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AGRONOMY AND SOILS

Irrigation and Planting Geometry Effects on Cotton (*Gossypium hirsutum* L.) Yield and Water Use

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ABSTRACT

Addressing the challenges of dwindling groundwater resources and ever-increasing demands for water necessitate enhancing water use efficiency (WUE) in irrigated agriculture. In a 2-year study, we examined the effects of different levels of irrigation and PG on lint yield and WUE of furrow irrigated cotton in a Dundee silt loam in the Mississippi Delta. The main plots were three irrigation regimes: irrigating every furrow (FI), alternate furrow (HI), and no irrigation (RF) and subplots were two planting geometries (PG): single-row (SR) and twin-row (TR). Across FI and HI no significant differences were observed in plant height and biomass yield at flowering, but chlorophyll content index and leaf area index (LAI) were positively affected. Canopy closure in TR planting occurred earlier than SR leading to higher leaf areas available for harvesting more light during photosynthesis. Averaged across the irrigation regimes, the TR planting enhanced lint yield by 10.6% in 2018 and 17.6% in 2019 compared to SR. The average lint yield in SR and TR were: 1779 and 2028 kg ha^{-1} under FI, 1803 and 2082 kg ha^{-1} under HI, and 1573 and 1788 kg ha^{-1} under RF treatments, respectively. In FI and HI treatments, TR had higher lint yield than RF treatment by 13.8% and 16.5%, respectively. Lint yield in HI with TR had the highest irrigation WUE (3.4 kg ha^{-1} mm^{-1}) followed by HI with SR (2.7 kg ha^{-1} mm^{-1}). These results demonstrated that cotton grown in TR with HI could reduce irrigation water demand in silt loams.

Cotton is the most important natural fiber crop worldwide, with approximately 34 M ha cultivated in 85 countries, mainly in Asia and North and South America (USDA-NAS, 2019). In Mississippi (MS), cotton is grown in more than 0.25 M ha with an estimated production of 1.46 M bales. A considerable number of cotton hectares in this region have shifted to soybean (*Glycine max* [L.] Merr.) and maize (*Zea mays* L.) production in response to fluctuating commodity prices and changes in the United States Department of Agriculture (USDA) farm program policies.

In the MS Delta, traditionally, cotton seeds are planted in single-row (SR) planting geometries on raised beds spaced between 96 and 102 cm (Fig. 1). However, planting the same number of seeds in twin-row (TR) geometries (two rows spaced between 18 and 38 cm on seedbeds centered on raised beds spaced between 96 and 102 cm) was reported to enhance returns from row crops (Bruns, 2011; Mascagni et al., 2008). Soybean and corn producers have started to adopt TR planting geometry for their production systems, and cotton growers are trying to follow a similar system for enhanced returns. However, planting cotton in the TR system has resulted in inconsistent yield responses (Boykin and Reddy, 2010; Reddy and Boykin, 2010; Reddy et al., 2009). Twin-row, or narrow-row, in comparison to a conventional 102-cm single row pattern, has been shown to increase root spacing, canopy closure, and yields. Two studies were conducted to assess the effect of alternative row patterns on fiber properties. The objective of the first study was to compare fiber properties for cotton in narrow-row (38-cm spacing). Reddy and Boykin (2010) and Stephenson and Brecke (2010) reported 35 to 106 kg ha^{-1} higher lint yield in the TR system, whereas Mascagni et al. (2008), Reddy et al. (2009), and Pettigrew (2015) reported no significant yield advantage in TR planted cotton over SR plantings. Reddy and Boykin (2010) compared irrigated cotton grown in TR on 102-cm beds (95,000 plants ha^{-1}) to conventional 102-cm SR system (110,000 plants ha^{-1}) and reported a 6% higher lint yield in TR. At higher plant densities of 130,000 and 260,000 plants ha^{-1}, the yield differences were

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not significant (Stephenson and Brecke, 2010). The same study also demonstrated a 24% higher lint yield in the TR system at a plant density of 70,000 plants ha^{-1}, which they attributed to enhanced canopy intercepted, photosynthetically active radiation (IPAR). In this study, compared to SR, the IPAR measured in TR planting geometry was higher by 55% and 76%, respectively, at 7 and 9 weeks after emergence. But these differences diminished as the season progressed (Pettigrew, 2015). Stephenson and Brecke (2010) and Reddy and Boykin (2010) reported higher plant stand, higher number of open bolls, and earlier canopy closure associated with higher lint yields in TR planting in the MS Delta. Based on a 2-year study conducted at Xinjiang, China, Zhang et al. (2016) reported an optimum plant density of 18.0 plants m^{-2} for optimum light use efficiency and yield returns. Narrow row width also resulted in greater canopy closure, but this did not consistently translate into yield gains in North Carolina (Riar et al., 2013).

Figure 1. Photograph of 102-cm single-row (SR), and 25-cm twin-row (TR) planting geometries.

