	60	55	0	0	
	T2	CCC	20	55	0	34	
		CSC	60	55	0	34	
		CCS	40	55	0	34	
		SCC	60	55	0	0	
	T3	CCC	20	55	0	34	
		CSC	60	55	0	34	
		CCS	40	55	0	34	
		SCC	60	55	0	0	
Rain (inches of depth)							
Off-season (Oct - Feb)	All	All	5.82	14.44	3.07	10.65	4.60
Pre and At Plant (Mar-May)	All	All	3.98	2.45	2.92	5.05	5.18
In Season (Jun-Sept)	All	All	15.05	10.46	8.23	9.42	10.64
Total Crop Year	All	All	24.85	27.35	14.22	25.12	20.42
Harvest Dates							
Cotton	All	All		2-Nov	30-Oct	6-Nov	
Sorghum	All	SCC	20-Sep	28-Sep	6-Sep	18-Sep	

Table 2. Pre-plant plus at plant, in-season, and total irrigation applied from three irrigation strategy and four cropping sequence treatments, Texas AgriLife Research at Halfway, 2004-2007.

Irrigation Period	Irrigation Strategy	Crop Sequence	2004	2005	2006	2007	Average
Pre-plant & At-plant	T1	CCC	0.53	0.70	1.96	0.00	0.80
		CSC	0.43	0.70	1.96	0.00	0.77
		CCS	0.43	0.70	1.96	0.00	0.77
		SCC	0.43	0.70	1.96	0.00	0.77
	T2	CCC	0.58	0.70	0.00	0.00	0.32
		CSC	0.43	0.70	0.00	0.00	0.28
		CCS	0.43	0.70	0.00	0.00	0.28
		SCC	0.43	0.70	0.00	0.00	0.28
	T3	CCC	0.58	0.70	1.96	0.00	0.81
		CSC	0.43	0.70	1.96	0.00	0.77
		CCS	0.43	0.70	1.96	0.00	0.77
		SCC	0.43	0.70	1.96	0.00	0.77
In-Season	T1	CCC	0.00	0.00	0.00	0.00	0.00
		CSC	0.00	0.00	0.00	0.00	0.00
		CCS	0.00	0.00	0.00	0.00	0.00
		SCC	0.00	0.00	0.00	0.00	0.00
	T2	CCC	2.50	3.38	0.00	5.00	2.72
		CSC	2.50	3.38	0.00	6.40	3.07
		CCS	2.50	3.38	0.00	6.40	3.07
		SCC	3.50	4.00	0.00	2.00	2.38
	T3	CCC	3.50	3.38	3.00	5.00	3.72
		CSC	3.50	3.38	4.50	6.40	4.45
		CCS	3.50	3.38	4.50	6.40	4.45
		SCC	4.50	4.00	0.00	2.00	2.63
Total	T1	CCC	0.53	0.70	1.96	0.00	0.80
		CSC	0.43	0.70	1.96	0.00	0.77
		CCS	0.43	0.70	1.96	0.00	0.77
		SCC	0.43	0.70	1.96	0.00	0.77
	T2	CCC	3.08	4.08	0.00	5.00	3.04
		CSC	2.93	4.08	0.00	6.40	3.35
		CCS	2.93	4.08	0.00	6.40	3.35
		SCC	3.93	4.70	0.00	2.00	2.66
	T3	CCC	4.08	4.08	4.96	5.00	4.53
		CSC	3.93	4.08	6.46	6.40	5.22
		CCS	3.93	4.08	6.46	6.40	5.22
		SCC	4.93	4.70	1.96	2.00	3.40

Results and Discussion

Rainfall

In this deficit irrigation experiment, year-to-year rainfall amounts and occurrences had a huge impact on irrigation treatment decisions and subsequent yields. Within Table 1 are rainfall amounts for three periods of each year as well as the 100-year rainfall mean for Plainview (15 miles E of Halfway) during corresponding periods. The five-month off-season period, from October through February, is typically dry with little rainfall storage for the summer growing season. Rainfall typically increases in the three month "pre- and at-plant" period, a time when a portion of the rain can build profile water in the soil. The 100-yr average for this period is five inches in depth. Historically, most rainfall occurs during the in-season period from June through September, with the 100-year Plainview mean of 10 inches of rainfall. Of the four crop years, the 12-month rainfall of the crop years 2004, 2005, and 2007 was much higher than the 100-year mean, with 40% more in-season rain in 2004, and 210% and 130% more off-season rain in 2005 and 2007, respectively. The 2006 crop year was dry with at least 23% lower rainfall than the 100-year mean in each of the three rainfall periods. These dry periods, quantified with soil water measurements, resulted in a 'no-plant" decision in the T2 strategy treatment in 2006.

