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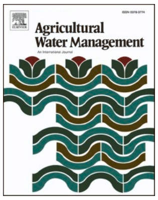

Investigating soybean (*Glycine max* L.) responses to irrigation on a large-scale farm in the humid climate of the Mississippi Delta region

Saseendran S. Anapalli [a,*], Srinivasa R. Pinnamaneni [a,d], Krishna N. Reddy [b], Ruixiu Sui [a], Gurbir Singh [c]

[a] *USDA-ARS, Sustainable Water Management Research Unit, P.O. Box 127, Stoneville, MS 38776, USA*
[b] *USDA-ARS, Crop Production Systems Research Unit, P.O. Box 350, Stoneville, MS 38776, USA*
[c] *Mississippi State University, Stoneville, MS 38776, USA*
[d] *Oak Ridge Institute for Science and Education*

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ABSTRACT

The shallow Lower Mississippi River Valley Alluvial Aquifer, which supports irrigated agriculture in the Lower Mississippi Delta (LMD) region, is fast depleting from unsustainable water extractions for irrigations. The survival of irrigated agriculture in the region today hinges on enhancing the irrigation use efficiencies of the water pumped out. Furrow irrigation practices (surface or flood irrigation) dominate the LMD region's irrigated agriculture scenario. We investigated soybean productivity in response to irrigations applied through every furrow (FI), applied through alternate furrow (AFI), and rainfed (RF, no irrigation). Approximately half the volume of water applied in FI was applied in the AFI. The experiments were conducted in 2016, 2018, and 2020, which constituted the soybean phases of a corn-soybean rotation trial conducted on a clay soil in farm-scale plots (15 ha). The plots were equipped with eddy covariance systems for quantifying crop water use (ET, evapotranspiration). There was no appreciable difference in soybean grain yield between FI and AFI, but RF yielded significantly lower than FI and AFI. Leaf area index was also significantly lower in RF compared to FI and AFI. Across the three years, the average reduction in soybean yield was only 2% in AFI, while it was 24% in RF compared to FI. Average grain yields were 4507, 4413, and 3422 kg ha^{-1}; seasonal ET were 549, 562, and 527 mm; and water use efficiencies (WUE) were 8, 8, and 7 kg ha^{-1} mm^{-1} in FI, AFI, and RF, respectively. This large farm-scale study demonstrated that grain yields from irrigating soybean through alternate furrows were comparable to irrigating through every furrow, thus saving about half the water pumped out of the aquifer. This unique study was conducted in farm-scale fields; as such, the results obtained directly apply to a farm environment, so they are ready for recommendation to soybean farmers for adoption without further field trials.

1. Introduction

Irrigated agriculture consumes over 70% of the freshwater extracted from groundwater reserves known as aquifers (Shiklomanov, 2000; Dalin et al., 2017). Aquifers worldwide are declining from water extractions for irrigation that far exceed their natural recharge rates. At this stage, the survival of irrigated agriculture depends on increasing productivity of the groundwater pumped out for irrigations (Wada et al., 2014; Gleeson et al., 2010; Scanlon et al., 2012). Wada et al. (2012) estimated the nonrenewable groundwater extraction worldwide to exceed over 20% per year. The shallow Lower Mississippi River Valley Alluvial Aquifer (MRVAA), underlying and supporting irrigated agriculture in the Lower Mississippi Delta (LMD) region, is drying up from unsustainable water extractions, which far exceeds its natural recharge capacities (Wax et al., 2009; Guzman et al., 2014). With limited access to surface water resources, groundwater is the main source of irrigation water in this region. Furrow irrigation practices (surface or flood irrigation) dominate the LMD region's irrigated agriculture scenario in which water delivered at the head of the furrows flows down to their tail end, irrigating crops grown on raised beds on either side (Wood et al., 2017). The efficiency of furrow irrigation systems was below 55%, the lowest compared to sprinkler and drip irrigation systems (Irmak et al., 2011). Notwithstanding, the flat terrain and sufficient groundwater availability combined with ample rainfall make furrow irrigation

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* Corresponding author.
E-mail address: saseendran.anapalli@usda.gov (S.S. Anapalli).

