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Effect of irrigation regimes and planting patterns on maize production in humid climates

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Abstract

Twin-row planting in maize (*Zea mays* L.) has potential for reducing plant-crowding stress for optimizing grain yield and resource use. A study was conducted in 2020 and 2021 on a Dundee silt loam in the Lower Mississippi Delta (LMD) region of the United States to evaluate maize grain yield and irrigation water use efficiency (IWUE) in single-row (SR) and twin-row (TR) planting patterns with same seed rate under four irrigation regimes: rainfed (RF), all-furrow irrigation (FI), alternate-furrow irrigation (AFI), and every third-furrow irrigation (TFI). The TR enhanced grain yield by 9.2% in 2020 and 10.9% in 2021 over the SR system. The average final plant density at the reproductive phase was highest under AFI (73,900 ha^{-1}) and lowest under RF (70,480 ha^{-1}). Across all irrigation regimes, the leaf area index was significantly higher in the TR system. Average grain yields under SR were 10.01, 10.44, 9.48 and 9.10 Mg ha^{-1}, respectively, in FI, AFI, TFI and RF; average grain yields under TR were 11.58, 11.32, 10.13 and 9.91 Mg ha^{-1}. The AFI and FI recorded similar grain yields. The IWUE was highest in TR planting (0.028 kg m^{-3}), followed by SR planting (0.024 kg m^{-3}) under AFI. The IWUE of TFI in TR planting was 0.020 kg m^{-3} and in SR was 0.011 kg m^{-3}. Economic analysis revealed that the TR-FI and TR-AFI had average profits of 446 and 432 US$ ha^{-1}, respectively. The study suggests that maize producers in the LMD can save a significant amount of irrigation water without compromising grain yields by adapting the AFI-TR system.

1 | INTRODUCTION

Maize (*Zea mays* L.) is a major row crop in the state of Mississippi with ~0.25 M ha planted in 2021, yielding about 2.82 Tg (USDA-NASS, 2022). In the lower Mississippi Delta (LMD), this crop is planted mostly in a single row (SR) planting pattern on flattened ridges spaced 0.96–1.02 m apart. The furrows between the raised beds serve as conduits for irrigation applications and drain the runoff water from rainfall or excess irrigation. In the past decade, many growers in Mississippi and neighboring states in the Mid-South have moved from the conventional SR to a twin-row (TR) planting pattern (Bruns, 2011a). Typically, TR consists of planting two paired rows on the raised beds separated by 25 cm in lieu of the SR. For a given seed rate, planting in a TR pattern

Abbreviations: AFI, alternate-furrow irrigation; ASI, anthesis silking interval; FI, all-furrow irrigation; GDD, growing degree days; IWUE, irrigation water use efficiency; LAI, leaf area index; LMD, Lower Mississippi Delta; MRVAA, Mississippi River Valley Alluvial Aquifer; PAR, photosynthetically active radiation; RF, rainfed; SR, Single-row; TFI, third-furrow irrigation; TR, twin-row.

increases the distance between individual plants within a row. A 3-yr study conducted on a Norfolk loamy sand during 1980–1982 showed an increase in yield of 637 kg ha^{-1} with TR configuration in South Carolina (Karlen & Camp, 1985). Humphrey & Schupp (1999) reported reduced plant competition for water, nutrients, and light stemming from population reduction that permits more plant energy to be diverted from survival and maintenance mechanisms to reproductive functions. A 2-yr study in Indiana demonstrated a higher leaf area in the TR planting, but no significant yield advantage was realized (Robles et al., 2012). Sorensen et al. (2021) reported no yield difference between SR and TR under irrigation when seed populations were equal. Kratochvil & Taylor (2005) and Nelson & Smoot (2009) also showed no benefit for using TR when using 76-cm row spacing, with similar plant populations that ranged between 59,300 and 111,200 seeds ha^{-1} (4.4–8.3 seeds m^{-1} of row).

Like maize, the current recommendation in Georgia and Alabama for peanut is to plant in a TR pattern for greater yield and grade. Planting peanut (*Arachis hypogaea* L.) in twin rows can increase pod yield by as much as 333 kg ha^{-1} and total complete, mature seeds by one percentage point (Sorensen et al., 2022). Studies in the LMD on soybean [*Glycine max* (L.) Merr.] and cotton (*Gossypium hirsutum* L.) showed a significant increase in seed and lint yields in the TR system than in the SR system (Pinnamaneni, Anapalli, Fisher, et al., 2020; Pinnamaneni, Anapalli, Reddy, et al., 2020). There is no dearth of research reports highlighting the advantages of a TR planting pattern adoption over a SR pattern: (a) suppressing weed growth by early canopy closure, (b) better interception of photosynthetic radiation, (c) improved plant survival rates, (d) better canopy microclimate, and (e) enhanced resource use efficiencies (Bruns, 2011a; Mascagni et al., 2008; Pinnamaneni, Anapalli, Fisher, et al., 2020; Pinnamaneni et al., 2021).

