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ARTICLE

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Assessing irrigation water use efficiency and economy of twin-row soybean in the Mississippi Delta

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Abstract

Twin-row planting in soybean (*Glycine max* L.) has been proposed for optimizing resource use and seed yield. Experiments were conducted in 2018 and 2019 on a Dundee silt loam to assess soybean seed yield and irrigation water use efficiency (IWUE) in response to single-row (SR) and twin-row (TR) planting geometries under rainfed (RF), all row or full irrigation (FI), and alternate row or half irrigations (HI). Averaged across two crop years and three irrigation regimes, TR enhanced seed yield by 13% over SR (4.5 vs. 4.0 Mg ha^{-1}). The final plant stands established in the FI, HI, and RF under TR were 32, 33, and 31 plants m^{-2}, whereas 30, 31, and 27 plants m^{-2} were established under SR. Under both SR and TR, irrigations produced a higher number of pods per plant than of RF. Averaged across crop years, yields in the irrigation–planting geometry combinations were 4.8 Mg ha^{-1} in FI-TR, 4.7 in Mg ha^{-1} in HI-TR, 4.2 Mg ha^{-1} in FI-SR, 4.1 Mg ha^{-1} each in RF-TR and HI-SR, and 3.6 Mg ha^{-1} in RF-SR. The HI-TR combination had the highest IWUE of about 0.0063 Mg ha^{-1} mm^{-1} of water, followed by HI-SR with 0.0053 Mg ha^{-1} mm^{-1}. The seed yield in FI-TR was not significantly higher than that of HI-TR. Thus, conversion from FI-TR to HI-TR can save half the amount of irrigation without compromising yield or economic returns. Conversion from SR to TR is profitable regardless of the irrigations.

1 | INTRODUCTION

Soybean (*Glycine max* L.) was grown globally in an area of about 125.5 Mha with a production of about 358 MT during 2018–2019, of which, the United States produced about 120 MT from 35.45 Mha (USDA-NASS, 2019). On a dry matter basis, soybean seeds contain about 21% oil, 40% protein, 34% carbohydrates, and 5% ash; as such, they are widely used for vegetable oil and livestock-feed production. As a legume crop, soybean also improves soil fertility by fixing atmospheric nitrogen with the help of symbiotic bacteria in the root nodules (Heatherly & Elmore, 2004).

Soybean is a major row crop in the state of Mississippi, with about 0.7 M ha planted in 2019 (USDA- NASS, 2019). In Mississippi, this crop was predominantly grown on raised beds (on ridges in a furrow-ridge seedbed preparation) that are typically on a 96- to 102-cm row spacing (SR, single row planting geometry). In the humid Mississippi climate, these raised beds help in draining rainwater

Abbreviations: FI, full irrigation; GDD, growing degree days; HI, half irrigation; ISU, irrigation set up; IWUE, irrigation water use efficiency; LAI, leaf area index; MG, maturity group; MRVAA, Mississippi River Valley Alluvial Aquifer; PAR, photosynthetically active radiation; RF, rainfed; SR, single row; TR, twin-row.

off the field in early spring. The furrows also serve as conduits for applying irrigations in the field during the summer crop season. In the past several years, many producers in Mississippi and adjoining states in the mid-South have shifted from the single-row (SR) systems into a twin-row (TR) planting geometry (Bruns, 2011a). Soybean is a photoperiod sensitive crop, which means the observed time required for the plant to mature is location-specific—later the planting in the season, the less photoperiod encountered by the growing plant. Soybean varieties with differing photoperiods were developed, called maturity groups (MG) having different phenological responses to temperature and photoperiod. A variety is classified into a specific MG according to the number of days required by the plant from planting until maturity. Beginning in early 2000, an early soybean production system involving MGs IV and V cultivars was introduced in the mid-southern United States to more efficiently use the region's water availability earlier in the growing season. Currently, in the mid-South Delta region, about 80% of planting is completed in the March–April period (Bruns, Ebelhar, & Abbas, 2012). The TR planting geometry is characterized by planting two rows of soybean spaced about 25 cm apart on raised beds (in place of a single row in the SR system) with centers separated by about 102 cm as in the SR planting. The advantage of using TR geometry over SR geometry has been well reported in the literature: (a) faster canopy closure that suppresses germination and establishment of late-season weeds; (b) increased light interception; (c) increased plant survival rates; and (d) improved nutrient- and water-use efficiencies (Bellaloui et al., 2015; Bowers, Rabb, Ashlock, & Santini, 2000; Bruns, 2011a, b; Grichar, 2007; Mascagni, Clawson, Lanclos, Boquet, & Ferguson, 2008; Robles, Ciampitti, & Vyn, 2012; Smith et al., 2019a, b). A study conducted on Mhoon silty clay soil revealed that greater light interception during the vegetative and early reproductive periods was responsible for increased yield in narrow-row culture due to a higher number of nodes and increased pods per node. (Board, Kamal, & Harville, 1992). Grichar (2007) reported up to 23% increase in soybean seed yields due to TR over SR at two locations along the Texas Gulf Coast involving both MG IV and MG V cultivars. Mascagni et al. (2008) observed a 0–13% yield increase with TR compared to SR planting geometries in Louisiana.

Similarly, Bruns (2011a, b) reported up to 12% seed yield increase in TR for an MG IV cultivar when seed rate was more than 40 m^{-2} on a Beulah fine sandy loam soil in Stoneville, MS. This increase in seed yield was attributed to a better plant stand established in the TR system, likely from improved soybean leaf area index (LAI) in this system that helped higher survivability of soybean seedlings (Bruns, 2011a; b). Although previous research has shown that the effectiveness of a TR production system depends on the availability of water, nutrients, and temperature (Bellaloui et al., 2015), no significant seed yield differences between TR and SR planting geometries were observed in a 2-yr study conducted on a fine sandy loam soil in Stoneville, MS (Turner et al., 2019). However, Dhakal, West, Deb, Villalobos, and Kharel (2020) reported that planting geometry (row spacing) could influence soil–plant–water relations and affect water use efficiency of alfalfa (*Medicago sativa* L.) in water-limited conditions.

Core Ideas

- Planting and irrigation strategies were investigated to enhance water saving.
- Twin-row planting enhanced grain yield regardless of irrigation.
- Twin-row with alternate-row irrigation use half the water with same returns.