In the lower MS Delta, rainfall received during the crop season is characterized by large inter- and intraseasonal variabilities in amounts and temporal distributions leading to unstable crop yield returns (Anapalli et al., 2016, 2019). For stable farm returns, more than 60% of cotton currently grown in the MS Delta is irrigated. The shallow Mississippi River Valley Aquifer (MRVA) provides most of this water (Clark et al., 2011). Overexploitation of this aquifer for irrigating crops is causing its rapid decline, threatening sustainability for supporting irrigated agriculture in this region. Lack of scientific research that enhances irrigation water use efficiency (WUE) was attributed as one of the primary reasons for the depletion (Clark et al., 2011). Plumblee et al. (2019) reported an increase in WUE by 61% by adopting a matric water potential sensor-based irrigation at -90 kPa average in a 100-cm soil depth in MS Delta. Pettigrew and Zeng (2014) reported a 25% increase in cotton lint yield with irrigation at Stoneville, MS. Compared to rainfed systems, irrigated cotton was reported to produce a greater number of bolls per unit area and approximately 2% longer fibers. As in TR studies cited above, a greater plant population under irrigated cotton increased light interception and canopy closure early in the season and these differences minimally affected crop maturity. Sui et al. (2017) reported a 26% enhanced lint yield due to irrigation, whereas Reddy et al. (2009) and Pettigrew (2015) reported no response from TR planting geometry from the studies conducted in Stoneville, MS.

In a drip irrigation study, Basal et al. (2009) reported enhanced seed cotton yields with an increase in irrigation levels. Cotton is known to benefit from some drought stress that can occur between irrigations. However, excessive irrigation can result in more vegetative growth that potentially shades the lower part of the canopy, which is often reported to be the typical cause that triggers boll drop and consequent cotton lint yield decline (Munk and Farahani, 2012). Knowledge of the main effects of different planting geometries, irrigation rates, and their interactions on cotton productivity and WUE in the MS Delta is lacking. Hence, the objective of this research was to investigate cotton yield and irrigation WUE responses to planting geometries in TR (seeds planted in twin rows 25 cm apart on 102-cm centered raised beds) with those planted in conventional single-row (SR, 102-cm wide row spacing) that were furrow irrigated at rates of (1) full irrigation (FI), (2) half irrigation (HI), and (3) rainfed (RF) at Stoneville, MS, to identify a combination of planting geometry and irrigation rate with higher WUE.

MATERIALS AND METHODS

Field studies were conducted at the USDA-ARS Crop Production Systems Research Unit's (CPSRU) farm, in Stoneville, MS (33° 42′ N, 90° 55′ W, elevation: 32 m above mean sea level) during the 2018 and 2019 crop seasons. The soil type of the experimental area was a Dundee silt loam (fine silty, mixed, active, thermic Typic Endoaqualfs) with 0.87% organic matter, 0.44% carbon, 0.06% nitrogen, and 1.28 g cm^{-3} bulk density averaged across 60-cm soil depth. The field saturated hydraulic conductivity (K_{fs}) of the soil ranged from 0.41 to 1.22 cm hr^{-1}. Field preparation after harvesting of the previous crop consisted of one or two deep tillage operations to break clay pans and overturn soils, bury crop residue, and kill weeds, followed by disc-tillage to generate furrows and ridges (102-cm row spacing) for planting cotton seeds and facilitating furrow irrigations. In spring, the raised-ridge seedbeds were re-hipped, and before planting, tops of the seedbeds were smoothed as needed to plant cotton in SR and TR planting geometries. A 7300 vacuum planter (John Deere, East Moline, IL) was utilized to plant the SR planting geometry. A Monosem NG+3 TR vacuum planter (A.T.I., Inc. Monosem, Lenexa, KS) was used to plant the TR planting geometry. Both planters were set to achieve a similar overall plant population density of approximately 120,000 plants ha^{-1}. Actual plant populations were estimated at harvest by counting plants in a 1 m^2 area in the two center rows at three randomly selected locations in each plot. In the MS Delta region, final plant populations of 100,000 to 125,000 plants ha^{-1} are recommended for 102-cm row cotton (Anonymous, 2019). Plots were maintained weed-free using both preemergence and postemergence herbicide programs. Existing weeds before planting were killed by spraying paraquat at 1.05 kg a.i. ha^{-1}. Fluometuron at 1.12 kg a.i. ha^{-1}, plus pendimethalin at 1.12 kg a.i. ha^{-1} were applied preemergence. Glufosinate-ammonium at 0.6 kg a.i. ha^{-1} was applied postemergence twice. Escaped weeds were hand-hoed as needed. Fertilizer application and insect control programs were standard for cotton production in this region.