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the most viable irrigation method widely accepted by the farmers in the region (Snipes et al., 2005).

To check the continued decline of the MRVAA, with the realization that the MRVAA water is finite, we must generate technologies and information focused on enhancing the productivity of the water pumped out of it for irrigations. Investigations for improving water use efficiencies (WUE), the amount of water needed to produce grains in specific soil-climates of cropping systems, have been, in general, hampered by the absence of viable methods for accurately quantifying water used by the crop in response to water applications, soil, and climate variability and change (Howell, 2001; Wada et al., 2012; Hanasaki et al., 2010; Anapalli et al., 2019a). Seckler (1996) and Seckler et al. (1998) demonstrated that one of the prime opportunities for enhancing the productivity of applied irrigation water lies in enhancing the productivity of water applied by reducing the loss from evaporation, runoff, and percolation while water is transported to the crops for irrigations. Many irrigated agricultural systems in the world use much more water to irrigate crops than the crop's need for consumptive water requirements (Howell, 2001; Wada et al., 2012). Grain yield response to irrigation rises linearly with water inputs to a maximum but falls with higher input rates (Geerts and Raes, 2009; Saseendran et al., 2015). Optimizing return from irrigation water applications at locations, climates, and soils requires accurate information on actual water used by crops and the grain yield returns. Technology that is portable across soils and cropping systems and easy to set up and collect data are prerequisites in this regard (Varzi, 2016).

Measuring crop water requirements directly by growing crops in large-scale field lysimeters was considered one of the highly accurate methods for quantification of ET from cropping systems. These systems often require sophisticated, costly equipment and highly technical personnel to install, maintain and collect data (Howell et al., 1995, 2004; Moorhead et al., 2019). The data collected also represents only the location-specific climate, soil, and crop conditions. But, for research aimed at enhancing WUE in agricultural systems, continuous monitoring of ET across multiple soils and climates representing the landscapes of interest is often required, which lysimeters are seldom capable of due to their non-portability. In these circumstances, the latest advancements in environmental monitoring and computing technology offer a portable, sound micrometeorological theory-based method, the eddy covariance (EC) technique, for quantifying ET (Foken et al., 2012; Nicolini et al., 2017; Anapalli et al., 2019a, 2020). In the pilot stages of development, the EC systems often had problems in balancing energy inputs and outputs from landscapes by about 0–30% (Baldocchi, 2003; Foken et al., 2006). Over the last couple of decades, sound micrometeorological theory and measurement-based methods have been developed for overcoming the energy balance non-closure issue in the EC measurements (for examples, Mauder and Foken, 2006; Meyers and Hollinger, 2004; Fratini and Mauder, 2014; De Roo et al., 2018). Denager et al. (2020) measured and compared six-year EC-based ET from an agricultural field with detailed water balance measurements; irrespective of the energy balance non-closure in half-hour energy fluxes, ET estimates from the two methods were comparable over a monthly scale. Using parameterizations based on large eddy simulation studies, De Roo et al. (2018) developed methods for applying energy balance residual corrections to sensible and latent heat fluxes to achieve energy balance closure between 90% and 100%. Using this method for analyzing EC flux data, Anapalli et al. (2018, 2019b, 2020) quantified and compared the ET and WUE efficiencies of corn (*Zea mays* L.), soybean (*Glycine max* L.), and cotton (*Gossypium hirsutum* L.) crops in the LMD for helping producers in selecting the best crop mix for natural resources conservation in the region.