In the lower Mississippi Delta, rainfall received during the crop season is characterized by large inter- and intra-seasonal variabilities in amounts and temporal distributions, leading to unstable crop yield returns in rainfed (RF) systems (Anapalli et al., 2016). To stabilize the farm returns, currently, over 60% of soybean grown in the Mississippi Delta region is irrigated. Each irrigation ha consumes over 2.3 Ml of groundwater (Kebede, Fisher, Sui, & Reddy, 2014). The Mississippi River Valley Alluvial Aquifer (MRVAA) underlying the Mississippi Delta region provides most of this water (Clark, Hart, & Gurdak, 2011). Because water removals from this shallow MRVAA exceeded its natural recharge levels in the past, the aquifer level has declined considerably, threatening its sustainability in supporting further irrigated cropping systems in this region. To contain and reverse this scenario, soil–water–crop management studies for enhancing irrigation water use efficiency (IWUE, amount of seed yields per unit of water used) in cropping systems in this region are required (Anapalli et al., 2018, 2019; Clark et al., 2011; Dalin, Wada, Kastner, & Puma, 2017). In an attempt to fill this gap in scientific research in the Mississippi Delta region, Plumblee et al. (2019) reported an increase in IWUE in cotton (*Gossypium* L.) of 61% after adopting an irrigation schedule that triggered irrigations at −90 kPa matric water potential in 100-cm soil depth. Although the physiological and agronomic advantages of a TR soybean production system compared with an SR system have been thoroughly researched, no information on the IWUE of a TR over an SR planting geometry was reported for the Mississippi Delta (Plumblee et al., 2019).

Thus, this study was designed to compare soybean yield between SR and TR planting geometries for optimizing IWUE of soybean in response to RF, all-row or full irrigation (FI), and alternate row or half irrigation (HI) regimes.

2 | MATERIALS AND METHODS

Experiments were conducted in a Dundee silt loam (fine silty, mixed, active, thermic Typic Endoaqualfs) at the USDA-ARS, Crop Production Systems Research Unit farm located in Stoneville, MS (33°42′N, 90°55′W; 32 m asl) in 2018 and 2019. The soil (top 15 cm) in the experimental field was sampled and characterized: 1.2% organic matter, 0.08% nitrogen, 125 mg L^{-1} potassium, and 22 mg L^{-1} phosphorous (Mehlich 3 Extraction). Bulk density of the soil averaged across 60-cm soil depth was 1.33 g cm^{-3} and field saturated hydraulic conductivity ranged between 0.52 and 1.49 cm h^{-1}. The field saturated hydraulic conductivity was measured using the Saturo infiltrometer using the appropriate protocol (METER Group, Pullman, WA). Field preparation was conducted in the fall after harvesting the crop and consisted of one or two deep tillage events to break clay pans and overturn soils, burying crop residue, and killing weeds followed by a disc-tillage to generate furrows and ridges (102-cm row spacing) for planting soybean and to facilitating furrow irrigations. The raised-ridge seedbeds were re-hipped during the spring season, and the tops of the seedbeds were smoothed before planting. The SR plantings were made using an Almaco cone plot planter (Allen Machine Company, Nevada, IA), and TR plots were planted with a four-unit Monosem NG-3 (Monosem, Edwardsville, KS) twin-row vacuum planter set on 102-cm centers and 25 cm between rows within a unit. Seeding depth was adjusted to place the seed in the top 25 mm of moist soil to facilitate germination. Both planters were set to achieve a similar overall plant population density of approximately 336,000 plants ha^{-1}. Currently, Mississippi State University recommends a seeding rate of 345,800 seeds ha^{-1} for an MG IV soybean planted in April to May on clay soil (Smith et al., 2019b). Plant populations were estimated at harvest by counting plants in 1-m^2 area in the SR and TR rows at three randomly selected locations in each plot. The experimental area was treated with paraquat at 1.12 kg a.i. ha^{-1} before planting to kill existing weeds. Plots were maintained weed-free using both preemergence and postemergence herbicide programs. *S*-metolachlor at 1.12 kg a.i. ha^{-1} plus pendimethalin at 1.12 kg a.i. ha^{-1} were applied preemergence. Glyphosate at 1.12 kg a.i. ha^{-1} plus metolachlor at 1.12 kg a.i.ha^{-1} were applied postemergence. The escaped weeds were hand-hoed as needed. Soybean cultivar ‘31RY45 Dyna-Gro’ (MGIV) was planted in a split-plot design with six replicates. The main plots were three irrigation regimes (a) FI, (b) HI, and (c) RF. Subplots consisted of two planting geometries: (a) SR, single rows evenly spaced at 102-cm centered seedbeds, and (b) TR, two rows spaced 25 cm apart on 102-cm centered seedbeds (Figure 1). As the seed rate is the same for both the planting geometries, the intra-row distance between the plants in SR geometry will be consequently high (data not collected). The amount of irrigation water applied in each plot was measured using a flow meter (Mc Propeller flowmeter, McCrometer, Hemet, CA). Soybean was planted on 8 May 2018 and 2 May 2019. Each plot consisted of four SR or eight TR 40-m-long rows. Sensors for measuring soil-matric water potential (Watermark 200SS, Irrometer Co., Riverside, CA.) were installed at depths of 15, 30, and 60 cm in selected representative plots. Irrigations were scheduled based on a soil-matric potential of about −90 kPa at 60 cm soil depths in the FI irrigation plots as recommended by Plumblee et al. (2019). In 2018, a total of 220 mm of irrigation was applied in the FI treatments in four irrigation events of 55 mm each applied through every furrow on 15 May, 20 June, 6 July, and 3 August, while the HI treatments received about half the amount of water on the same dates but in every other furrow, amounting to total water applied of about 115 vs 220 mm in the FI. In 2019, total irrigation applied was 152 mm in the FI treatment, in three irrigation events of 51 mm each on 10 June, 29 July, and 7 August, while in HI treatments, 75 mm of water was applied on the same dates. Irrigation was stopped at the R6 stage of growth of pod development in both years. Weather data were collected from the mid-South Agricultural Weather Service, Delta Research and Extension Center, Stoneville, MS, weather station located within a mile of the experimental field. The amount of precipitation received during the 2018 crop season was 731 mm, whereas 896 mm was received in 2019. The growing degree days (GDD), in °C, were calculated using a base temperature (T base) of 10 °C (Desclaux & Roumet, 1996):

$$\mathrm{GDD} = \left(\frac{\mathrm{Tmax} + \mathrm{Tmin}}{2}\right) - \mathrm{Tbase} \qquad (1)$$

Where, $(\mathrm{Tmax} + \mathrm{Tmin})/2 < 10, \mathrm{GDD} = 0.0$.