Up to two inches of irrigation was applied near or at planting to satisfy the treatment strategy pre-plant irrigation protocol and to insure plant stands. Based on the treatment, seasonal irrigations of cotton occurred from mid July to mid August in weekly events. Seasonal irrigation of sorghum occurred at approximately 30-days following emergence, early boot stage, and/or grain fill with the quantity depending on rainfall immediately prior to these periods and decisions to transfer water from sorghum to cotton.

Crop Rotation

One perceived advantage of the cotton-sorghum rotation compared to continuous cotton is increased flexibility and timing of limited irrigation amounts. Early planted sorghum can be irrigated more heavily at the beginning of the growing season, allowing limited mid and late-season water supplies to be concentrated on the cotton, after sorghum yield potential has been addressed. Or, based on relative crop prices, all or a portion of the irrigation water normally applied to one crop could be diverted to the other. Among the crop rotation sequences, the lower than normal in-season rainfall in 2006 and 2007 resulted in a decision to apply 3 inches of the irrigation available for the sorghum (SCC plots) to the cotton (CCS and CSC plots). Therefore, total irrigation of these cotton plots exceeded the 5-inch annual irrigation depth while proportionally reducing total irrigation for sorghum (Table 2). Decisions to move water from sorghum to cotton were based on the higher cotton lint price relative to the sorghum grain prices at the time.

Crop Yield and Commodity Price

Crop yields varied from year to year depending on rainfall, cropping sequence, and irrigation strategy. Average yield by year during the test period for each treatment is given in Table 3. The overall high rainfall during the experiment resulted in high cotton yields. The average pre-plant only treatments (T1) resulting in yields of 674, 719, and 659 lb/ac in the CCC, CCS, and CSC crop sequences, respectively, with average annual irrigations of only 0.8 inches (Table 2). As total annual irrigations increased in the T2 (3.04 to 3.35 inches/year) and T3 (4.53 to 5.22 inches/year) strategy treatments, 4-year average cotton yields increased to 917, 905, and 951 lb/ac and 1021, 1081, and 1050 lb/ac, respectively. These yields compare favorably to the average 2004-2006 Hale county average yields for non-irrigated and irrigated cotton at 479 lb/ac and 938 lb/ac, respectively (TX Agricultural Statistics, 2004 - 2006).

Table 3. Crop yield, commodity prices, residual irrigation quantity, and gross value at residual irrigation valued at $12 per inch of depth from three irrigation strategy and four cropping sequence treatments, Texas AgriLife Research at Halfway, 2004-2007.