Leininger et al. (2019) demonstrated that by irrigating alternate furrows instead of every furrow, a 1.8-fold increase in irrigation WUE could be achieved in peanut cropping systems in sandy loam soils in the LMD. The investigations were based on the irrigations applied; lacking measurements of actual water used by the crop. Notwithstanding, the substantial enhancement in WUE indirectly established that even with alternate furrow irrigations, which delivered about half of the water supplied through all-furrow irrigations, the ET demand of the crop could be fully met from the water available in the soil for the plant uptake. Pinnamaneni et al. (2020a, 2020b) reported comparable yield and economic returns from cotton and soybean in a silt loam soil in the LMD when irrigations were applied through all the furrows, and half that much water was applied through alternate furrows. However, actual water used by the crops was not established in those experiments. For strong recommendations for adopting the technologies developed in small-plot experiments, repeating the experiments at multi-locations and climates in farm-scale plots was advocated (Yan et al., 2002; Schmidt et al., 2018). The farm-scale, on-farm trials provide the opportunity to evaluate irrigation water management technologies under realistic farming conditions. Yet another need for farm-scale experiments from the concept of soil-water-plant-atmosphere, the pathway for water moving through the crop system, which render water applied through irrigations spread three-dimensionally. As the water in the system spread in all directions, in small plots, we may not be able to do experiments without treatment interactions, but this may be possible in larger farm-scale plots. This necessitates the instruments like lysimeters, eddy covariance systems, and energy balance systems used in the quantification of ET from cropping systems to have enough land size (farm-scale, for example) for the air entering the crop-field to have homogenized with the physical properties of the crop canopy environment for measurements (Burba and Anderson, 2005; Moorhead et al., 2019). Objectives of our study were to (1) evaluate soybean yield responses to irrigations applied through all the furrows (FI, full irrigation), alternate furrows (AFI, half of FI), and rainfed (RF, no irrigation), and (2) Quantify ET and WUE responses of the crop in response to these irrigations using eddy covariance instrumentation in farm-scale experiments.

2. Materials and methods

2.1. Soybean experiments

The experiment was an irrigated corn-soybean rotation conducted between 2016 and 2020 at the United States Department of Agriculture (USDA)-Agricultural Research Service (ARS), Crop Production Systems Research Unit farm, Stoneville, Mississippi, USA (33° 39′ N, 90° 59′ W, 42 m elevation above mean sea level) located in the LMD. Data from the soybean phase of the experiments in 2016, 2018, and 2020 were used in this investigation. The investigation aimed to evaluate soybean production responses to FI, AFI, and RF in the furrow irrigation scenario and quantify the water used by the crop in these systems using the EC technology. The sensors used in the EC system for measuring water and energy fluxes from landscapes require a measurement height to horizontal distance to the edge of the field, the fetch ratio, of at least 1:100 in all directions (Nicolini et al., 2017; Burba and Anderson, 2005). To achieve these conditions, the field trials were conducted in three 15 ha (farm-scale) fields, and the EC sensors were centrally located in the fields to obtain maximum fetch in all directions. The three farm-size plots required for this research restricted the experiments to be conducted without replications in a single season. However, we randomly applied the FI, AFI, and RF treatments to the three plots and repeated the experiment over three years. The three years were considered as three blocks in which the three treatments were randomly applied. This unique layout rendered the experiments a randomized complete block design with three replications for statistical analysis (Casler, 2015).

Irrigations were surface applied (flood) at the head of furrows through lay-flat polyethylene pipes to run continuously down the 1% slope artificially maintained in the plots. The EC sensors were periodically adjusted at about twice the plant height above the soybean canopy using hand pump-operated height-adjustable towers. This procedure gave confidence that the sensors are in the constant flux layer above the