In the LMD, inconsistent crop yields in rainfed (RF) production systems are attributed to the large within- and across-seasonal precipitation variabilities (Anapalli et al., 2016). Over 60% of maize growers in the LMD irrigate their crops to enhance yields from the underlying Mississippi River Valley Alluvial Aquifer (MRVAA). About 2.7 million L of groundwater is pumped out to irrigate 1 ha of maize (Kebede et al., 2014). This practice contributes to the MRVAA level decline as water withdrawal for irrigation exceeds its natural recharge levels, threatening overall crop production ecosystem sustainability. Hence, irrigation management studies for increasing irrigation water use efficiency (IWUE; i.e., quantity of grain yield per unit of water applied) are required to stop the rapid MRVAA decline (Anapalli et al., 2018, 2019). Although the TR production system's agronomic benefits compared with the SR system were thoroughly investigated in the LMD (Pinnamaneni, Anapalli, Fisher, et al., 2020; Plumblee et al., 2019), no data on the IWUE of TR and SR planting pattern under varying irrigation levels and farm economics in maize are available. Hence, the objective of this study was to evaluate the effects of two planting patterns (SR and TR) under four irrigation regimes, namely (a) all furrow irrigation (FI), (b) alternate furrow irrigation (AFI), (c) every third furrow irrigation (TFI), and (d) rainfed (RF), on maize grain yield, IWUE, and on-farm profitability.

Core Ideas

- The twin-row system improves grain yield over the single-row system.
- Alternate-furrow irrigation (AFI) saves water without compromising grain yield.
- Higher plant stand, kernels m^{-2}, and ears per plant contributed to higher seed yield in the TR system.
- Third-furrow irrigation saves irrigation water, but grain yields are lower.
- AFI and all-furrow irrigation grain yields were not significantly different.

2 | MATERIALS AND METHODS

Field experiments were conducted at Stoneville, MS (33˚42′ N, 90˚55′ W) in 2020 and 2021. The soil samples, collected up to 30 cm in depth from Dundee silt loam experimental plots, were air-dried, ground, and sieved to pass through a 2-mm screen for further analysis. One sample from each plot was collected, and mean values were presented. Soil pH and electrical conductivity were measured in a 1:1 soil/deionized water mixture (Schofield & Taylor, 1955). Soil total C and total N contents were determined using a Vario EL cube Elemental Analyzer (Elementar Co.) via Leco combustion. Soil Mehlich 3 extractable P, K, Ca, Mg, and S were determined using inductively coupled plasma atomic emission spectrophotometry (Spectro Citros CCD, SPECTRO Analytical Instruments) (Sikora & Moore, 2014): 1.18% organic matter, 0.10% nitrogen, 165 mg kg^{-1} potassium, and 30 mg kg^{-1} phosphorous (Mehlich 3 extraction). The saturated hydraulic conductivity ranged between 0.92 and 1.44 cm h^{-1} (Saturo infiltrometer, METER Group, Inc.), and the bulk density was 1.34 g cm^{-3}. One deep tillage was done in fall to break clay pans, followed by disking in early spring to generate ridges, spaced 102 cm. Harrowing was done to flatten the ridges 24 h before planting. A John Deere 1705 planter (John Deere Company) was used for SR planting, and a four-unit planter (NG-3, Monosem) performed TR planting. The rows are separated by 102 cm in the SR pattern; the two rows on the same ridge are separated by 25 cm, and both the planters were adjusted to realize a similar plant density (average, 78,750 plants ha^{-1}). The final plant density was estimated by counting the number of plants on a 2-m section along the rows in both SR and TR patterns at the physiological maturity (R6) stage, avoiding peripheral rows at three randomly selected locations in each plot. Row width correction factor was applied because the distance between ridges was 1.02 m. The urea ammonium nitrate (source of N) was injected into the soil at 224 kg N ha^{-1} 4 wk after crop emergence through a coulter knife. The weeds were controlled by pre-emergence spray at planting with atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine, 1.7 kg a.i. ha^{-1}) S-metolachlor (2.3 kg a.i. ha^{-1}) and late emergence control at 1 mo after corn emergence with atrazine (1.7 kg a.i. ha^{-1}) and glyphosate (1.14 kg a.i. ha^{-1}). Maize cultivar Terral Rev 24BHR99 was planted in a split-plot design with six replicates. The main plots were four irrigation regimes: FI, SFI, TFI, and RF. Subplots consisted of two planting patterns: (a) SR and (b) TR. Maize was planted on 28 Apr. 2020 and 16 Apr. 2021. Each plot was 40 m long and 8 m wide (eight rows). The irrigation water applied in each plot was measured using an Mc Propeller flowmeter flow meter (McCrometer). Sentek sensors (SDI-12 Drill & Drop probe-120 cm length) for monitoring soil water content (Sentek Technologies USA) were installed on the center of the bed in line with the row of corn plants in representative plots (i.e., two randomly selected plots for each irrigation level and planting geometry combination). Irrigations were scheduled when soil moisture content was about 50% plant available water in the top 40 cm of soil. Based on the field capacity and plant wilting point water contents for a silt loam soil reported in Rawls et al. (1982), the soil water level at which the plant available water falls to 50% was 0.232 m^3 m^{-3}. For initiating irrigation, we depended on the dynamic soil moisture retention curve available at https://myfarm.highyieldag.com/, which considers the GPS location of each sensor installed in the experimental plot and the input data on permanent wilting point, field capacity of silt loam soil was provided based on the averaged values from 10 sites within the experimental area. However, the amount of water applied is dependent on irrigation water entering plots from the polypipes and flowing lengthwise in the furrow (40 m length) to the other end, which is dyked (2 m width between two blocks), thus preventing lateral flow of water between the plots. In 2020, FI plots received a total of 109 mm of irrigation water on 18 June, 17 July, and 31 July; the AFI and TFI received 66.50 and 41.24 mm water on the same dates. In 2021, the FI, AFI, and TFI treatments received 115, 71.30, and 44.10 mm of irrigation water, respectively, on 25 June, 9 July, and 15 July. Irrigation was stopped at the onset of the dent stage (R5) of maize growth in both seasons. Weather data were collected from the nearest weather station (Mid-South Agricultural Weather Service, Delta Research and Extension Center, Stoneville, MS). During the 2020 growing season, the precipitation recorded was 467 mm; 608 mm was received in 2021. The growing degree days (GDDs) were calculated using a base temperature (T base) of 10 ˚C, as detailed in Pinnamaneni, Anapalli, Fisher, et al. (2020).