Cotton cv. Fiber Max 1944 was planted in a randomized complete block arranged in a split-plot design with six replicates. The main plots were three irrigation regimes: (1) FI, (2) HI, and (3) RF. Subplots consisted of two planting geometries (1) SR—rows evenly spaced at 102 cm and (2) TR—two rows spaced at 25 cm apart on 102-cm centered seedbeds (Fig. 1). Cotton seeds were planted on 8 May 2018 and 16 May 2019. Each plot consisted of four SR or eight TR rows by 40 m long. Sensors for measuring soil-matrix water potential (Irrometer Co., Inc., Riverside, CA) were installed at soil depths of 15, 30, and 60 cm in selected representative plots. Irrigations were scheduled based on a soil-matrix potential of approximately -90 kPa at 45-cm soil depths, as recommended by Plumblee et al. (2019). The amount of irrigation water applied during each season in each plot was measured using a flow meter (Mc Propeller, McCrometer Inc., CA). Irrigation water was applied through furrows using a poly-pipe system, a common practice in MS Delta. The irrigation strategy followed in this study was what farmers were following for irrigating their crops in the field. In this strategy, when irrigation becomes due, on average, 3 to 4 cm of water per irrigation were applied. Typically, this amount of water is enough to bring the soil to its field capacity water level. In 2018, a total of 19.2 cm water was applied in the FI treatments in six irrigation events of 3.84 cm each applied through every furrow on 15 May, 21 and 29 June, 6 and 24 July, and 4 August, totaling 19.2 cm, while the HI treatments received half the amount of water but in every other furrow, totaling approximately 9.6 cm. In 2019, total irrigation applied was 15.2 cm in the FI treatment in four irrigation events of 3.8 cm each on 26 May, 29 June, 24 July, and 6 August, while HI treatments received 7.5 cm of water. Irrigation was stopped at first boll cracking stage of growth of cotton in both the years. Weather data was collected from the Mid-South Agricultural Weather Service, Delta Research and Extension Center, Stoneville, MS. The growing degree days (GDD), in ºC were calculated as [(Max. temp + Min. temp.)/2] – 10 (Desclaux and Roumet, 1996).

During mid-to-late September each year, the cotton was defoliated using a two-step process. A mixture of 0.035 kg thidiazuron ha^{-1} and 0.0175 kg diuron ha^{-1} was applied to the canopy as the first step in mid-September. One week later, a second treatment of a mixture of 0.035 kg thidiazuron ha^{-1}, 0.0175 kg diuron ha^{-1}, and 1.68 kg ethephon ha^{-1} was applied to complete defoliation and open the remaining unopened bolls. Defoliation was initiated when approximately 65% of the bolls had opened. Approximately 2 wks after the second defoliant application yield data was collected by handpicking from a 1-m^2 section in the two center rows at three randomly selected locations in each plot.

Above-ground biomass was harvested from a 1-m^{-2} section of bed from each plot at three locations, avoiding the row ends. These bed sections were 1-m long and 1-m wide with one row sampled for the SR pattern and two rows sampled for the TR pattern. Plant heights and the number of open bolls at harvest were recorded. Leaf area index (LAI) was measured at biweekly intervals using an AccuPAR LP 80 Ceptometer (Decagon Devices, Inc., Pullman, WA). The chlorophyll content index (CCI) was measured at the first cracked boll stage on the fully expanded terminal leaf using CCM 200 plus chlorophyll content meter (Opti Sciences, Hudson, NH). Plant heights (h) were collected at critical stages. All plant measurements were replicated at five random locations in the plot and used in the calculation of standard error (SE) of measurements. The number of cotton plants and open bolls per plant was recorded while handpicking seed cotton. Seed cotton was ginned on a 10-saw laboratory gin (Continental Eagle, Prattville, AL), and the lint yield was calculated on a per hectare basis. Irrigation WUE (kg lint mm^{-1} of irrigation water applied) was calculated as:

$$WUE = \left(\frac{Yi - Yr}{I} \right)$$

where *Yi* is lint yield in the FI or HI treatment (kg ha^{-1}), *Yr* is lint yield in the RF (kg ha^{-1}), and *I* is irrigation water applied (mm).

Data collected on yield responses to treatments were subjected to analysis of variance using PROC MIXED in Statistical Analysis System (SAS® version 9.4; SAS Institute Inc., Cary, NC) and treatment means were separated at the 5% level of significance using Fisher's protected least significant difference (LSD) test. Canopy closure data are presented for each year because of growth differences in cotton.

RESULTS AND DISCUSSION

Seasonal Weather. Weather conditions during the two cropping seasons in 2018 and 2019 were dramatically different (Fig. 2). The period of reproductive growth and boll filling (July-September) during 2019 was warmer with 92 GDD more than 2018. In general, the 2019 crop season was dry (348 mm less rainfall) and had more cumulative solar radiation of 500 MJ m^{-2} than 2018. However, vegetative growth (May-July) in 2018 coincided with periods of lower rainfall (375 mm less than 2019) and higher mean minimum and maximum temperatures. Hence, the analysis of variance (ANOVA) revealed a year has significant interaction on lint yield and seed yield (Table 1).

LAI in Three Irrigation Regimes and Two Planting Geometries. LAI is one of the dynamic indicators of crop growth and vigor. Generally, LAI of cotton increased until anthesis and then decreased as the older leaves senesced. The plant growth regulator, mepiquat chloride, was applied at 120 g a.i. ha^{-1} to control cotton plant height and excessive vegetative growth. Cotton was defoliated in early-to-mid September as described above. Consequently, after the second round of defoliant application there was a sharp decline in measured LAI in all treatments.