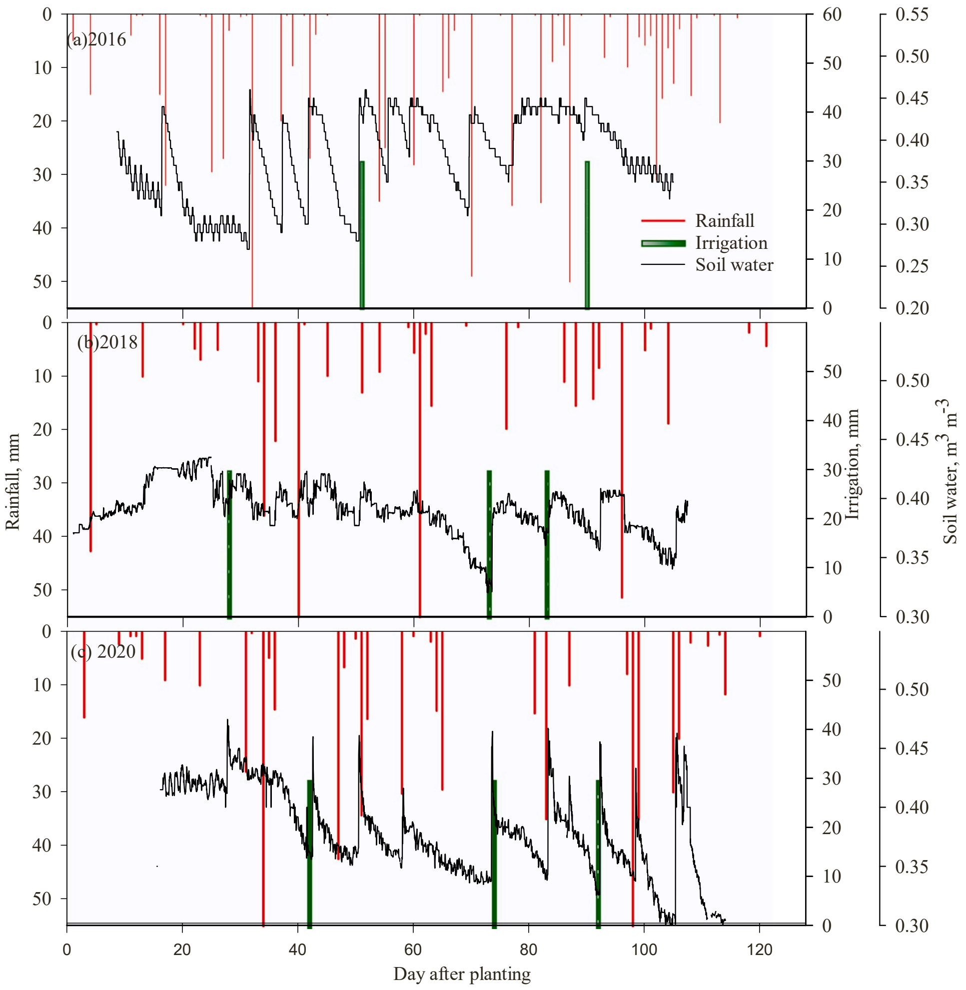

Fig. 1. Measured soil water at 15 cm depth, rainfall, and irrigation in 2016, 2018, and 2020 crop seasons. Irrigation amounts applied through all the furrows (FI treatment) are shown. About half of irrigation amounts applied in FI was applied in the alternate furrow irrigation (AFI) treatments. RF is the rainfed (no irrigations) treatment. ed (RF) treatments in 2016, 2018, and 2020.

frictional sublayer in the atmosphere above the plant canopy. Irrigations were initiated when the measured water content in the top 30-cm soil layer declined to about 65% of plant-available water (PAW). Irrigation supply to individual furrows was shut down when water running down the field reached their tail-ends. When 80% of the furrows were completely irrigated this way, irrigation to the whole FI plots was shut down. As there was water loss between the flow meter and delivery point at the head of the furrow, we could not get the exact amount of water applied in each irrigation. Based on measurements in 2016, we estimated that one irrigation at FI rate consumed about 30 mm of water if water was shut down when about 80% of the rows were fully irrigated. Irrigations in AFI were about half of FI irrigations, and this was achieved by shutting down irrigations when about 70% of the rows (in which irrigations were applied) were completely irrigated. In two parallel experiments with FI and AFI trials in soybean and cotton at the location, we established that AFI treatment consumes about half the amount of irrigation water applied in the FI (Pinnamaneni et al., 2020a, 2020b). In the FI, we applied two irrigations (60 mm) in 2016, and three irrigations (90 mm) per season in 2018 and 2020 (Table 5, Fig. 1). The AFI treatments were 30, 45, and 45 mm of water per season, in 2016, 2018, and 2020, respectively.

From the textural analysis of soil samples to a depth of 45 cm, the soil was identified as clay (Sharkey clay, clayey over loamy, montmorillonitic, non-acid, thermic Vertic Halaquepet) (https://websoilsurvey.