After physiological maturity, maize plants were harvested from a 1-m section along the row at five randomly selected locations in each plot, excluding peripheral rows, and ears were separated. The ears and plants were dried in an oven for 2 d. The ears were threshed by passing through a plot thresher (Almaco), and data on 100-seed weight were recorded and adjusted to a standard seed moisture content of 155 g kg^{-1}. The number of seeds m^{-2} was calculated by dividing seed yield m^{-2} (g) with the test weight and multiplied by 100. The dried plant biomass and seed weight was recorded after applying the row-width factor to arrive at 1 m^{-2} used to calculate the harvest index as the ratio of seed weight to biomass weight. After applying the row width factor, the number of ears was expressed per square meter. Leaf area index (LAI) was measured at biweekly intervals using an AccuPAR LP 80 Ceptometer (Decagon Devices, Inc.), based on the photosynthetically active radiation (PAR) recorded above the canopy and PAR at the ground level. All plant measurements (e.g., plant height and ears m^{-2}) were replicated at five random locations in each plot and used to calculate the standard error of measurements. Grain yields were adjusted to a moisture content of 155 g kg^{-1}. The anthesis silking interval (ASI) was derived as the difference in days between 50% pollen dispersal from tassel and 50% silk emergence. The IWUE of irrigation water applied was calculated as the ratio of grain yield to irrigation water applied (rainfall inputs were excluded from the calculations).

The Mississippi State University's Department of Agricultural Economics planning budget reports (Department of Agricultural Economics, 2019, 2020) were used to compute maize production costs in different irrigation regimes and planting pattern combinations. The production cost of RF-SR maize was taken directly from the published budget reports (operational costs: land preparation, fertilizer, herbicide, seed, planting, spraying, tractor and combine operation, hauling, fuel, irrigation supplies, interest on operating capital, etc.; fixed costs: implements, tractors, combine, well), and the production costs of the remaining treatments were computed following Pinnamaneni, Anapalli, Reddy, et al. (2020). The September average bid prices at local county elevators were used in estimating the returns as the crop was harvested in September. Market prices of maize were significantly higher in 2021 than in 2020 (US$158.65 and US$210.22 Mg^{-1} in 2020 and 2021, respectively).

2.1 | Statistical analysis

The ANOVA for agronomic variables and yield components was performed using JMP Pro v. 16.0 software (SAS Insti-

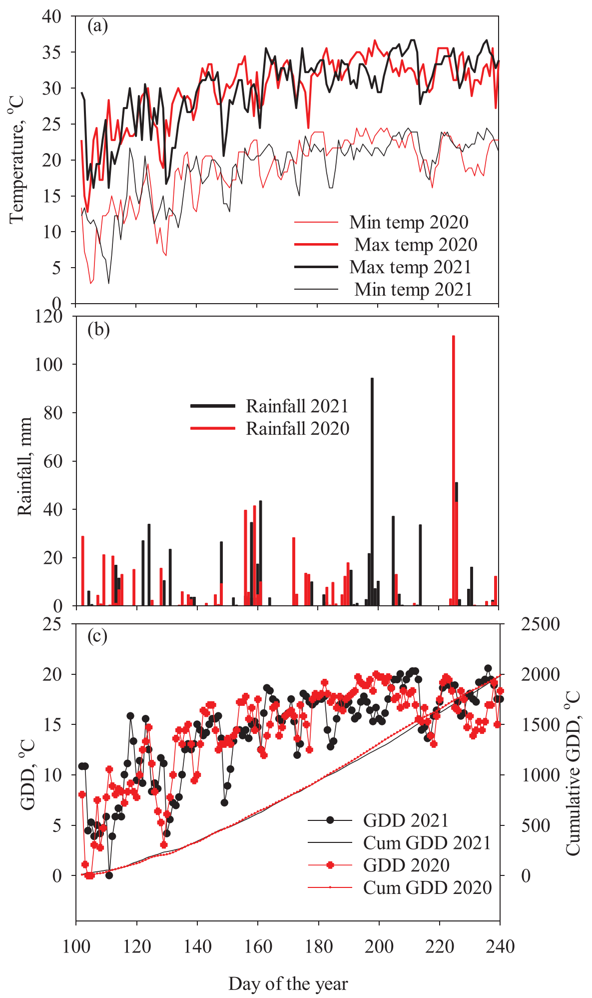

FIGURE 1 Observed daily (a) air temperature, (b) precipitation, and (c) growing degree days (GDD) in the 2020 and 2021 corn growing seasons at Stoneville, Mississippi. Cum GDD, cumulative GDD

tute) following the PROC MIXED model. Irrigation level and planting pattern were considered fixed effects, and replicates and year were considered random effects. The Tukey HSD test was used for mean comparisons at $P \leq .05$.