The maximum LAI measured was between 92 to 97 d after cotton planting (before defoliant application) in the FI-irrigated TR plots were 8.96 in 2018 and 8.98 in 2019 (Fig. 3), which could be attributed to higher vegetative growth as plants reached up to 1.5-m height and produced 45 to 52 leaves per plant (data not reported). Ünlü et al. (2011) reported similar results in cotton grown in a Mediterranian environment, where LAI responded positively to increasing amounts of irrigation water with the highest LAI of 5.3 recorded under full irrigation. Until the defoliant applications in the RF irrigation treatment with SR planting geometry, cotton had consistently recorded lower LAI in both years. Further, the TR plantings across the three irrigation treatments had significantly higher LAI until the boll cracking stage. However, the LAI recorded in 2019 was consistently lower than 2018 across all the three irrigation regimes, probably due to differences in the weather conditions as reflected in the cooler temperatures and consequent accumulation of a lower number of GDD during the vegetative phase. These results conform with the earlier reports where TR geometry and GDD were positively associated with high LAI (Pettigrew, 2015; Sundaram et al., 2009). The higher LAI measured under TR planting geometry optimized the interception of seasonal solar radiation that enhanced photosynthesis and biomass accumulation, resulting in significant improvement in lint yield production (10.62% in 2018 and 17.62% in 2019) than SR geometry. Pettigrew (2015) and Feng et al. (2017) reported that a higher LAI with early planting dates and supplemental irrigation increased the interception of solar radiation, which led to greater CO_2 fixation, accumulation of photosynthates, and lint yield. It was anticipated that early canopy closure with TR systems suppressed late-season weed-seed germination and establishment after the C1 stage, thereby reducing crop-weed interactions and competition for resources and helping boost crop growth, resulting in better yield. As discussed above, LAI in irrigated treatments was consistently higher than the RF treatment. Consequently, as Feng et al. (2017) observed, the photosynthetic rate of irrigated cotton (FI and HI) was maintained at a comparatively higher level and declined at a slower rate during the boll development to cracking phase than that of the RF treatment.