	2004	2005	2006	2007	Average
Yield (lb/ac)					
CCC (Continuous Cotton)					
T1	791	1216	96	592	674
T2	875	1449	0	1343	917
T3	969	1453	354	1308	1021
CCS (Cotton 1 yr After Sorghum)					
T1	728	1353	145	649	719
T2	796	1539	0	1284	905
T3	928	1541	600	1254	1081
CSC (Cotton 2 yr After Sorghum)					
T1	750	1277	101	509	659
T2	841	1574	0	1388	951
T3	983	1438	476	1301	1050
SCC (Sorghum after 2 yr Cotton)					
T1	1005	4841	0	3034	2220
T2	4410	6105	0	5286	3950
T3	4840	5608	0	4273	3680
Commodity Price ($/lb)					
CCC (Continuous Cotton)					
T1	0.521	0.576	0.564	0.522	0.546
T2	0.512	0.576	0.581	0.582	0.563
T3	0.519	0.576	0.581	0.575	0.563
CCS (Cotton 1 yr After Sorghum)					
T1	0.523	0.561	0.576	0.528	0.547
T2	0.482	0.574	0.576	0.582	0.554
T3	0.515	0.574	0.576	0.569	0.558
CSC (Cotton 2 yr After Sorghum)					
T1	0.520	0.574	0.566	0.516	0.544
T2	0.527	0.576	0.577	0.583	0.566
T3	0.535	0.576	0.577	0.577	0.566
SCC (Sorghum after 2 yr Cotton)					
T1	0.044	0.039	0.047	0.062	0.048
T2	0.044	0.039	0.047	0.062	0.048
T3	0.044	0.039	0.047	0.062	0.048
Residual Water Amount (inches of depth)					
CCC (Continuous Cotton)					
T1	4.47	4.30	3.04	5.00	4.20
T2	1.92	0.92	5.00	0.00	1.96
T3	0.92	0.92	0.04	0.00	0.47
CCS (Cotton 1 yr After Sorghum)					
T1	4.47	4.30	3.04	5.00	4.20
T2	2.07	0.92	5.00	-1.40	1.65
T3	1.07	0.92	-1.46	-1.40	-0.22
CSC (Cotton 2 yr After Sorghum)					
T1	4.47	4.30	3.04	5.00	4.20
T2	2.07	0.92	5.00	-1.40	1.65
T3	1.07	0.92	-1.46	-1.40	-0.22
SCC (Sorghum after 2 yr Cotton)					
T1	4.57	4.30	3.04	5.00	4.23
T2	1.07	0.30	5.00	3.00	2.34
T3	0.07	0.30	3.04	3.00	1.60
Gross Return from Crops and Residual Water ($/ac)					
CCC (Continuous Cotton)					
T1	466	752	91	369	419
T2	471	846	60	781	539
T3	514	848	206	752	580
CCS (Cotton 1 yr After Sorghum)					
T1	434	811	120	403	442
T2	409	894	60	731	523
T3	491	896	328	696	603
CSC (Cotton 2 yr After Sorghum)					
T1	444	785	94	323	411
T2	468	918	60	793	560
T3	539	839	257	734	592
SCC (Sorghum after 2 yr Cotton)					
T1	99	238	36	249	156
T2	205	239	60	365	217
T3	211	220	36	302	192
Gross Return from Crops plus Residual Water Value ($/ac)					
Continuous Cotton					
T1	466	752	91	369	419
T2	471	846	60	781	539
T3	514	848	206	752	580
Cotton-Sorghum Rotation					
T1	326	611	83	325	336
T2	360	684	60	630	433
T3	414	651	207	577	462

2004 sorghum yields estimated based on bird damaged hand samples.
Sorghum price based on average sorghum prices through Aug 2007 (TX Ag Statistics. 2007).

The cropping sequences with sorghum (CCS and CSC) did not consistently increase lint yield compared to continuous cotton (CCC). Based on the 4-year average, cotton following grain sorghum (CCS) increased lint yield in the T1 and T3 irrigation strategies, but not the T2. Cotton rotation with grain sorghum appeared to have the greatest consistent increase in yield over continuous cotton in the very dry growing season of 2006. In this year, in rotation treatments one year out of grain sorghum, cotton yield increased by 50% (145 lb/ac - CCS x T1 vs. 96 lb/ac - CCC x T1) and 69% (600 lb/ac - CCS x T3 vs. 354 lb/ac – CCC x T3) compared to continuous cotton treatments. Two years following grain sorghum resulted in 5% and 34% lint yield increases in the T1 and T3 treatments, respectively. Higher than normal rainfall in three out of the four test years may have compensated for positive water conservation effects of rotation compared to continuous cotton treatments thus eliminating expected yield differences in respective treatments.

Grain sorghum yields averaged 2220, 3950, and 3680 lbs/ac for treatments T1, T2, and T3 respectively. These yield values were low, however, 4-year average irrigation amounts for these three treatments were only 0.77, 2.66, and 3.40 inches of depth, respectively (Table 2).

Commodity prices based on crop quality and year of harvest over the test period are in Table 3. Irrigation treatment and strategies had little effect on prices during this period. Cotton loan prices were low in the 2004 crop year, ranging from $0.482 to $0.535 / lb of lint, and in the non-seasonally irrigated treatments (T1) in 2007, ranging from $0.516 to $0.528 / lb of lint. Higher loan prices occurred in the 2005, 2006, and the seasonally irrigated treatments in 2007, ranging from $0.561 to $0.583 / lb of lint. These results are generally attributed to a change in cotton variety in 2005 resulting in better fiber properties and due to extreme water stress in the T1 treatments in 2007. Grain sorghum prices increased in 2007 due to increased interest in ethanol production from grain.

Residual Water

Residual or "saved" water was determined for each treatment by year and is given in Table 3. As previously discussed, residual water refers to the portions of the maximum permitted 5 inches of irrigation depth per year that were not used for crop production and were "saved" for future or alternative uses. Negative values, as well as values above five inches occurred due to planned movement of irrigation water from sorghum to cotton in rotation treatments in 2006 and 2007. As expected, residual water was the highest at 4.2 inches/yr in the T1 strategy treatment where irrigations were only used to establish the crop and lowest at near zero in the T3 strategy where all permitted water was used.