At the physiological maturity growth stage of soybean, aboveground biomass was harvested from 1-m^2 section of row-beds from each plot at three random locations, avoiding the row ends. Yield data were collected by handpicking from 1-m^2 section in the two center rows at three randomly selected locations in each plot. 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. An AccuPar model LP-80 PAR/LAI Ceptometer sensor (Decagon Devices, Pullman, WA) was used to measure LAI. Stomatal

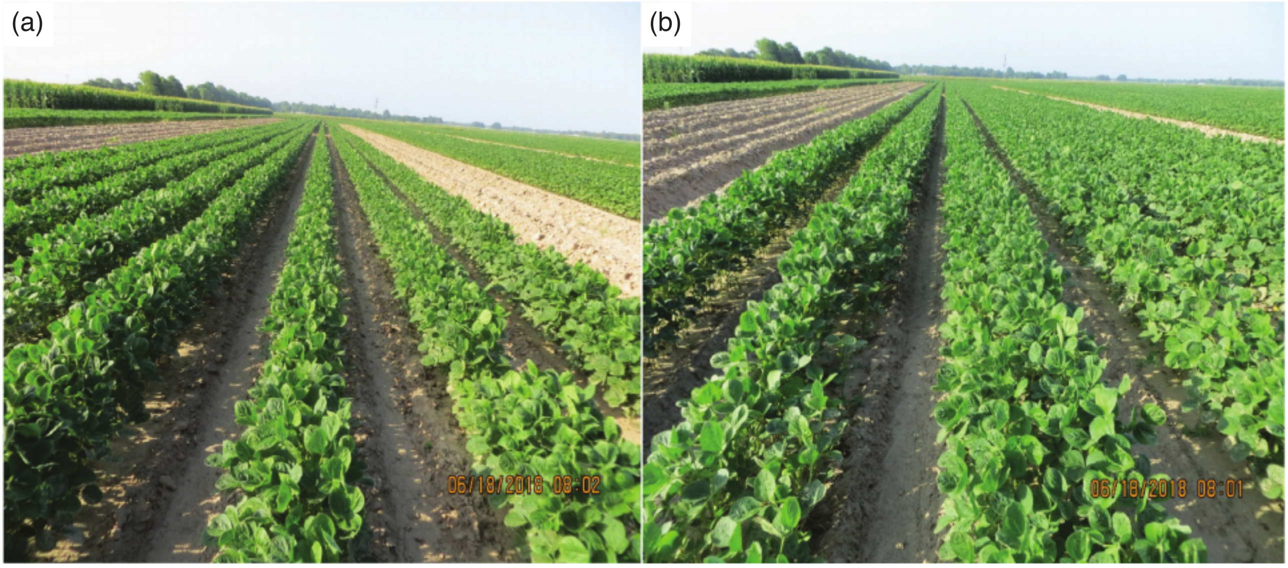

FIGURE 1 Soybean plants in 102-cm single-row (a), 25-cm twin-row (b) planting geometries

conductance (μmol m^{-2} s^{-1}) of the fully expanded terminal leaves of five randomly tagged plants was recorded by using a leaf porometer (SC-1 Porometer, Decagon Devices, Pullman, WA) at R1 stage. Ambient photosynthetically active radiation (PAR) conditions were measured in full sunlight just above the canopy. The light sensor was then placed on the ground below the soybean canopy, and the PAR was measured at six locations within each plot on a non-cloudy day between 9:00 a.m. and 12:00 p.m. CST, and the mean LAI was computed. All plant measurements were replicated at five random locations in each plot and used in the calculation of standard error (SE) of measurements. The IWUE of irrigation water applied was calculated as:

$$\text{IWUE} = \left(\frac{Y_i - Y_r}{I}\right) \quad (2)$$

where Y_i is the seed yield in the FI or HI treatment, Y_r is the seed yield in the RF, and I is the irrigation applied.

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, Cary, NC) with year, irrigation, planting geometry, and their interactions as fixed effects and replication and whole plot (irrigation) as random effects. The treatment means were separated at the 5% level of significance using Fisher's protected least significant difference (LSD) test.

For estimating costs of soybean crop production in the economic analysis, crop planning budgets from the Mississippi State University's Department of Agricultural Economics were used. Production cost for RF-SR soybean was obtained directly from the published budget, but production cost for FI-SR was adjusted to reflect the amount of water pumped, so it differs from the planning budgets by the amount of labor, fuel, wear and tear required. A similar adjustment was employed for HI-SR. Production costs for TR were adjusted to reflect additional stress on a power unit to operate heavier TR equipment in comparison to SR as well as to reflect the increased capital cost associated with TR planters. Finally, to reflect a common circumstance in the Mississippi Delta, production costs were calculated for the RF but irrigation-set-up scenario (RF-ISU) in which the farmer sets up their well and roll-out pipes for irrigation but ultimately does not apply irrigation, that is, all irrigation costs except pumping-related costs.

Soybean prices were calculated as the average bid prices between 17 September and 1 November reported daily as of 2:00 p.m. for seed at county elevators in Greenville, MS, by the USDA Economics, Statistics and Market Information System (ESMIS). Depressed market prices were observed at U.S. \$292.08 Mg^{-1} in 2018 and \$334.33 Mg^{-1} in 2019.

3 | RESULTS AND DISCUSSION

3.1 | Weather

Considerable differences in climate during the two cropping seasons in 2018 and 2019 were noticed (Figure 2). The reproductive growth and pod development (July–Sept.) period in 2018 received 461 mm, and a similar period in 2019 received 221 mm of rainfall. The growth period (June–Aug.) in 2019 recorded additional GDD than in 2018.