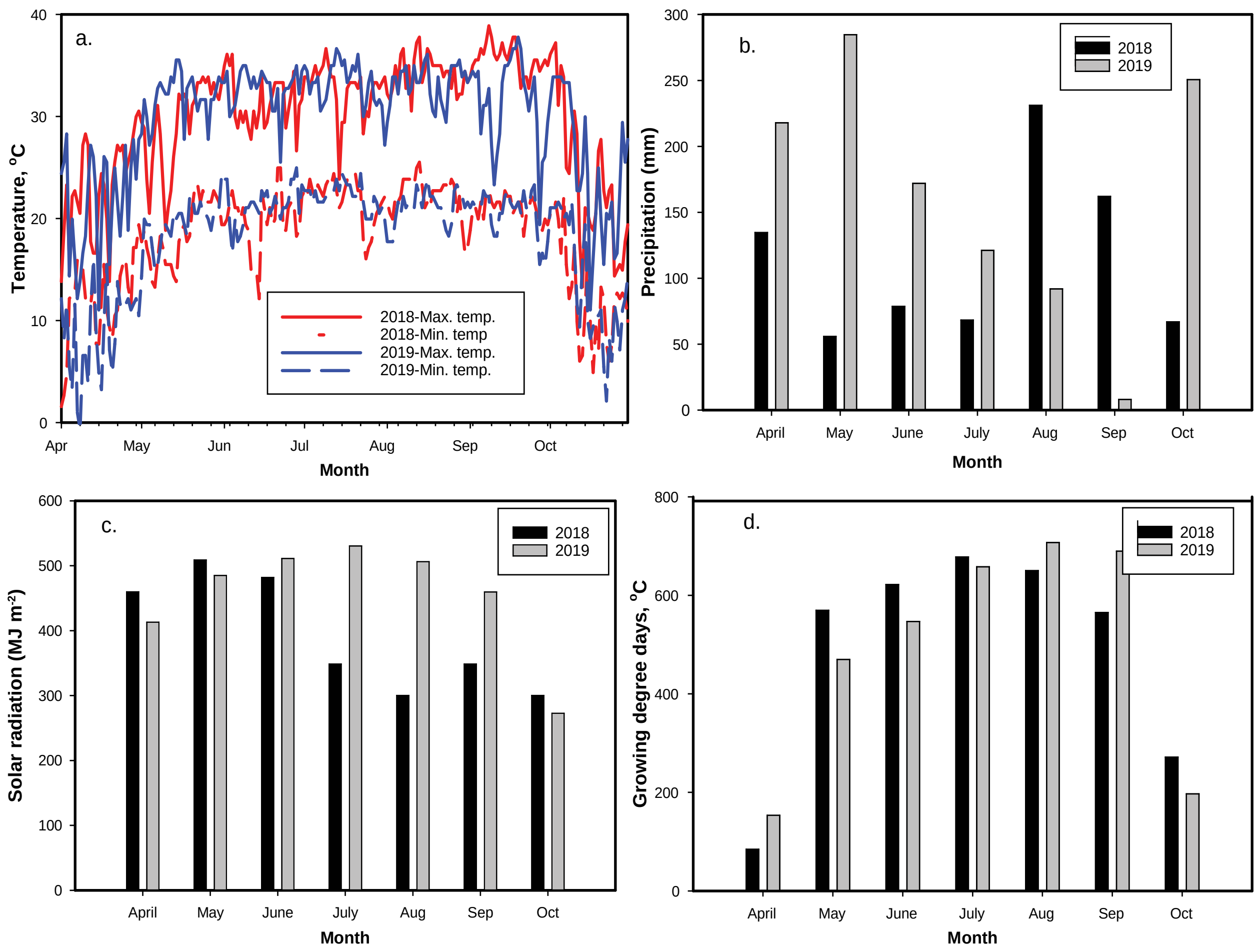

Figure 2. Measured (a) air temperature, (b) precipitation, (c) solar radiation, and (d) growing degree days (GDD) for 2018 and 2019 cotton growing seasons at Stoneville, MS.

Table 1. Significance of the main effects of irrigation regimes, year, and planting geometry (PG) and their interactions

Source of variance	df	Lint Yield	No. of bolls	Seed cotton	Chlorophyll content index	Biomass	100-seed weight	Population	Plant height[z] B1	FT	CU	Leaf area index B1	FT	CU
Irrigation level	2	<.0001*[y]	0.3846	0.2464	<0.0001*	0.289	<0.0001*	0.092*	0.2553	0.3567	0.6391	0.3768	<.0001*	<.0001*
PG	1	<.0001*	0.0068*	<.0001*	0.1146	0.7705	0.1742	<.0001*	0.2159	0.0015*	0.0103*	<.0001*	<.0001*	<.0001*
Year	1	<.0001*	0.0227*	<.0001*	0.0044*	0.0965	0.0176*	0.6926	0.7123	0.2476	0.2432	0.4435	0.6834	0.7504
Irrigation level*PG	2	0.7973	0.1424	0.5566	0.6465	0.978	0.6111	0.0006*	<.0001*	0.0653	<.0001*	<.0001*	0.0937	0.0012*
Irrigation level* Year	2	0.0003*	0.9159	0.3073	0.22	0.4381	0.0034*	0.1735	0.0027*	0.4081	0.0602	0.0095*	0.1943	0.0007*
PG*Year	1	0.0948	0.9207	0.5764	0.8473	0.5976	0.5164	0.9456	0.3605	0.291	0.2448	0.2226	<.0001*	0.3434
Irrigation level*PG* Year	2	0.0521	0.8247	0.6822	0.9135	0.8819	0.3351	0.7019	0.4084	0.1172	0.3853	0.3293	0.1104	0.5741

[z] B1: Square, FM: Anthesis, cu: Cracked boll stage;