3 | RESULTS AND DISCUSSION

3.1 | Weather

The two cropping seasons (2020 and 2021) recorded considerable differences in observed weather (Figure 1). Growing seasons 2020 and 2021 received 446 and 487 mm rainfall, respectively. The tasseling and ear development (May–July) period in 2021 received 458 mm of precipitation, and the same period in 2020 received 274 mm. This period in 2021 was warmer by about 53 cumulative GDDs compared with 2020. However, the average maize seasonal temperature was lower by 0.58 ˚C in 2020 than in 2021 (25.29 and 24.71 ˚C in 2021 and 2020, respectively). The growing season in 2021 received higher rainfall and higher average temperatures, leading to early maturity by about 11 d, compared with the 2020 crop season (Table 1). The observed differences in weather parameters between the two cropping seasons might have led to the significant differences in grain yield–associated traits, as revealed in the ANOVA tests, and hence are presented data year-wise (Table 2).

3.2 | Phenology

A better understanding of crop growth phenology helps farmers schedule various crop management practices. However, because phenology was significantly affected by weather parameters such as temperature, precipitation, photoperiod, and GDDs, it was difficult to predict the onsets of its different stages from calendar days for timely management (Desclaux & Roumet, 1996). The results of the study reveal that phenological stages did not vary within the season between FI, AFI, TFI, and RF grown under TR and SR patterns (Table 1). However, data across the two crop seasons indicated that the vegetative stages in 2020 took more calendar days than in 2021. This could result from prevailing cool weather and a greater number of cloudy days (data not given), coinciding with the crop vegetative phase (April–May) in 2020 (Figure 1a).

3.3 | ANOVA of grain yield and associated components

The ANOVA showed that year, planting pattern, and irrigation level affected grain yield, 100-seed weight, plant density, LAI, and plant height (Table 2). Year × irrigation level interactions were significant for grain yield, LAI, and plant height. The planting pattern affected all the agronomic parameters studied. Because year interacted with irrigation level and planting pattern for most agronomic parameters, results are presented yearly (Tables 3–5).

3.4 | Planting pattern effects

Planting patterns significantly influenced the ASI, plant density, height, ears m^{-2}, seeds m^{-2}, 100-seed weight, harvest index, and grain yield (Table 3). Though statistically significant, the impact of planting pattern and irrigation levels on observed ASI were within about 1 d, so it is not expected to affect grain yield substantially. The data on plant density at the dent stage (R5) stage across the two crop seasons revealed TR planting facilitated significantly higher density (75,018 ha^{-1}) than under the SR planting (69,506 ha^{-1}). This

TABLE 1 Maize phenology during 2020 and 2021 crop seasons at Stoneville, Mississippi

Growth stage	2020			2021		
	DoY	DAP	GDD	DoY	DAP	GDD
Emergence (VE)	124	5	61	107	5	40
First leaf (V1)	130	11	110	111	9	55
Second leaf (V2)	138	19	204	116	14	77
Third leaf (V3)	145	26	299	121	19	137
Fourth leaf (V4)	151	32	383	130	28	235
Fifth leaf (V5)	158	39	492	138	36	314
Sixth leaf (V6)	164	45	579	147	45	447
Seventh leaf (V7)	169	50	656	153	51	515
Eighth leaf (V8)	174	55	734	157	55	571
Ninth leaf (V9)	181	62	848	161	59	629
Tasseling (VT)	174	55	734	154	52	530
Silk (R1)	179	47	812	159	57	601
Blister (R2)	193	74	1,060	168	66	747
Milk (R3)	202	83	1,234	176	74	873
Dough (R4)	213	94	1,432	187	85	1,050
Dent (R5)	221	106	1,513	193	91	1,149
Physiological maturity (R6)	230	115	1,617	206	104	1,372

Note. DAP, days after planting; DoY, day of year; GDD, growing degree day.

was probably because, in the TR, plants were distributed more evenly in the soil to access and use water, nutrients, and sunlight (i.e., the resources critical for plant growth and survival), with less interplant competition than plants in the SR. Similar reports are available in the literature (Balkcom et al., 2010, 2011; Bruns et al., 2012a; Pinnamaneni, Anapalli, Reddy, et al., 2020; Sconyers et al., 2007). The year-wise differences in mean plant density (71,909 in 2020 and 72,465 in 2021) can be attributed to better distributed precipitation events during the V1-R1 stages in 2021 than in 2020 (Figure 1). The final plant densities established, averaged across the seasons, in the FI, AFI, TFI, and RF under the TR planting pattern were 75,732, 76,772, 74,420, and 73,147 plants ha^{-1}, respectively, and 68,979, 71,027, 69,608, and 68,411 plants ha^{-1}, respectively, under the SR system (Table 3). The higher plant density in AFI might be due to better root aeration when irrigation (irrigation water inputs under AFI is nearly half of water applied under FI) is followed by heavy precipitation in the V1-V3 stages, but this needs further investigation to substantiate. The soil condition is exacerbated by the relatively low soil hydraulic conductivity, ranging between 0.92 and 1.44 cm h^{-1}. Higher water input from irrigations can produce waterlogging conditions followed by heavy precipitation.