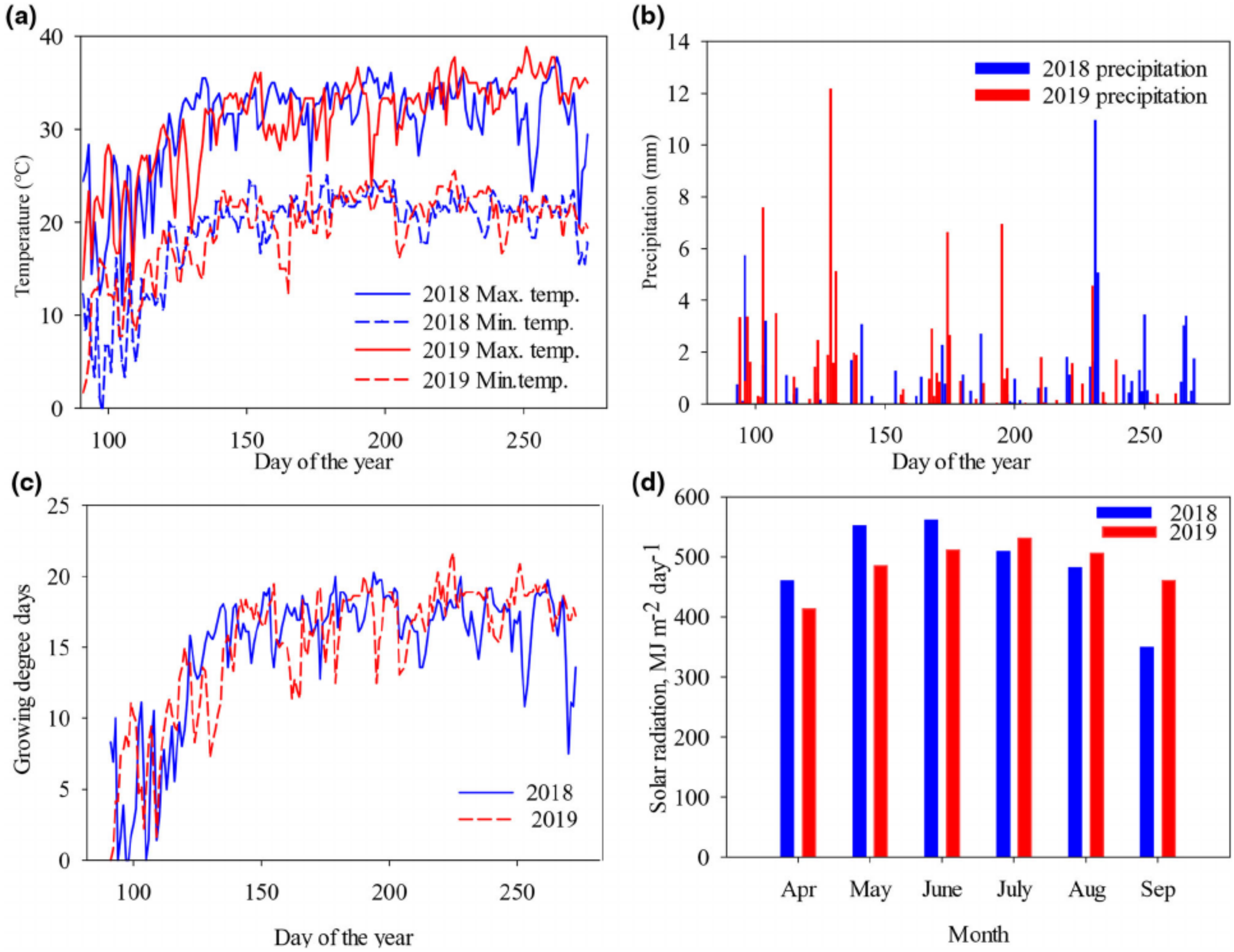

FIGURE 2 Measured air temperature (a), precipitation (b), solar radiation (c), and growing degree days (d) in 2018 and 2019 soybean growing seasons at Stoneville, MS

Though the growing season in 2018 received more rainfall, the rainfall received during the soybean vegetative growth period (May–July) in 2018 coincided with periods of lower rainfall (375 mm less than in 2019) and higher mean minimum and maximum air temperatures. These differences in weather during the two crop seasons were reflected in the significant differences in seed yield-related traits between 2018 and 2019 revealed in the analysis of variance (ANOVA) tests (Table 1).

3.2 | Phenology

Knowledge of crop phenology is useful in scheduling crop management events, and it was shown to be significantly influenced by environmental factors such as temperature, photoperiod, soil moisture, and soil fertility (Desclaux & Roumet, 1996). Data collected at different phenological stages from emergence (VE) to physiological maturity (R8) are presented in Table 2. There were no differences in phenological events among the irrigation regimes and planting geometries in the same year (data not presented in Table 1). However, the comparison between the two crop seasons revealed that the transition between different vegetative stages took a higher number of calendar days in 2018 than in 2019. This could be the result of prevailing lower temperatures coinciding with the vegetative phase in 2018 (Figure 2). The aggregate GDD in 2018 was 1,812 and 1,747 in 2019, which were similar to earlier reports for an MG IV cultivar in humid climates, which varied between 1,881 and 2,599 aggregate GDD (Desclaux & Roumet, 1996; Kukal & Irmak, 2018).

3.3 | Planting geometry effects

Planting geometry significantly influenced plant population, plant height, stomatal conductance, LAI, pod number per plant, 100-seed weight, and seed yield (Table 3a, 3b). Plant population count at the R7 stage, across the three

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

	df	Seed Yield	Stomatal conductance	Chlorophyl l content index	Biomass	100-seed weight	Plant population	Plant height	Pods per plant	Leaf area index			
										V4[a]	R1	R4	R7
Irrigation level	2	<.006*	.047*	.308	.609	.005*	.024*	.254	.045*	0.378	<0.001*	0.031*	0.089
PG	1	.003*	.003*	.155	.113	<.002*	<.001*	.047*	.001*	0.008*	<0.001*	<0.001*	0.089
Year	1	.068	.105	.854	.450	<.001*	.078	<.001*	.756	0.443	0.010*	0.009*	0.512
Irrigation level × PG	2	.805	.113	.646	.271	.611	.976	.294	.652	1.235	0.093	0.061	0.113
Irrigation level × Year	2	.703	.943	.617	.777	.003	.983	.171	.983	0.952	0.194	0.061	0.731
PG × Year	1	.170	.514	.685	.724	.516	.425	.002*	.946	0.222	0.154	0.233	0.539
Irrigation level × PG × Year	2	.974	.248	.197	.508	.335	.692	.181	.754	0.329	0.110	0.574	0.229

*Significantly different at the .05 probability level.