[y]*Significantly different at $p \le 0.05$ level

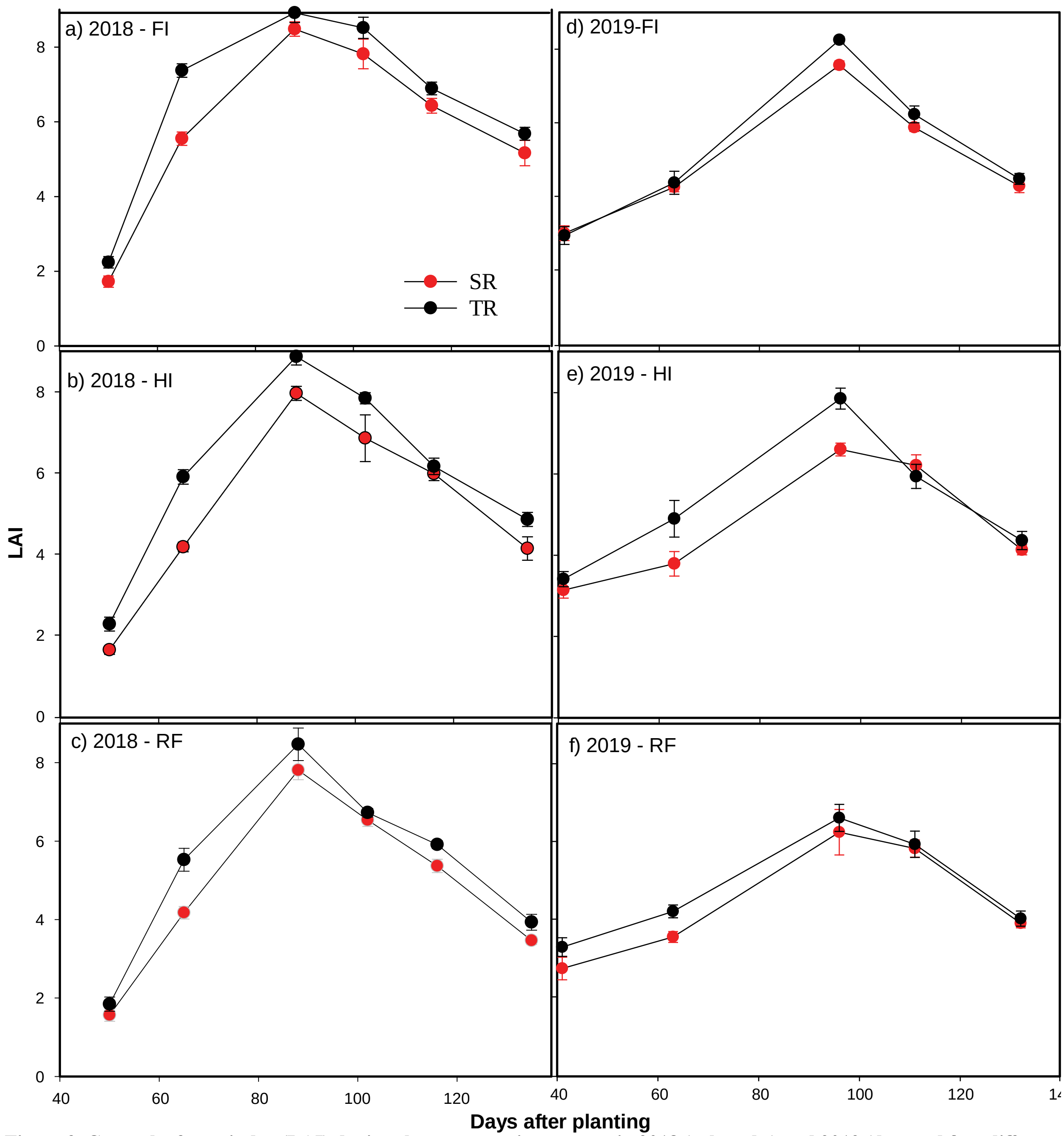

Figure 3. Cotton leaf area index (LAI) during the crop growing seasons in 2018 (a, b and c) and 2019 (d, e, and f) at different levels of irrigation (RF, HI, and FI) and planting geometries (SR and TR).

Planting Geometry Effects. Planting geometry significantly influenced plant population, LAI, lint yield, and cottonseed yield. The interaction effects of irrigation and planting geometry were significant for plant height and LAI at boll formation growth stages of the crop (Table 1). Plant population count at the boll formation stage, across the three irrigation regimes (FI, HI, and RF) and crop seasons (2018 and 2019), revealed a higher plant stand under the TR planting than under SR planting. Also, the more favorable weather for crop growth in 2019, mainly more evenly distributed precipitation events, favored the establishment of more plants in 2019 than in 2018 (Fig. 2). The mean number of plant stands established in the FI and HI irrigated plots were 10.4 plants m^{-2} in both FI- and HI-irrigated TR plots, and 8.6 plants m^{-2} in FI with SR and 8.2 plants m^{-2} in HI with SR planting geometries (Table 2a). RF with TR planting geometries had a mean of 9.34 plants m^{-2}, and there were 7.6 plants m^{-2} in RF with SR. The TR planting geometry produced a significantly higher number of bolls (75 bolls m^{-2}) than SR (64 bolls m^{-2}). Overall, across the three irrigation regimes, TR planting geometry had a 14% yield advantage: lint yield harvested in TR was 1966 kg ha^{-1} and in SR was 1719 kg ha^{-1}. Here TR had higher plant population establishment and more bolls m^{-2} leading to higher lint yields, probably due to better use of resources (water, nutrients, radiation). Similar results of enhanced yields in TR plantings were reported in MS Delta by Reddy and Boykin (2010) in cotton, Pinnamaneni et al. (2020) in soybean, and Bruns et al. (2012) in corn.

Irrigation Effects on the Crop. Irrigation levels had significant impacts on lint yield, chlorophyll index, 100-seed weight, and LAI (Table 1). The number of bolls per unit area in both FI and HI irrigated plots were significantly higher than that of RF in both SR and TR plantings (Table 2a). The mean number of bolls was higher in 2018 (78) than in 2019 (62) in all treatments, probably due to no drought during boll formation and development as well as higher GDD accumulation during pre-flowering phase as also observed by Stephenson and Brecke (2010) and Pettigrew (2015). Averaged across seasons, the plant biomass at harvest did not differ significantly among the three irrigation regimes and planting geometries (Table 2a).

Table 2a. Yield and yield components of full (FI) and half irrigated (HI) and rainfed (RF) cotton grown in Dundee silt loam with single-row (SR) and twin-row planting (TR) geometries