Table 1
Selected soil physical and chemical properties of soils under all furrow irrigations (FI), alternate furrow irrigations (AFI), and RF irrigation treatments at Stoneville, MS, measured in 2018, and 2020.

Crop season	Soil depth (cm)	Soil Texture	p^H	Organic matter (%)	CEC (Meq 100 g^{-1})	Mehlich-3 extractable nutrients (mg Kg^{-1})						
						P	K	Ca	Mg	Zn	S	Cu
2016	0–15	Clay	6.61	1.38	22.1	23	188	2843	576	2.4	4.9	3.6
2016	15–30	Clay	6.51	1.26	18.2	24	310	2151	784	2.3	6.3	2.2
2016	30–45	Clay	6.48	1.24	21.3	26	242	1371	669	1.8	7.1	1.3
2020	0–15	Clay	6.55	1.66	24.8	19	218	1636	769	2.2	6.1	4.3
2020	15–30	Clay	6.13	1.38	18.7	22	165	3270	357	2.6	1.4	2.4
2020	30–45	Clay	6.44	1.32	20.4	27	239	3012	709	1.5	8.7	3.8

FI = full irrigation applied through every furrow; AFI = half of FI applied through alternate furrows; RF = rainfed.

Table 2
Observed phenological growth stages of soybean in 2016, 2018, and 2020 irrigation experiments.

Phenological stages	2016 DAP	2018 DAP	2020 DAP
Planting	0 (May 04)	0 (May 10)	0 (Apr 30)
Emergence (VE)	7 (May 10)	7 (May 16)	5 (May 5)
Beginning Bloom (R1)	39	44	42
Full flowering (R2)	50	53	56
Beginning pod (R3)	56	59	59
Full pod (R4)	70	72	69
Beginning seed (R5)	85	86	78
Full seed (R6)	109	102	99
Beginning maturity (R7)	112 (Aug. 30)	107 (Aug. 31)	115 (Aug. 26)
Full maturity (R8)	126 (Sept. 13)	117 (Sept 10)	125 (Sept. 4)
GDD during the EGP	1871	1893	1814

DAP is days after planting. Observed phenology remained constant across full irrigation applied through every furrow (FI), half of FI applied through alternate furrows (AFI), and rainfed (RF) treatments. EGP is the effective growth period, that is, from VE to the R7 stage. GDD is growing degree days computed in oC.