[a]V4, fourth trifoliate; R1, beginning flowering; R4, full pod; R7, beginning maturity.

irrigation regimes (FI, HI, and RF) and crop seasons (2018 and 2019), revealed higher plant stand was established under the TR planting (32 plants m^{-2}) than under the SR planting (29 plants m^{-2}; Table 3a). The final plant stands established averaged across the years in the FI, HI, and RF under the TR planting geometry was 32, 33, and 31 plants m^{-2}, respectively, and 30, 31, and 27 plants m^{-2} were recorded under the SR planting geometry (Table 3a). The high plant stand in HI can be attributed to better root aeration when heavy precipitation is followed by irrigation in early vegetative stages. Plants in the SR planting geometry had significantly higher plant heights across the three irrigation regimes. More favorable weather conditions were observed during the V1–R1 stages in 2019, mainly due to more evenly distributed precipitation events (Figure 2) which favored the establishment of more plants in 2019 than in 2018 (Table 3a, b). Leaf area index is one of the dynamic indicators of crop canopy closure, and it was measured at different growth stages. Leaf area index under the TR geometry was significantly higher than under the SR geometry from the V4 stage to the R6 stage, whereas no differences were observed between planting geometries and irrigation regimes at V1–V3 (data not shown) and at R7 to R8 stages (Table 1; Figure 3). Furthermore, the TR plantings in both the seasons and three irrigation treatments showed significantly higher LAI until the R6 stage, probably due to higher plant stand and growth (Figure 3a, b). However, the LAI recorded in 2019 was consistently lower than in 2018 across all three irrigation regimes, probably due to differences in the weather conditions as reflected in the cooler temperatures and consequent accumulation of a smaller number of GDD during the vegetative phase. The higher LAI measured under TR planting geometry could have been due to improved interception of PAR that enhanced photosynthesis and biomass accumulation, resulting in significant improvement in seed yield production (17.3% in 2018 and 10.9% in 2019) over the SR geometry. It was reported that an early canopy closure in TR and higher interception of PAR led to greater CO_2 fixation, and the accumulation of photosynthates in the pods resulted in higher seed yield (Smith et al., 2019b). In this study, we expect that early canopy closure under the TR system suppressed mid-season weed-seed germination and establishment (data not collected), which helped boost crop growth resulting in better yield returns. Suppression of weeds also helped in reducing crop–weed competition for water, nutrients, and PAR resources in the growth environment.

The soybean leaf stomatal conductance in TR geometry was consistently higher than in SR across the three irrigation regimes and years. The TR planting geometry produced a significantly lower number of pods (56 pods plant^{-1}) than SR (61 pods plant^{-1}) across the seasons.

TABLE 2 Phenology of soybean during 2018–2019

Growth stage	2018 DOY[a]	2018 GDD	2019 DOY	2019 GDD
Emergence	131	63	127	67
Cotyledon	136	149	131	107
First trifoliate	141	231	136	167
Second trifoliate	147	324	139	227
Third trifoliate	154	446	143	280
Fourth trifoliate	162	577	153	454
Fifth trifoliate	169	700	159	554
Sixth trifoliate	172	749	166	649
Seventh trifoliate	173	762	170	710
Eighth trifoliate	177	831	175	795
Ninth trifoliate	180	887	181	890
Tenth trifoliate	183	943	185	963
Beginning flowering	169	700	165	630
Full flowering	176	813	170	710
Beginning pod	179	870	176	811
Full pod	184	960	183	927
Beginning seed	196	1,178	190	1,058
Full seed	214	1,482	202	1,269
Beginning maturity	228	1,731	215	1,571
Physiological maturity	236	1,859	232	1,800

[a] DOY, day of the year; GDD, growing degree days.

Similar results were reported by Bruns (2011a), wherein TR plantings tended to produce fewer pods plant^{-1} than SR plantings with 57 vs. 61 pods plant^{-1} on the Beulah sandy loam and 63 vs. 70 pods plant^{-1} on a Sharkey clay, probably due to negative effect of plant density on pod production at fertile nodes. Overall, across the three irrigation regimes during 2018 and 2019, yields from the TR planting geometry had a 13% yield advantage: seed yield harvested in TR was 4.5 Mg ha^{-1} and 4.0 Mg ha^{-1} in SR. Similar results of enhanced soybean yields in TR plantings were reported earlier (Bellaloui et al., 2015; Bruns, 2011a,b; Gulluoglu, Bakal, & Arioglu, 2016; Smith et al., 2019b; Thompson et al., 2015). The enhanced yield in TR geometry is attributed to early canopy closure leading to higher intercepted photosynthetically active radiation, more population, reduced crop–weed competition due to suppression of postemergence weeds during late vegetative (V5) to first reproductive phase (R1), and efficient use of resources such as nutrients, water, and light. TR geometry recorded a higher percentage of canopy closure than the SR due to higher LAI from R1 to R7 reproductive stages in a study conducted in Stoneville, MS, during 2017–2018 (Turner et al., 2019). Similarly, greater interception of radiation in narrow row soybean resulted in higher seed yield (Board et al., 1992; Sampaio Ferreira, Antonio Balbinot, Werner, & Zucareli, 2019). It appears the higher plant stand established per unit area in TR has contributed to enhanced yields. These results conform with the findings of Gulluoglu et al. (2016), who reported a 24.5% yield increase in TR geometry due to significantly higher plant stand establishment.

3.4 | Irrigation effects on the crop

Irrigation levels had significant effects on seed yield, 100-seed weight, stomatal conductance, plant population, and LAI (Table 2). The number of pods plant^{-1} in both FI and HI irrigated plots were significantly higher than that of RF in both SR and TR geometries (Table 2b). The mean number of pods per plant in FI and HI plots was 61, while RF averaged only 55 pods per plant under both SR and TR geometries. Averaged across seasons, the plant biomass at flowering differed significantly among the three irrigation regimes. At the same time, differences were prominent in planting geometries, that was only under RF (SR: 16.7 t ha^{-1} vs. TR: 17.5 t ha^{-1}; Table 3a).