Treatment	Planting geometry	Population (plant m^{-2})			Number of open bolls (bolls m^{-2})			Biomass (t ha^{-1})		
		2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
FI	SR	7.7^{bc}	9.6^{ab}	8.6^{bc}	70.3^{bc}	58.0^{b}	65.7^{bc}	8.29^{a}	7.37^{c}	7.83^{a}
	TR	9.6^{a}	11.2^{a}	10.4^{a}	86.1^{a}	74.8^{a}	80.5^{a}	8.39^{a}	7.45^{ab}	7.92^{a}
HI	SR	7.5^{bc}	8.8^{bc}	8.2^{cd}	70.6^{bc}	55.8^{b}	67.1^{bc}	7.57^{c}	6.95^{d}	7.27^{c}
	TR	9.9^{a}	10.8^{a}	10.4^{a}	83.1^{ab}	72.8^{a}	79.1^{a}	7.60^{c}	7.23^{c}	7.41^{c}
RF	SR	7.4^{c}	7.7c	7.5^{d}	63.6^{c}	54.3^{b}	61.3^{d}	7.91^{b}	7.53^{a}	7.72^{ab}
	TR	8.9^{ab}	9.7^{ab}	9.3^{b}	70.5^{bc}	58.5^{b}	65.8^{bc}	7.59^{c}	7.87^{a}	7.73^{ab}
LSD(0.05)		0.6	1.1	1.0	8.2	10.5	8.6	0.31	0.27	0.21

Means followed by the same letter or letters are not statistically different ($p \leq 0.05$)

Table 2b. Yield components of full (FI) and half irrigated (HI) and rainfed (RF) cotton grown in Dundee silt loam with single-row (SR) and twin-row planting (TR) geometries

Treatment	Planting geometry	Lint yield (kg ha^{-1})			100-seed weight (g)			Seed cotton (kg ha^{-1})		
		2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
FI	SR	1688^{bc}	1870^{b}	1779^{b}	15.4^{a}	14.5^{ab}	14.9^{a}	3806^{b}	3327^{bc}	3566^{c}
	TR	1743^{bc}	2314^{a}	2028^{a}	15.3^{a}	14.5^{ab}	14.7^{a}	4289^{ab}	4586^{a}	4437^{a}
HI	SR	1737^{bc}	1869^{b}	1803^{b}	15.9^{a}	14.78^{a}	15.3^{a}	3996^{ab}	3453^{bc}	3725^{bc}
	TR	1980^{a}	2183^{a}	2082^{a}	15.1^{a}	14.7^{a}	15.2^{a}	4479^{a}	4135^{ab}	4307^{ab}
RF	SR	1573^{c}	1543^{c}	1558^{c}	13.8^{b}	13.9^{c}	13.8^{b}	3758^{b}	3125^{c}	3441^{c}
	TR	1822^{ab}	1753^{bc}	1788^{b}	13.7^{b}	14.1^{bc}	13.8^{b}	4335^{ab}	3605^{bc}	3970^{bc}
LSD (0.05)		78	94	89	0.8	0.7	0.7	289	356	296

Means followed by the same letter or letters are not statistically different ($p \leq 0.05$)

Significant differences in 100-seed weight were observed among the three irrigation regimes, although planting geometries failed to produce such effects (Table 2b). The 100-seed weight in both the FI (14.9 g in SR and 14.7 g in TR) and HI (15.4 g in SR and 15.2 g in TR) were higher than those of RF (13.8 g in SR and 13.9 g in TR). Irrigation did not significantly impact cottonseed yield. However, the average seed cotton yield in TR was 17% higher than SR in 2018, and 21% higher in 2019 due to planting geometry and seasonal differences (Table 2b). The enhanced seed cotton yield in TR could be due to more bolls retained per plant per unit area. Under RF, due to moisture stress, younger bolls were shed to enable the development of older bolls. In cotton this phenomenon is considered a survival mechanism during drought by lessening competition for the declining biomass production, placing priority on seed and fiber development (Pettigrew and Zeng, 2014; Shareef et al., 2018; Zhang et al., 2016). This could be the reason for no significant difference of cotton seed weight across three irrigation regimes.

Irrigations and planting geometry significantly enhanced lint yields. The average lint yields in the irrigation and planting geometry combinations were: 1779 kg ha^{-1} in FI-SR, 2029 kg ha^{-1} in FI-TR, 1803 kg ha^{-1} in HI-SR, 2082 kg ha^{-1} in HI-TR, 1573 kg ha^{-1} in RF-SR, and 1788 kg ha^{-1} in RF-TR (Table 2b). Although lint yields were similar in both FI and HI treatments, FI had a 13% and HI exhibited a 16% yield advantage over RF treatment. Sui et al. (2017) reported a 26% irrigation response in the MS Delta, whereas Ünlü et al. (2011) and Zhang et al. (2016) showed a 4 and 34% yield advantage under a range of irrigation regimes in Turkey and northwest China, respectively. Our findings were akin to the results of the studies mentioned above. In humid climates like MS Delta, the higher lint yield in HI treatments could be due to optimum water availability in the active root zone unlike FI, wherein excess water around the root zone from heavy precipitation events following the irrigation that coincided with boll formation and developmental stages in July and August (Fig. 1), and probably resulted in hypoxia, nutrient leaching, and lower water uptake resulting in higher vegetative growth at the expense of reproductive growth as evidenced by higher LAI (up to 9) and plant height (1.5 m). Wanjura et al. (2002) reported a lower R^2 of 0.46 between irrigation and lint yield from 11 years of irrigation studies (1988 to 1999) at Lubbock, TX.