Leaf area index was monitored at different growth stages to understand crop canopy closures under various irrigation levels and planting patterns. A comparison of LAI under SR and TR revealed that SR planting attained consistently lower LAI than TR throughout the crop's life cycle (Figure 2). At the same time, no differences were observed among all the treatments until the V3 stage (Figure 2). Further, compared with plants under the SR planting, the TR planting across the seasons under four irrigation regimes showed significantly higher LAI, probably due to higher plant density ha^{-1} and better canopy distribution. However, in the 2021 crop season, LAI was consistently higher than in 2020 in irrigated and RF regimes, probably due to differences in the weather and soil conditions. Another reason could be a lower number of GDDs at flowering (Table 1). The increased LAI of the TR planting pattern led to the better interception of PAR that improved carbon assimilation and biomass production, resulting in higher grain yield production (9.2% in 2020 and 10.9% in 2021) over the SR pattern (Table 4). A study in Indiana reported that TR slightly increased LAI at the silk emergence stage in 2 out of 3 yr, and no significant yield advantage was realized (Robles et al., 2012). However, another study inferred that higher LAI expansion growth during the reproductive stages resulted in a significant increase of LAI under the TR system, resulting in enhanced grain yields (Turner et al., 2019). A study on TR maize demonstrated that the TR system has a growth environment through reduced crop–weed competition for resources like moisture, nutrients, and radiation (Bruns et al., 2012). In the current study, the faster canopy development in the TR system helped the crop in more than one way: (a) it restricted weed establishment and growth, and (b) it intercepted higher PAR resulting

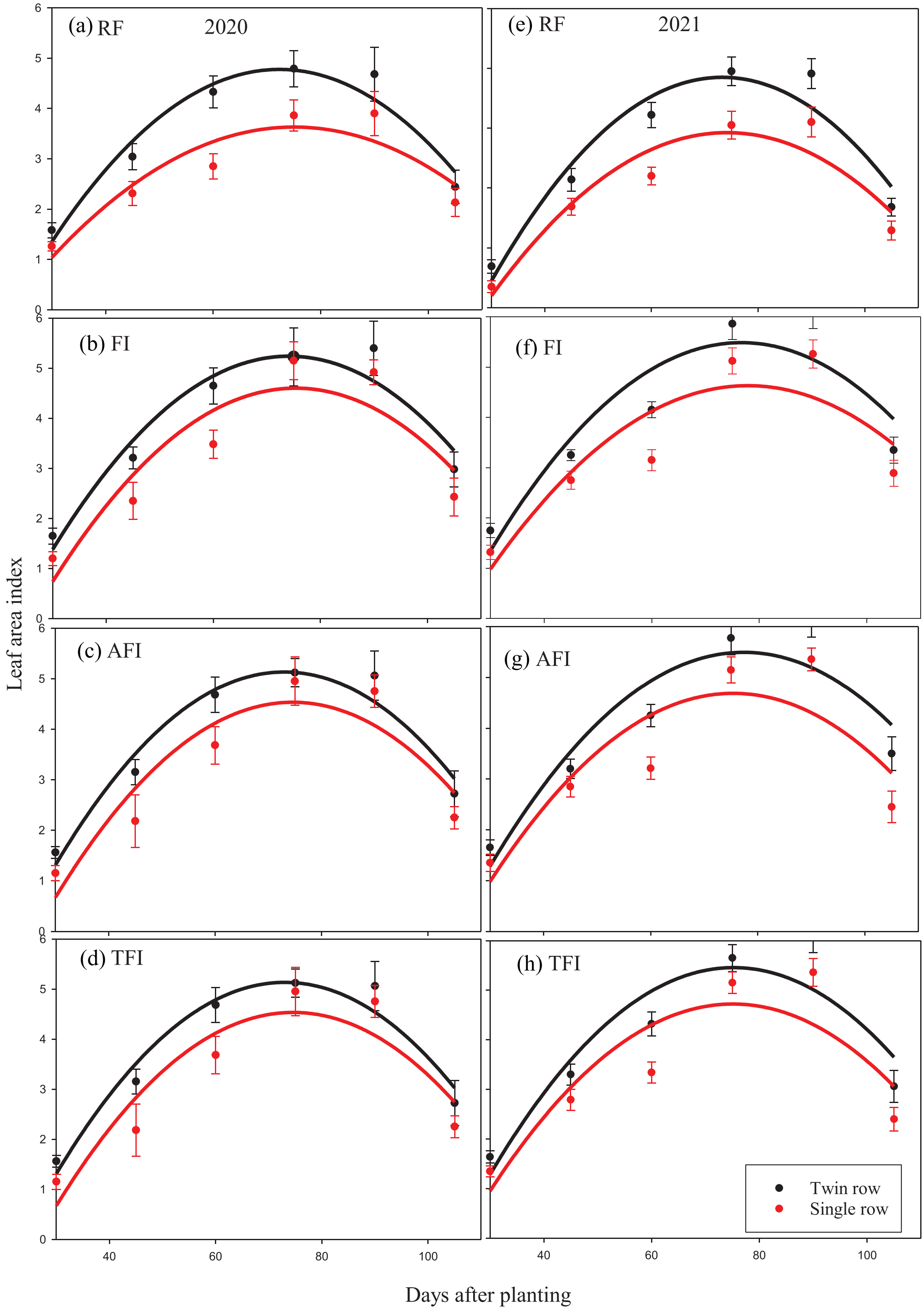

FIGURE 2 Corn leaf area index (LAI) during the crop growing seasons in (a–d) 2020 and (e–h) 2021 with rainfed (RF), all-furrow (FI), alternate-furrow (AFI), every third furrow irrigation (TFI) treatments under single-row and twin-row planting patterns