The higher measured LAI, 5.7 in 2018 and 5.8 in 2019, were in the FI irrigated TR plots (Figure 3); this probably contributed to higher solar radiation interception and consequent higher photosynthate assimilation, ultimately resulting in higher seed yields (Table 3a, b). Similar results in soybean were reported, where higher LAI of the

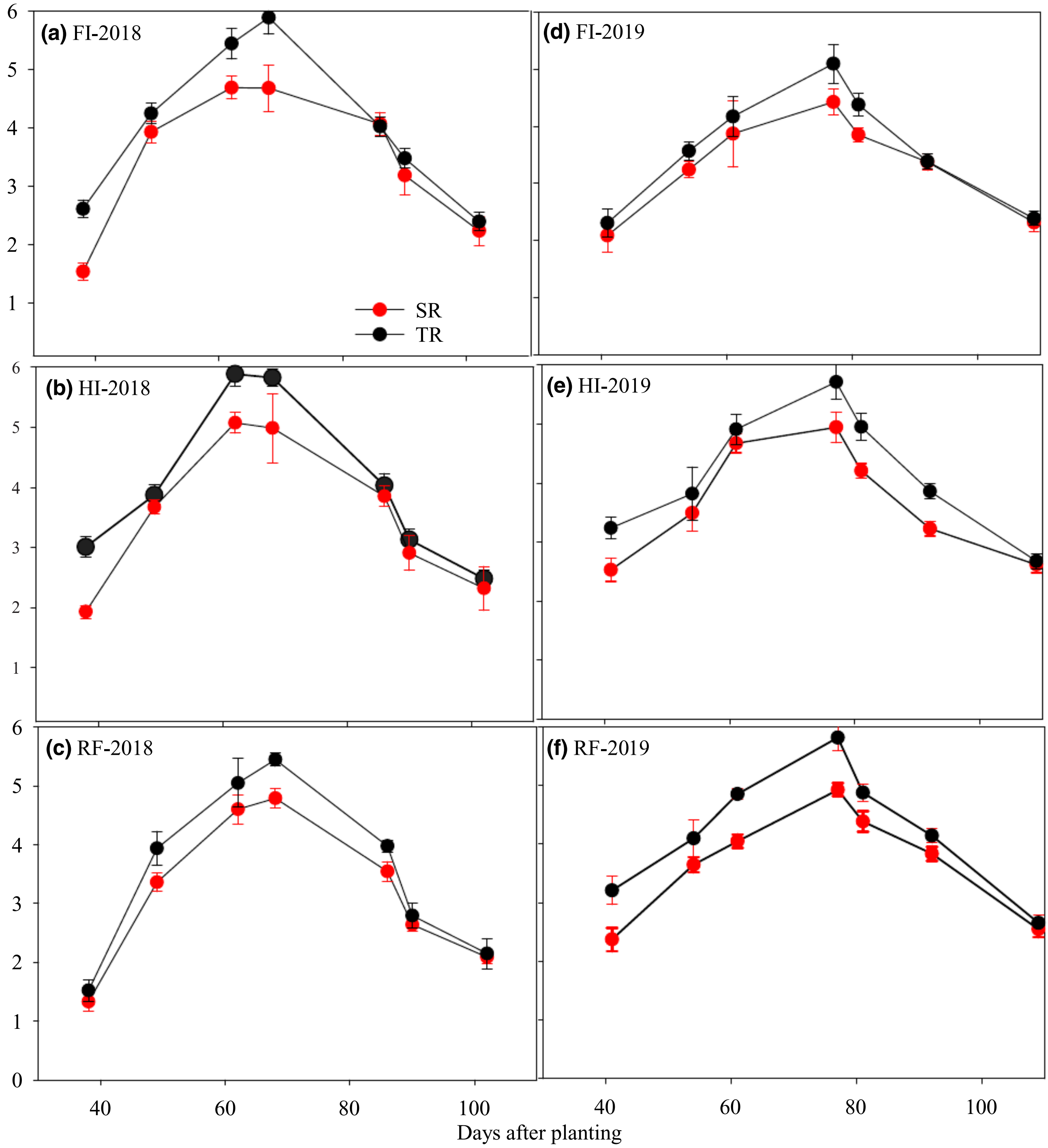

FIGURE 3 Soybean leaf area index during the crop growing seasons in 2018 (a, b, and c) and 2019 (d, e, and f) at different levels of irrigation (rainfed, RF; half irrigation, HI; and full irrigation, FI) and planting geometries (single row, SR; twin row, TR). Error bars represent one standard deviation of the mean across replicated measurements

vegetative canopy was associated with enhanced seed yield in a humid subtropical environment (Müller, Rakocevic, Caverzan, & Chavarria, 2017). In the RF irrigation treatment (no-irrigation) with SR planting geometry, soybean had consistently recorded lower LAI in both years. Also, soybean under FI and HI produced higher LAI till R7 stage; and this contributed to enhanced seed filling rate during pod maturity by transporting most of the leaf synthesized sugars coming to the phloem to the nearest sinks for carbohydrates, that is, pods on the nodes where leaves (photosynthetic source) are located (Müller et al., 2017).

Significant differences in 100-seed weight were observed among the three irrigation regimes and planting geometries (Table 3b). The 100-seed weights in both the FI (19.63 g

TABLE 3a Soybean biomass, yield components, plant height, and stomatal conductance of full (FI) and half irrigated (HI) and rainfed (RF) soybean grown in Dundee silt loam with single-row (SR) and twin-row planting (TR) geometries

		Population Plants m^{-2}			Plant height cm			Biomass Mg ha^{-1}			Stomatal conductance M mol m^{-2} s^{-1}		
Treatment	Planting geometry	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
FI	SR	31cd[a]	29bcd	30bc	121a	102a	111a	17.1 ab	17.5 ab	17.3ab	542c	535c	539c
	TR	33a	32abc	32ab	116b	96c	106bc	17.4 ab	18.3a	17.9a	854a	844ab	849a
HI	SR	31abc	30bcd	31bc	119ab	97bc	108b	17 ab	17.4 ab	17.2b	544c	552c	548c
	TR	34a	33abc	33a	111cd	97bc	104cd	17.5 ab	17.2 ab	17.3ab	692abc	671abc	682b
RF	SR	26de	27de	27d	120a	101a	110a	16.5b	16.7b	16.6c	515cd	522cd	518c
	TR	31cd	30bcd	31abc	106d	98b	102d	17.3ab	17.5ab	17.3ab	632bc	691bc	661b

[a]Means followed by the same letter or letters are not statistically different by least significant different means ($P \leq .05$).