Irrigation WUE. In the two crop seasons, a total of ten irrigations were applied. The total irrigation per season and average irrigation applied in FI were 173 mm and 87 mm in HI (Table 3), whereas the annual precipitation during the crop season was 798 mm and 1146 mm in 2018 and 2019, respectively (Fig 2b). Average irrigations applied per event was 38.4 mm in FI, and 19.2 mm in HI and during the 2018 season, whereas 38.9 mm and 19.2 mm were given in FI and HI, respectively, in the irrigation events in 2019.

In the current study, as expected, the highest irrigation WUE was recorded in HI under TR planting (3.43 kg ha^{-1} mm^{-1}), followed by HI-SR (2.70 kg ha^{-1} mm^{-1}), whereas FI had lower irrigation WUE (TR, 1.38 and SR, 1.19 kg ha^{-1} mm^{-1}) with greater interseason variability. Our study is the first to report irrigation WUE in SR versus TR planting geometries with different irrigation regimes. Further, HI-irrigated TR cotton had a significantly higher yield of 16.5% than the RF system with TR planting. The FI-irrigated TR cotton resulted in a 13.8% higher lint yield than the RF system as well (Table 3). The lower WUE and lint yields in the FI system compared to HI system could be due to hypoxia in the root zone due to the reasons explained above. Water applications far in excess of crop evapotranspiration has resulted in higher vegetative growth and poor yields (Ayars et al., 1991; Wanjura et al., 2002) crop water use and yield response of cotton. The experiment was conducted in the San Joaquin Valley of California using a linear move sprinkler system which had been modified to apply water at 3 different levels of uniformity and 2 different scale lengths. The effects of these application uniformities on cotton growth and yield were evaluated at 4 different average levels of water application (0.7, 0.9, 1.1, and 1.3 times crop evapotranspiration. In the literature, researchers in different regions reported a diverse range of irrigation WUE (Dağdelen et al., 2009; Shareef et al., 2018; Ünlü et al., 2011). Ünlü et al. (2011) reported WUE of 6.3 kg ha^{-1} mm^{-1} under full irrigation and 20.5 kg ha^{-1} mm^{-1} under 50% deficit irrigation in a Mediterranean environment, whereas Shareef et al. (2018) observed irrigation WUE in the range of 0.42 to 0.68 kg m^{-3} in northwest China. Irrigation WUE was found to increase from 0.62 to 0.71 kg m^{-3} as the irrigation water applied was reduced from 100 to 75% of soil water depletion (Basal et al., 2009). Basal et al. (2009) and Dağdelen et al. (2009) measured the highest irrigation WUE in western Turkey with a lower level of irrigation water as WUE decreased with increased water application. Based on the above observations, we concluded that by adopting HI with TR planting geometry, cotton producers could reduce irrigation water application by half while enhancing productivity by 16.5 %, which can potentially decelerate further decline of the MRVA.

Table 3. Irrigation water use efficiency (WUE) and lint yield at different irrigation regimes and planting geometries (SR and TR)

Treatment[z]	Irrigation water applied (mm)			WUE (kg ha^{-1} mm^{-1})			Yield increase over RF (%)		
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
FI – SR	195.4	152	173.7	0.59^{b}	2.15^{c}	1.2^{c}	7.3^{b}	21.1^{c}	14.2^{c}
FI - TR	195.4	152	173.7	-0.40^{c}	3.69^{b}	1.4^{c}	-4.3^{c}	32.0^{a}	13.8^{c}
HI - SR	96.2	75	85.6	1.70^{a}	4.35^{b}	2.7^{b}	10.4^{a}	21.1^{c}	15.7^{b}
HI - TR	96.2	75	85.6	1.64^{a}	5.73^{a}	3.4^{a}	8.6^{b}	24.5^{b}	16.5^{a}
RF-SR	0	0	0			-			-
RF-TR	0	0	0			-			-
LSD (0.05)				0.32	0.95	0.5	1.05	3.02	0.71

Means followed by the same letter within a column are not significantly different ($p \leq 0.05$)

[z] FI = All-row irrigation, SR = Single-row, TR = Twin-row, HI = Alternate row irrigation, RF = Rainfed

SUMMARY AND CONCLUSIONS

Globally, the primary source of water for irrigated agriculture has been underground aquifers (Clark et al., 2011). However, these groundwater sources have declined significantly over many years of unsustainable withdrawal of water for irrigation and other human enterprises. In the mid-southern U.S., a significant decline in MRVA was observed during the past three decades. Our investigation for developing agro-management systems that help conserve more water in the aquifer without compromising yield returns from agriculture revealed that planting cotton in a TR planting geometry had significant yield advantage (13.5-16.4%) over SR planting geometries. Further, HI with TR planting geometry combination has the highest irrigation WUE (3.4 kg ha^{-1} mm^{-1}), hence reduces the use of water for irrigation while producing higher lint yield (16%). Our preliminary results indicate that by adopting HI with TR planting geometry, cotton producers can reduce irrigation water application considerably while sustaining cotton productivity. Further, multilocation, multiseason study in farm-size fields would be required to produce a strong recommendation on adopting the TR combined with HI strategy to the farmers in the region.

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