TABLE 2 Effects of irrigation levels, year, and planting pattern (PP) and their interactions in the experiments in 2020 and 2021

Source	df	ASI[a]	Plant height	Plant density	Ears m^{-2}	Grain yield	100-seed weight	Seeds m^{-2}	Harvest index	Leaf area index V4	VT	R4	R6
Irrigation level	3	0.02*	0.03*	0.45	0.42	0.03*	0.02*	0.01*	0.25	0.36	0.03*	0.02*	0.04*
PP	1	0.03*	0.04*	<0.01**	0.04*	<0.01**	0.04*	0.03*	0.02*	0.04*	<0.01**	<0.01**	0.02*
Year	1	0.03*	*	0.03*	0.57	<0.01**	0.02*	0.04*	0.52	0.89	0.03*	0.04*	0.01*
Irrigation level × PP	3	0.23	0.03*	0.48	0.63	0.03*	0.05	0.04*	0.03*	0.05	1.26	0.02*	4.65
Irrigation level × year	3	0.31	0.03*	0.65	0.24	0.04*	0.58	0.03*	0.25	0.04*	0.03*	< 0.01**	0.03*
PP × year	1	0.26	0.57	3.12	0.29	1.87	2.64	9.65	1.68	12.35	0.04*	5.68	11.52
Irrigation level × PP × year	3	0.38	0.92	6.59	4.36	14.35	1.96	2.62	2.95	3.46	5.68	19.65	13.98

Note. ASI, anthesis–silking interval; R4, dough stage; R6, physiological maturity; V4, fourth leaf stage; VT, tasseling stage.
*Significant at the .05 probability level.
**Significant at the .01 probability level.

TABLE 3 Maize biomass, yield components, plant height at flowering, and harvest index of all-row (FI), alternate-furrow (AFI), third furrow (TFI), and rainfed (RF) irrigation treatments in Dundee silt loam under single-row (SR) and twin-row (TR) plantings

Planting pattern	ASI[a] 2020	ASI 2021	Plant height 2020	Plant height 2021	Population density 2020	Population density 2021	Ears m^{-2} 2020	Ears m^{-2} 2021	Seeds m^{-2} 2020	Seeds m^{-2} 2021	Grain yield 2020	Grain yield 2021	Test weight 2020	Test weight 2021	Harvest index 2020	Harvest index 2021
	d		m		plants ha^{-1}						Mg ha^{-1}		g			
FI																
SR	3.0b	4.0b	2.76a	2.84a	68,471c	69,488b	7.75b	8.33c	2469c	2543d	11.86b	12.07b	48.05b	47.45a	56b	58b
TR	3.0b	4.0b	2.72b	2.77b	75,459a	76,006a	9.00a	9.00b	2930a	3098a	13.56a	14.05a	46.26c	45.34b	60a	61a
AFI																
SR	4.0a	5.0a	2.67b	2.76b	71,079b	70,976b	8.00b	8.00c	2503c	2697c	12.07b	12.83b	48.21b	47.57a	55b	57
TR	3.0b	4.0b	2.60c	2.75b	76,444a	77,100a	9.00a	9.33ab	2821b	3123a	12.79a	14.21a	45.34d	45.51b	61a	62a
TFI																
SR	3.0b	4.0b	2.63c	2.71b	70,866b	68,351b	7.77b	8.00c	2227d	2501d	11.05c	11.77bc	49.64a	47.06a	51c	55c
TR	3.0b	4.0b	2.57c	2.75b	72,835b	76,006a	9.00a	9.66a	2494c	2768b	11.77b	12.38b	47.18c	44.71c	56b	58b
RF																
SR	3.0b	4.0b	2.47d	2.70b	68,471c	68,351b	7.33b	8.00c	2159d	2420e	10.16d	11.43c	47.06c	47.25a	51c	52d
TR	3.0b	3.0c	2.37d	2.64c	71,648b	73,447b	9.00a	9.00b	2435cd	2656c	11.15c	11.97b	45.78d	45.07b	54b	55c

Note. Numbers within columns followed by the same letter are not significantly different according to Tukey's HSD at the .05 level of significance.
[a]Anthesis–silking interval.

TABLE 4 Average maize yield and irrigation water use efficiency (IWUE) in all-furrow (FI), alternate-furrow (AFI), third furrow (TFI), and rainfed (RF) irrigation treatments and single-row (SR) and twin-row (TR) planting patterns

Planting pattern	Grain yield		Yield increase due to twin rows		Irrigation water applied		IWUE		Yield increase due to irrigations	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
	Mg ha^{-1}		%		mm		kg m^{-3}		%	
FI										
SR	11.86	12.07			109.00	115	0.016d	0.005d	16.78c	5.53c
TR	13.56	14.05	14.27	16.40	109.00	115	0.022c	0.018b	21.60a	17.33a
AFI										
SR	12.07	12.83			66.49	71.32	0.029a	0.020b	18.78b	12.20b
TR	12.79	14.21	6.03	10.78	66.49	71.32	0.025b	0.031a	14.76d	18.73a
TFI										
SR	11.05	11.77			41.24	44.10	0.022c	0.008c	8.80e	2.92c
TR	11.77	12.38	6.47	5.17	41.24	44.10	0.015d	0.009c	5.56e	3.39c
RF										
SR	10.16	11.43			–	–	–	–	–	–
TR	11.15	11.97	9.74	4.69	–	–	–	–	–	–

Note. Numbers within columns followed by the same letter are not significantly different according to Tukey's HSD at the .05 level of significance.