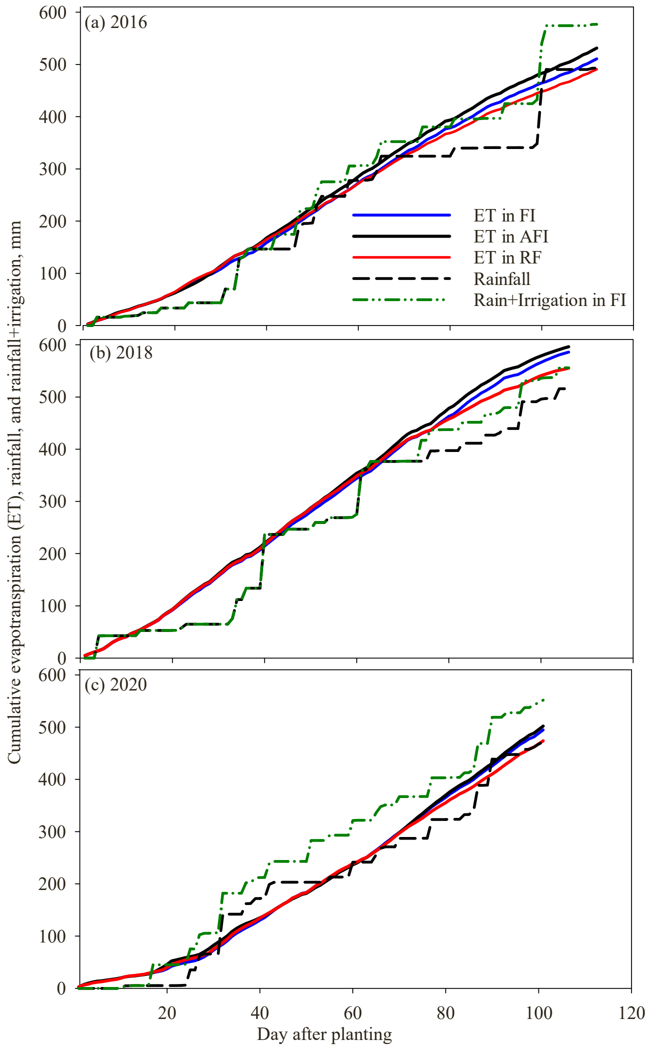

Fig. 2. Measured seasonal cumulative rainfall, rainfall and irrigations, and evapotranspiration (ET) measured in the all furrow irrigation (FI), alternate furrow irrigation (AFI), and rainfed (RF) treatments in 2016, 2018, and 2020.

nrcs.usda.gov/app/WebSoilSurvey.aspx), uniform across the three plots (Table 1). The crops were planted under conventional tillage practices prevalent in the LMD region, which consisted of one or two tillage passes with a row crop cultivator for killing weeds and a pass of post-harvest chisel plow or disk harrow tillage to destroy weeds and incorporate previous crop residue and to generate raised bed (ridges) for soybean planting and furrows in between to facilitate furrow irrigations. Before planting, in spring, a passage of a spike-tooth harrow was used to smooth the seedbeds for planting. Pre- and post-emergent herbicides, as required, were applied to control weeds. A row crop cultivator with shallow sweeps was used after plant emergence to improve furrows between planted soybean rows for smooth flow of rain or irrigation water.

2.2. *Soybean growth data*

A mid-maturity group IV soybean cultivar, Dyna Grow 31RY45, was planted in the experiments without applied fertilizers. Phenological measurements were visual, based on Fehr and Caviness (1977) modified by Hodges and French (1985) soybean growth stages (Table 2). Leaf Area Index (LAI) was measured biweekly using an AccuPAR LP-80 Ceptometer (Decagon Devices Inc., Pullman, WA, USA) (Fig. 2). All the plant measurements were replicated in at least four random locations in each plot divided into three equal subsections. A GPS-enabled combine was used to harvest soybean grains, weigh, and geo-reference the data for geo-spatial analysis. Grains were harvested every year after about a week from the full seed maturity stage (R8 stage, Table 2). Moisture contents of harvested grain weights were adjusted to 13%. Soil water contents at 8 and 30 cm depths, two on either side of ridges and one in the middle of furrows, were monitored using Stevens HydraProbe (Stevens Water Monitoring Systems Inc., Portland, OR, USA).

2.3. *Eddy covariance measurements for quantifying ET*

In the EC system, a sonic anemometer (Gill New Wind Master, Gill Instruments, Lymington, UK) was used for measuring the velocity of components for wind, speed of propagation of eddies, and sonic temperature. An open-path infrared gas analyzer (LI-7500-RS, LI-COR Inc., Nebraska, USA) was used to measure water vapor density in the eddies. A hand-pump-operated telescopic height adjustable mast (EC tower), centrally located in each plot, was used for installing the sonic anemometer and infrared gas analyzer above the crop canopy. The sensor heights were constantly maintained at about twice the plant canopy height above the plant canopy, that is, within the constant flux layer. We recorded the measurements at 10 Hz on a data logger.

For characterizing the microclimate and energy balance of the crop canopy, we also measured (1) soil heat flux using six self-calibrating soil heat flux plates (HP01SC, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) at 8-cm depth in the soil, (2) water content and temperature at multiple points in the soil layer above the heat flux plates and soil surface using Stevens HydraProbe (Stevens Water Monitoring Systems, Inc.), (3) net solar radiation (NR-LITE2, Kipp & Zonen B.V., Delft, The Netherlands), (4) air relative humidity and temperature (HMP 155, Vaisala, Helsinki, Finland), and (5) precipitation using a tipping bucket rain gauge (TR 525, Texas Electronics). These data were sampled at 1-minute intervals and half-hour averaged for energy balance computations.