Water Value and Gross Return

Table 3 contains the gross return from each crop sequence and irrigation strategy by year and averaged over the 4-year period. Gross return was determined by multiplying individual treatment yields by respective commodity prices and adding the product of the residual water amount of each individual treatment by the conservative water value of $12/acre-inch. Determining a 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 could be affected by local water markets. The $12/acre-inch value was determined by adding a current $8/ac-inch fuel cost to $4/ac-inch fixed cost and is possibly the lowest water value that should be considered. Over time, water value will increase with population growth and decrease in groundwater. One might compare the $12/acre-inch value to $100/acre-inch which is an estimated cost of developing a municipal water supply for the city of Lubbock from the recently constructed Lake Alan Henry (LERWP, 2006). The city of Lubbock, as well as other entities, will be looking for less expensive alternatives and will be competing with the agricultural community for water resources in the future.

Evaluating treatment factors contained in this experiment based on *net* rather than *gross* economic returns is beyond the scope of this paper. However, consideration of gross returns that include residual water value provide some general observations. First, the 4-year average gross return of the irrigation treatments, with water value at $12/ac-in, was high ranging from $419/ac (CCC x T1) to $603/ac (CCS x T3). Also, within each cropping sequence, the T1 strategy provided the lowest 4-year average return, ranging from $411/ac (CCC) to $442/ac (CCS) compared to the T2 strategy requiring approximately 2.5 inches additional irrigation and ranging from $523/ac (CCS) to $560/ac (CSC). The T3 strategy, with an addition of approximately 1.75 inches above the T2 treatments, resulted in gross returns ranging from $592/ac to $603/ac. From this, at the $12/ac-in water value, the residual water saved in the T1 treatment did not compensate for the increase in crop value received by applying more irrigation in the T2 and T3 treatments. In addition, direct comparisons of continuous cotton to the cotton-sorghum rotation were made by averaging gross returns of the rotation sequences containing sorghum (CCS, CSC, and SCC) and comparing them to those of the continuous cotton treatments (CCC). Except in the dry year of 2006, where no sorghum was harvested, the continuous cotton treatment consistently resulted in higher gross returns than did corresponding rotation treatments. Continuous cotton versus cotton-sorghum rotation gross returns were $419/ac vs. $336/ac, $539/ac vs. $433/ac, and $580/ac vs. $462/ac for T1, T2, and T3 strategies, respectively.

Irrigation Water Use Efficiency

Four year total yield, total irrigation, irrigation water use efficiency, and seasonal irrigation water use efficiency is summarized in Table 4. Irrigation water use efficiency (IWUE) was determined by dividing lint or grain yield by the total irrigation applied over the 2004 to 2007 period. As expected, at each of the four cropping sequences, the strategy to only apply irrigation to establish the crop (T1) resulted in the highest IWUE, while the strategy to use all available irrigation (T3) resulted in the lowest IWUE. For example within the continuous cotton treatment (CCC), T1, T2, and T3 resulted in IWUE's of 845, 302, and 225 lb of lint/acre-inch of irrigation. However, a more meaningful comparison is seasonal irrigation water use efficiency (SIWUE) relative to standard norms. SIWUE is the increase in yield above the T1 treatment divided by the increase in irrigation quantity to make this yield. Traditionally, water use efficiency of 50 lb lint/ac-in for cotton and 350 lb grain/ac-in for grain sorghum are considered normal on the THP. Irrigation strategies T2 and T3 exceeded these levels in all cases. Four year average SIWUE for the T2 and T3 strategy treatments were 108 and 93 lb lint/ac-in; 72 and 81 lb lint/ac-in; 113 and 88 lb lint/ac-in; and 918 and 556 lb grain/ac-in for CCC, CCS, CSC, and SCC crop sequences, respectively. With the exception on the CCS cropping sequence, the SIWUE of the T2 strategy was consistently higher than that of the T3 strategy.

Table 4. Sum of crop 2004 – 2007 yields, sum of 2004 – 2007 irrigation amounts, irrigation water use efficiency, and seasonal irrigation water use efficiency for deficit irrigation study, Texas AgriLife Research, Halfway, 2004-2007.