TABLE 5 Effects of all-furrow (FI), alternate-furrow (AFI), third furrow (TFI), and rainfed (RF) irrigation treatments and single-row (SR) and twin-row (TR) planting patterns on farm profitability in 2020 and 2021 maize seasons

Planting pattern	Grain revenue			Production cost			Expected profits		
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
	US$ ha^{-1}								
FI									
SR	1,882	2,537	2,209	1,707	1,666	1,687	175	871	523
TR	2,151	2,953	2,552	1,715	1,674	1,695	436	1,279	857
AFI									
SR	1,914	2,697	2,306	1,685	1,644	1,665	229	1,053	641
TR	2,030	2,988	2,509	1,693	1,652	1,673	337	1,336	836
TFI									
SR	1,754	2,474	2,114	1,674	1,633	1,654	80	841	460
TR	1,867	2,602	2,234	1,682	1,641	1,662	185	961	573
RF									
SR	1,612	2,404	2,008	1,253	1,253	1,253	359	1,151	755
TR	1,769	2,517	2,143	1,261	1,261	1,261	508	1,256	882

in enhanced carbon fixation, leading to higher grain yield returns.

Similar results of increased grain yields under the TR system have been reported (Bruns et al., 2012; Karlen et al., 1987; Nedeljković et al., 2021). The enhanced yield in the TR pattern is attributed to faster canopy development for higher PAR interception, higher density, keeping post-emergence weeds under control, and higher resource use efficiency of soil moisture, nutrients, and light besides lower evaporation from the soil. It was demonstrated that the TR system yields significantly higher for other row crops (e.g., soybean and cotton) in Mississippi Delta (Bruns, 2011b; Pinnamaneni, Anapalli, Fisher, et al., 2020; Pinnamaneni, Anapalli, Reddy, et al., 2020; Thompson et al., 2015).

3.5 | Crop responses to irrigation

Irrigation levels significantly affected plant density, plant height, LAI, 100-seed weight, harvest index, and grain yield

(Table 2). The ASI was significantly lower in RF plots than in irrigated (FI, AFI, and TFI) plots. The plant heights at flowering in FI, AFI, and TFI treatments were significantly higher than those in non-irrigated plots under both planting patterns (Table 3). The average plant height in irrigated plots was 2.71 m, whereas RF averaged consistently lower by 2.55 m. The mean plant density per hectare at R5 stage varied significantly among the four irrigation treatments (FI: 72,356, AFI: 73,900, TFI: 72,015, RF: 70,480) (Table 3).

The LAI gradually increased from vegetative stages and reached a maximum around 68–75 d after planting maize in the irrigated crop under TR (5.2 in 2020 and 6.0 in 2021), which possibly aided in higher PAR interception resulting in higher carbon assimilation and enhanced grain yields (Figure 2). Similar enhanced maize productivity in a similar environment was reported, attributed to higher LAI realized under the TR plantings (Bruns et al., 2012; Karlen & Camp, 1985; Karlen et al., 1987). The RF system consistently lowered LAI among the four irrigation treatments in both years. The LAI of FI and AFI exhibited a higher LAI until the R5 stage. This potentially led to a greater seed-filling rate during ear maturity by translocation of sugars from mesophyll cells of photosynthesizing leaves to the developing seeds (Novacek et al., 2013).

The data on 100-seed weight revealed significant differences among the four irrigation treatments and planting patterns (Table 3). The 100-seed weights in the FI (47.75 g in SR and 45.80 g in TR), AFI (47.89 g in SR and 45.43 g in TR), and TFI (48.35 g in SR and 45.95 g in TR) were significantly more than those of non-irrigated crop (47.16 g in SR and 45.43 g in TR). The number of seeds per square meter in the FI (2,506 in SR and 3,014 in TR), AFI (2,600 in SR and 2,972 in TR), and TFI (2,364 in SR and 2,631 in TR) was significantly more than those of RF crop (2,289 in SR and 2,545 in TR). The increased grain yield in the irrigated TR pattern was possibly due to more plants and ears per m^2. Further, the significantly greater 100-seed weight under SR did not offset the greater seeds m^{-2} under TR in contributing to the overall grain yield. Grain yields were highly affected by irrigations and planting patterns (Table 3). The harvest index was significantly higher in the TR pattern under FI (0.61) and AFI (0.62) compared with TFI (0.57) and RF (0.55). The mean grain yields across the seasons under SR were 11.96, 12.45, 11.41, and 10.80 Mg ha^{-1}, respectively, in FI, AFI, TFI, and RF; under TR, they were 13.80, 13.50, 12.07, and 11.56 Mg ha^{-1}. The FI, AFI, and TFI exhibited 15.3, 16.1, and 5.0% yield gain over the non-irrigated treatment, respectively (Table 4). The grain yield differences among FI and AFI treatments were statistically nonsignificant. These observations echo the results of a study conducted in China on maize, which showed that AFI could result in up to 50% gross water savings without diminishing grain yields significantly over the FI system (Kang et al., 2000).