The EC data collected were processed for the latent heat of evaporation of water (LE, Wm^{-2}) every half hour using the EddyPro v 6.1.0 (LI-COR Inc., Lincoln, NE, USA) software installed in the SmartFlux system (LI-COR Inc, Lincoln, NE, USA), which was mounted and connected to the dataloggers on the flux-tower. The LE flux and microclimate data were processed every 30 min. These data were post-processed for quality control and removing implausible fluxes using the Tovi™ software (LI-COR Inc, Lincoln, NE, USA) developed based on the OzFlux methodology (Isaac et al., 2017). In this procedure, the Mauder and Foken (2006) method was followed for removing periods with under-developed air turbulence resulting from calm wind conditions. The latent and sensible heat fluxes were also corrected by adopting the energy balance residual correction recommended by De Roo et al.

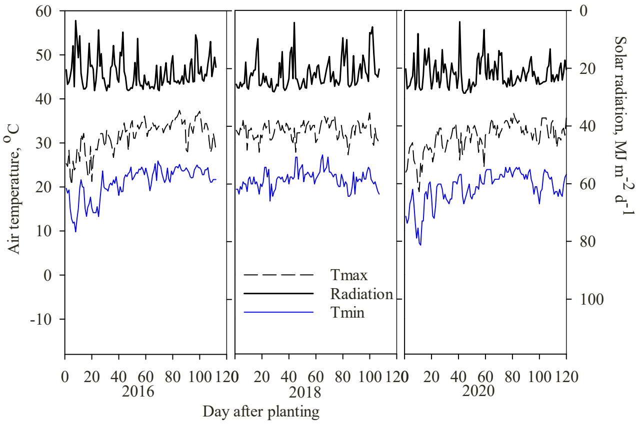

Fig. 3. Measured daily air temperature maximum (Tmax), minimum (Tmin), and solar radiation (Radiation) during 2016, 2018, and 2020 soybean growth seasons (planting to beginning grain filling stage).

(2018). As a last step in the process, data gaps in the fluxes were filled following the marginal distribution sampling technique (Reichstein et al., 2005). ET in mm was obtained by multiplying the LE flux in W m^{-2} with a conversion factor of 0.00073 mm W^{-1} m^2.

2.4. Yield data analysis

Soybean grains were harvested after the R8 stage (grain maturity, Table 2) using a harvester combine equipped with a global positioning system-assisted yield monitor (Case IH 5140, Racine, Wisconsin, USA) and data recorded at 13% moisture content. Unrealistic yield data points that were likely caused by significant positional errors or operating errors such as abrupt changes of speed, partial swath entering the combine, and combine stops and starts, were removed from the data before the statistical analysis (Sudduth et al., 2012). Data were evaluated for normality, and outliers were removed. Yield data were analyzed using the Glimmix procedure in SAS statistical software (SAS v9.4). Irrigation treatments were treated as fixed effects. In the repeated measure model statement, years of yield collection (2016, 2018, and 2020) were treated as random factors. A spatial-temporal covariance structure type=SP(POW)(c-list) selected based on the lowest Akaike's Information Criteria (AIC) was used for spatial yield data having longitude and latitude associated with each yield data point. (Littell et al., 2007). The Tukey-Kramer test was used for testing mean differences at alpha = 0.05.