	4-year Yield Total (lb/ac)	4-year Irrigation Total (inches of depth)	IWUE over 4 Years (lb/ac-in)	Seasonal Irrigation Water Use Efficiency (lb/ac-in)
CCC (Continuous Cotton)				
T1	2695	3.19	845	
T2	3667	12.16	302	108
T3	4084	18.12	225	93
CCS (Cotton 1 yr After Sorghum)				
T1	2875	3.09	930	
T2	3619	13.41	270	72
T3	4323	20.87	207	81
CSC (Cotton 2 yr After Sorghum)				
T1	2637	3.09	853	
T2	3803	13.41	284	113
T3	4198	20.87	201	88
SCC (Sorghum after 2 yr Cotton)				
T1	8880	3.09	2874	
T2	15801	10.63	1486	918
T3	14721	13.59	1083	556

Conclusions

The objective of this field experiment was to determine yield and seasonal irrigation water use efficiency of cotton and cotton/sorghum rotations while evaluating "water saving" strategies with annual irrigation depths limited to less than 5 inches per year. The strategy treatments of pre-plant irrigation only (T1) resulted in average annual cotton yields ranging from 674 to 719 lb/ac with annual irrigations of 0.8 inches; treatments of irrigation only if soil water is greater than 50% field capacity at planting (T2) resulted in yields ranging from 905 to 951 lb/ac with irrigations of 3.04 to 3.35 inches; and treatments using all water in a timely manner (T3) resulted in yields ranging from 1021 to1050 lb/ac with total annual irrigations of 4.53 to 5.22 inches. By evaluating treatments using gross returns including residual or "saved" water valued at $12/ac-in, water savings in the T1 treatment did not compensate for the increase in crop value received by applying more irrigation in the T2 and T3 treatments. An economic evaluation based on net return and using higher water value could easily change this result. Except in the dry year of 2006, where no sorghum was harvested, the continuous cotton sequence (CCC) consistently resulted in higher gross returns than did the corresponding cotton-sorghum rotation. The seasonal irrigation water use efficiency of cropping sequences using irrigation strategies T2 and T3 exceeded normal levels of water use efficiency in a range from 44 to 126% over the 4-year test period. Additional economic evaluations will be made in the future.

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References

Blackshear J. and P. Johnson. 2003. Profitability of irrigated cotton-grain sorghum rotations in the Southern High Plains of Texas. In 2003 Proc. Beltwide Cotton Conferences, 474-480. Memphis, TN: National Cotton Council.

Bordovsky, J.P., W.M. Lyle, and J.W. Keeling. 1994. Crop rotation and tillage effects on soil water and cotton yield. Agron. J. 86(1):1-6.

Dutton, Alan R. 2007. Integration of information on groundwater age dating, recharge rates, and results of groundwater modeling of the High Plains (Ogallala) aquifer in the Texas Panhandle. Geological Society of America *Abstracts with Programs*, Vol. 39, No. 6, p. 188. Earth and Environmental Sciences, University of Texas San Antonio, San Antonio, TX 78249-0663

Francis, C.A., and M.D. Clegg. 1990. Crop rotations in sustainable production systems. pp.107-121. In: Sustainable Agricultural Systems, Soil and Water Conservation Society, Ankeny, IA.

Howell, T.A., Tolk, J.A., Baumhardt, R.L., Evett, S.R. 2004. Furrow irrigated cotton-sorghum rotation for the Texas northern plains. Agronomy Abstracts, ASA-CSSA-SSSA Annual Meeting, Seattle, Washington.

Keeling, W., E. Segerra, and J.R. Abernathy. 1989. Evaluation of conservation tillage cropping systems for cotton on the Texas High Plains. J. Prod. Agric. 2(3):269-273.

Llano Estacado Regional Water Plan (Region O). April 2006. Addendum No. 1. Texas Water Development Board, Austin, TX.

Lyle, W.M. and J.P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Trans. of ASAE 24(5):241-245.

NASS. 2007. National Agricultural Statistics Service. United States Department of Agriculture.

Parr, J.F., R.I. Papendick, I.G. Young, and R.E. Meyer. 1990. Sustainable agriculture in the United States. pp. 50-76. In: Sustainable Agricultural Systems, Soil and Water Conservation Society, Ankeny, IA.

Segarra, E., J.W. Keeling, and J.R. Abernathy. 1991. Tillage and cropping system effects on cotton yield and profitability on the Texas Southern High Plains. J. Prod. Agric. 4(4):566-571.

TASS. 2005. 2004 Texas Agricultural Statistics. Austin, TX: United States Department of Agriculture, National Agricultural Statistics Service.