TABLE 3b Soybean yield and yield components of full (FI) and half irrigated (HI) and rainfed (RF) soybean grown in Dundee silt loam with single-row (SR) and twin-row planting (TR) geometries in 2018 and 2019

		Seed yield t ha^{-1}			100-seed weight g			Pod number $plant^{-1}$		
Treatment	Planting geometry	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
FI	SR	4.3b[a]	4.1b	4.2b	18.11a	19.63a	18.87a	65a	61a	63a
	TR	5.0a	4.6a	4.8a	17.25c	18.76	18.0b	59bc	58bc	58b
HI	SR	4.2b	4.0b	4.1b	18.45a	19.82a	18.82a	64a	63a	64a
	TR	4.9a	4.5ab	4.7a	17.23c	19.45ab	17.89b	58bc	55c	57bc
RF	SR	3.6c	3.8c	3.7c	17.33b	17.26c	17.29b	56c	57bc	57bc
	TR	4.2b	4.0b	4.1b	15.89d	16.83d	16.20c	52d	51d	52c

[a]Means followed by the same letter or letters are not statistically different by least significant different means ($P \leq .05$).

TABLE 4 Averaged across the two crop years, soybean yield, irrigation water use efficiency (IWUE), and harvest index (HI) at different levels of irrigation (RF, HI, and FI) and planting geometries (SR and TR)

Treatment	Seed yield	Irrigation water applied	IWUE	Harvest index	Yield increase due to irrigations
	Mg ha^{-1}	mm	Mg ha^{-1} mm^{-1}		%
FI-SR[a]	4.2	186	0.0032c[b]	.32c	13.6b
FI-TR	4.8	186	0.0038c	.37b	15.9a
HI-SR	4.1	95	0.0053b	.31c	11.0c
HI-TR	4.7	95	0.0063a	.37a	13.2b
RF-SR	3.6	–	–	.29d	–
RF-TR	4.1		–	.31c	–

[a]FI, all-row or full irrigation; HI, alternate row irrigation; SR, single-row planting geometry; TR, twin-row planting geometry; RF, rainfed; ISU, rainfed but irrigation-set-up scenario.
[b]Means followed by the same letter or letters are not statistically different by least significant different means ($P \leq .05$).

in SR and 18.76 g in TR) and HI (18.82 g in SR and 17.89 g in TR) were higher than those of RF (17.29 g in SR and 16.2 g in TR). The enhanced seed yield in irrigated TR geometry was probably due to higher plant stand per unit area. Under RF, the reduced seed yields were due to moisture stress at critical stages of crop growth, incomplete filling of pods, and poor stand establishment, which are validated by less photosynthesis activity, as evidenced by lower stomatal conductance. Notwithstanding, the seed yields were significantly influenced by irrigation and planting geometry. The two-season average seed yields in the irrigation and planting geometry combinations were 4.2 Mg ha^{-1} in FI-SR, 4.8 Mg ha^{-1} in FI-TR, 4.1 Mg ha^{-1} in HI-SR, 4.7 Mg ha^{-1} in HI-TR, 3.6 Mg ha^{-1} in RF-SR, and 4.1 Mg ha^{-1} in RF-TR (Table 3b). Although the seed yield differences were not significant among FI and HI treatments, FI had a 14.7% and HI exhibited a 12.1% yield advantage over the RF treatment. These results conform with the findings of a study conducted in Nebraska on soybean, which indicated that FI did not enhance seed yields significantly over the HI system. Still, HI had resulted in 46% gross water saving (Graterol, Eisenhauer, & Elmore, 1993). The differences between FI and HI treatments could be due to soil–cultivar–weather variability.

4 | IWUE

Averaged across the two seasons, the amount of irrigation water applied in FI was 186 mm, and in HI was 95 mm (Table 4). Irrigations applied per event were 55 mm in FI and 28 mm in HI during the 2018 season, whereas 56 mm and 28 mm were applied in FI and HI, respectively, in 2019.

Seed yields measured in HI with TR planting geometry (4.7 Mg ha^{-1}) were comparable to FI with TR planting geometry (4.8 Mg ha^{-1}). Significant differences were observed in IWUE among the planting geometries in HI, while the differences were insignificant under the FI system (Table 4). The highest IWUE was also recorded for HI with TR planting (0.0063 Mg ha^{-1} mm^{-1}) followed by the HI with SR planting geometry (0.0053 Mg ha^{-1} mm^{-1}), while the FI exhibited lower IWUE both under TR (0.0038 Mg ha^{-1} mm^{-1}) and SR (0.0032 Mg ha^{-1} mm^{-1}; Table 4). Furthermore, the FI and HI irrigated TR soybeans had significantly higher yield advantages of about 15.9% and 13.2%, respectively, over the RF system with TR (Table 4). These results indicate that seed yield increased further with an increase in irrigation above HI; however, IWUE decreased when irrigation amount increased due to non-proportional gains in seed yield vis a vis irrigation applied. The yield advantage under SR with FI was about the same as TR under HI. It was reported that narrow row spacing leads to enhanced IWUE in corn (*Zea mays* L.; Welde & Gebremariam, 2016), while deficit irrigation improved IWUE significantly (Shareef et al., 2018; Sincik et al., 2008). Improving IWUE to optimize the benefits of irrigation is of paramount importance to soybean growers in the region, as irrigation water is becoming an increasingly scarce resource in many areas. The harvest index under different irrigation and planting geometry combinations ranged between .29 and .37 (Table 4) and could not find any association with IWUE as the linear response function was very low (r^2 = .05). Our results show that switching from conventional SR to TR planting geometries and irrigation water management with HI (alternate row or skip-row irrigation, which used about half the irrigation water compared to what was used FI or all-row irrigations) have high potential to optimize soybean yield and maximize net return conserving the water resources.