3.6 | IWUE

Seasonally, in the AFI treatments, irrigation amounts of 66.50 and 71.30 mm were applied in 2020 and 2021, respectively, in three events (Table 4). Corresponding irrigation amounts in the FI treatments were 109 and 115 mm (Table 4). The TFI plots received 41.20 mm in 2020 and 44.10 mm in 2021. About 36.33 mm in FI, 22.20 mm in AFI, and 13.75 mm were applied per irrigation event in in TFI in 2020, whereas 38.33, 23.77, and 13.75 mm were applied per irrigation event in FI, AFI, and TFI, respectively, in 2021.

The average grain yields measured in AFI (12.88 Mg ha^{-1}) were similar to FI with the TR planting pattern (12.98 Mg ha^{-1}) (Table 3). The AFI with TR planting recorded the maximum IWUE (0.028 kg m^{-3}) closely followed by the AFI with SR planting pattern (0.024 kg m^{-3}), whereas a lower IWUE was observed under all-row irrigated TR (0.016 kg m^{-3}) and SR plots (0.009 kg m^{-3}) (Table 4). The IWUE of TFI in the TR system was 0.011 kg m^{-3} and in SR was 0.012 kg m^{-3}. Additionally, the all-row irrigated TR maize exhibited a yield advantage of about 19.5% over the RF-TR system. The AFI-irrigated TR maize resulted in a 15.5% higher grain yield over the RF system (Table 4). The range of IWUE is very high in the literature, probably due to different growing conditions and soil edaphic factors. For example, a study conducted in Nebraska reported an IWUE of 0.0061 Mg ha^{-1} mm^{-1} under AFI and 0.0057 Mg ha^{-1} mm^{-1} for all row-irrigated soybean (Graterol et al., 1993). Mubarak (2020) reported significantly higher IWUE for paired row sweet maize under Mediterranean conditions. Our results are comparable with previously published reports (Lehrsch et al., 2000; Pinnamaneni, Anapalli, Fisher, et al., 2020; Pinnamaneni, Anapalli, Reddy, et al., 2020; Pinnamaneni et al., 2021). In a study in Idaho, AFI yielded similarly to FI irrigation at a row spacing of 0.76 m (Lehrsch et al., 2000). Alternative planting patterns consistently exhibited higher IWUE in maize and sorghum (*Sorghum bicolor* L. Moench) when grown under varying irrigation regimes (Sorensen et al., 2021; Thapa et al., 2020).

3.7 | Farm profitability effects

A summary of production costs, grain revenue based on the prevailing market prices, and profit estimates is presented in Table 5. The year-to-year maize price varied significantly, leading to a profit scenario in all the treatment combinations in 2021, as the average maize market price increased by 33% in 2021 compared with 2020. Averaged across the seasons, the TR planting pattern appears profitable regardless of the irrigation treatment. Twin-row planting resulted in 882, 857, 836, and 573 US$ ha^{-1} higher profits under RF, FI, AFI, and TFI, respectively. Under TR, FI and AFI had profits of 436 and

336 US$ ha^{-1} in 2020 and 1,279 and 1,336 US$ ha^{-1} in 2021, respectively, but the differences were statistically nonsignificant. The TR pattern profits were higher than the SR pattern by 334, 195, 113, and 127 US$ ha^{-1} in FI, AFI, TFI, and RF treatments, respectively. These findings echo the earlier observations of enhanced profitability under the TR system in soybean and cotton production systems in the LMD (Pinnamaneni, Anapalli, Reddy, et al., 2020; Quintana-Ashwell et al., 2021). The grain yields were not statistically different under FI and AFI regimes with the TR pattern; the revenues may be equivalent, but it reduces water inputs. These observations indicate that AFI under TR may be more attractive to the growers due to crop productivity akin to the FI system, and it also reduces irrigation water use significantly. Of late, a greater emphasis has been given by the (USDA and Natural Resources Conservation Survey by sponsoring several programs intended for water and soil conservation (Reba & Massey, 2020). The proposed AFI under the TR system of maize production in the LMD needs to be demonstrated in growers' fields with county agents' involvement and other stakeholders to assess the benefits and probably to adapt as a water conservation practice at later stages if found feasible economically.

4 | SUMMARY AND CONCLUSIONS

In the LMD, the sharp decline of MRVAA observed in recent decades resulted primarily from pumping out groundwater liberally for crop irrigations. The current field study on crop planting pattern choices (SR vs. TR) and irrigation water management alternatives (FI, AFI, TFI, and RF) reveals that planting maize in a TR planting pattern can result in a yield gain of 10% over the conventional SR planting. Furthermore, investigations on the planting patterns under different irrigation regimes indicated that the AFI with the TR system has the maximum IWUE of about 0.021 kg m^{-3}. Economic analysis revealed that the FI and AFI under TR planting had an average profit of US$857 and US$836 ha^{-1}. This irrigation–planting pattern combination can cut irrigation water use by about 50% without compromising the grain yield while accruing farm profits on par with the all-row irrigated paired row system. This is the first study in the LMD reporting the available alternatives for planting patterns and irrigation options. Maize producers can consider adopting the AFI with TR system in Dundee silt loams to conserve groundwater resources for irrigation, thereby increasing the sustainability of the regional production system.

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Trade names were necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product or service. Using such names in this manuscript implies no approval of the product or service to exclude others that may also be suitable.

AUTHOR CONTRIBUTIONS

Srinivasa R. Pinnamaneni: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing-original draft. Saseendran S. Anapalli: Resources; Software; Supervision; Validation; Visualization. Krishna Reddy: Funding acquisition; Project administration; Resources; Supervision; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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