Additionally, agronomic practices for maintaining grain yield while reducing external input requirements can also help ensure economic, ecological, and environmental sustainability in the region. In the literature, researchers in different regions reported a diverse range of IWUE in irrigated soybean. For example, Graterol et al. (1993) reported HI had 0.0061 Mg ha^{-1} mm^{-1} IWUE while FI had 0.0057 Mg ha^{-1} mm^{-1}. A range of IWUE (0.0045–0.0123 Mg ha^{-1} mm^{-1}) was reported under double and relay cropping of soybean with camelina from west-central Minnesota (Graterol et al., 1993). In the sub-humid climate of Turkey, 25% deficit irrigation has recorded the highest IWUE of 4.14 Kg ha^{-1} mm^{-1} whereas all row irrigation to field capacity had recorded only 2.74 Kg ha^{-1} mm^{-1} (Sincik et al., 2008). In western Mediterranean conditions, IWUE under surface drip irrigation ranged between 0.0052 and 0.0087 Mg ha^{-1} mm^{-1} (Aydinsakir, 2018). Our results correspond well with these studies reported in the literature. The higher IWUE in 2018 was possibly due in part to a more even distribution of precipitation in 2018 (Figure 2) which led to the maintenance of relatively higher soil moisture level during the cropping season compared to 2019, perhaps resulting in more efficient use of water for seed development and maturation (data not shown).

4.1 | Farm profitability effects

Table 5 summarizes the revenues, specified costs, and profits expected under each treatment. The TR was a profitable practice regardless of irrigation treatment; compared to SR, TR shows $112.91 ha^{-1} higher profit under RF, and $177.66 ha^{-1} higher profit under irrigation (FI & HI). Although a positive return was estimated for 2019 under RF-ISU, SR is unprofitable on average, with a loss of $47.37 ha^{-1}. Table 6 summarizes the profitability of shifting from SR to TR. Under the specified production costs and observed market prices, irrigation under SR was unprofitable, with a $34.16 ha^{-1} loss under FI and a $45.52 ha^{-1} loss under HI on average. In contrast, irrigation under TR was profitable in all cases yielding $143.50 ha^{-1} under FI and $132.15 ha^{-1} under HI on average. The financial effect can be sizeable, considering that a farm in Mississippi operates an average of 123 ha.

While HI resulted in lower calculated profits than FI, the difference in benefits was driven by the estimated yield difference. However, because yield difference was not statistically significant between FI-TR and HI-TR, the revenues may be considered equivalent. Furthermore, the reduced cost of pumping less groundwater under HI would suggest that HI-TR may be more profitable than FI-TR in many cases.

The substantial water savings under HI merit serious consideration by conservation agencies, even when HI was slightly less profitable. For instance, a report by the U.S. Department of Agriculture (USDA), Natural Resources

TABLE 5 Effects of irrigation treatments on farm profitability in 2018 and 2019 soybean years

Treatment	Planting geometry	Seed revenue			Production cost			Expected profits[a]		
		2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
		US $ ha^{-1}								
FI[b]	SR	1,256	1,371	1,314	1,297	1,398	1,348	(41)	(27)	(34)
	TR	1,460	1,538	1,499	1,306	1,405	1,356	154	133	144
HI	SR	1,227	1,337	1,282	1,277	1,378	1,328	(50)	(41)	(46)
	TR	1,431	1,505	1,468	1,286	1,385	1,336	145	120	133
RF-ISU	SR	1,052	1,270	1,161	1158	1,259	1,208	(106)	12	(47)
	TR	1,227	1,337	1,282	1167	1,266	1,217	60	71	66
RF	SR	1,052	1,270	1,161	975	1,054	1,054	77	217	147
	TR	1,227	1,337	1,282	984	1,061	1,022	243	277	260

[a]Profits given within parenthesis show a net loss.
[b]FI, all-row or full irrigation; HI, alternate row irrigation; SR, single-row planting geometry; TR, twin-row planting geometry; RF, rainfed; ISU, rainfed but irrigation-set-up scenario.

TABLE 6 The profitability of adopting twin-row (TR) planting geometry over single-row (SR) planting geometry

SR to TR	2018	2019	Mean
	US $ ha^{-1}		
FI & HI	195.29	160.04	177.66
RF	166.08	59.74	112.91

TABLE 7 The implicit cost of water conservation from conversion from full irrigation (FI) to half irrigation (HI)

FI to HI	2018	2019
Water-saving, mm	105	77
Profit differential, U.S. $ ha^{-1}	−8.98	−13.73
Price of conserved water, U.S. $ mm^{-1}	0.09	0.18

Conservation Survey (NRCS) indicates that an investment of $17.2 M over 4 yr on various soil–water conservation measures yielded up to 178,854 Ml yr^{-1} in water savings. The implicit price of water conserved by the program was $0.97 mm^{-1}. Table 7 shows that the implied price of water savings with HI is $0.09 mm^{-1} in 2018 and $0.18 mm^{-1} in 2019. This comparison indicates that HI has merits to become a sponsored water conservation practice.

5 | SUMMARY AND CONCLUSIONS

In the mid-southern United States, a significant decline in the MRVAA has been observed due to water withdrawals for crop irrigations. In this study, we explored crop (SR vs. TR) planting geometry and water management (FI, HI, and RF) practices that potentially enhanced IWUE and seed yield returns in soybean cropping systems in this region. Our investigations revealed that planting soybean in a TR planting geometry had a significant yield advantage of about 13% over SR planting geometries. Studies on the planting geometry interactions with irrigations revealed that the HI irrigation level with the TR planting geometry combination has the highest IWUE of about 0.0063 Mg ha^{-1} mm^{-1} of water. This irrigation–planting geometry combination has the potential for cutting the use of irrigation water by half while producing seed yield and economic returns on par with FI-TR combination. Our study pioneered in reporting the IWUE in SR vs. TR planting geometries with different irrigation regimes in the Mississippi Delta. Soybean producers could adopt the HI irrigation level with TR planting geometries to reduce pressure on groundwater resources for irrigating soybean for enhanced sustainability of the production system. The economic analysis indicates that conservation incentives for farmer adoption of HI can be a cost-effective groundwater conservation strategy.

DISCLAIMER

Trade names are necessary to report factually on available data, however, the USDA neither guarantees nor warrants the standard of the product or service, and the use of the name by USDA implies no approval of the product or service to the exclusion of others that may also be suitable.

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