3. Results and discussion

3.1. Weather during the crop seasons

The LMD region has a humid subtropical climate with mild winters and warm summers (Kottek et al., 2006). The mean annual rainfall is about 130 cm, out of which only about 30% is usually received during the core soybean growing season from May to August (Anapalli et al., 2016). In the three years of this experiment, soybean plantings were on May 4, 2016, May 10, 2018, and April 30, 2020 (Table 2). Variations in planting dates across crop seasons were primarily due to rains that rendered the fields too wet for planting seeds. The crop reached full maturity (stage R8) on 126, 117, and 125 days in 2016, 2018, and 2020, respectively. Effective growth periods (EGP), that is, from planting to beginning maturity (stage R7), during which the plant roots uptake water from the soil for active growth, were 112, 107, and 115 days after planting (DAP). The plant senesces quickly from the R7 stage until full maturity (R8). Rainfall received in the three years during the EGP were 493, 516, and 472 mm, respectively (Figs. 1, 2), and the number of rainy days in the three years was 28, 30, and 41. The highest daily rainfalls recorded were 106 mm in 2016, 103 mm in 2018, and 76 mm in 2020. The three largest continuous rain-free days were 10, 11, and 15 days in 2016, 5, 6, and 9 days in 2018, and 4, 9, and 9 days in 2020. These long non-rainy days, together with insignificant rainy days during the EGP, necessitated irrigations twice in 2016, and thrice each in 2018 and 2020 crop seasons (Fig. 1). Air temperature across the three growing seasons varied between 7 °C (daily minimum temperature) in May and 37 °C (daily maximum temperature) in July (Fig. 3). The weather variable that exhibited the highest variability during the crop growth period was solar radiation received at the crop canopy, and varied between 4 and 28 MJ m^{-2} d^{-1}, owing to skies partially to fully overcast from frequent cloud developments in the humid climate of this region.

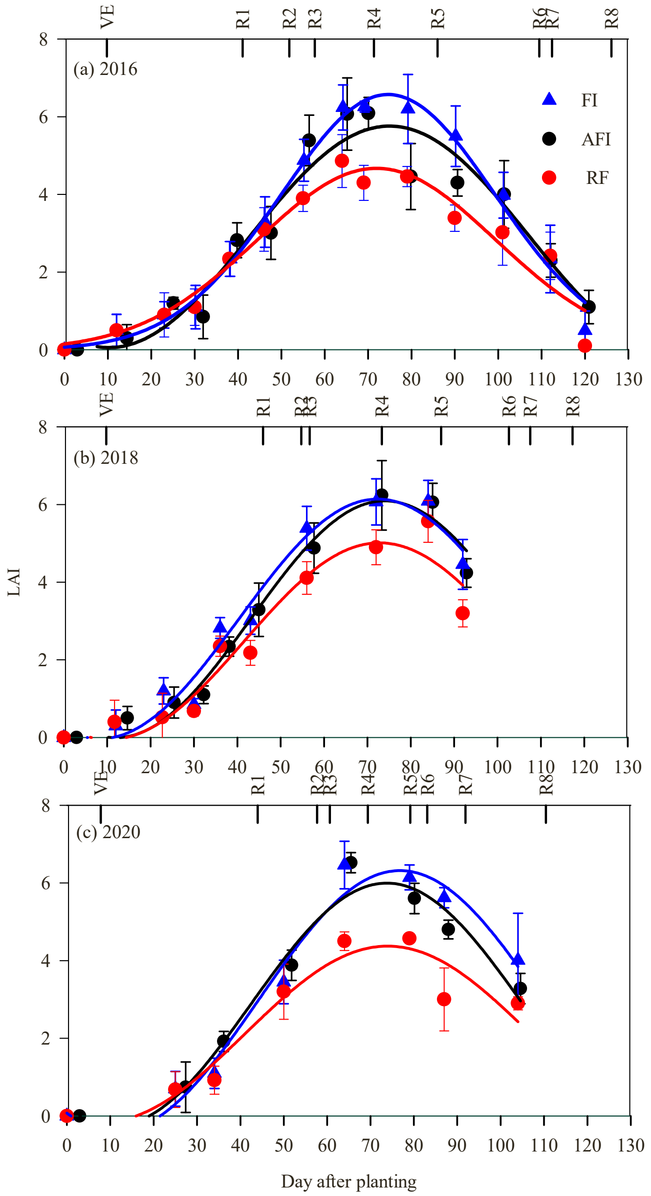

Fig. 4. Comparisons of soybean LAI measured across the all furrow irrigation (FI), alternate furrow irrigation (AFI), and rainfed treatments in 2016, 2018, and 2020.

3.2. Phenology

There were no noticeable differences in occurrences of the phenological stages of growth of the soybean plants across the three irrigation treatments. Soybean seeds emerged 7, 7, and 5 days after planting (DAP)

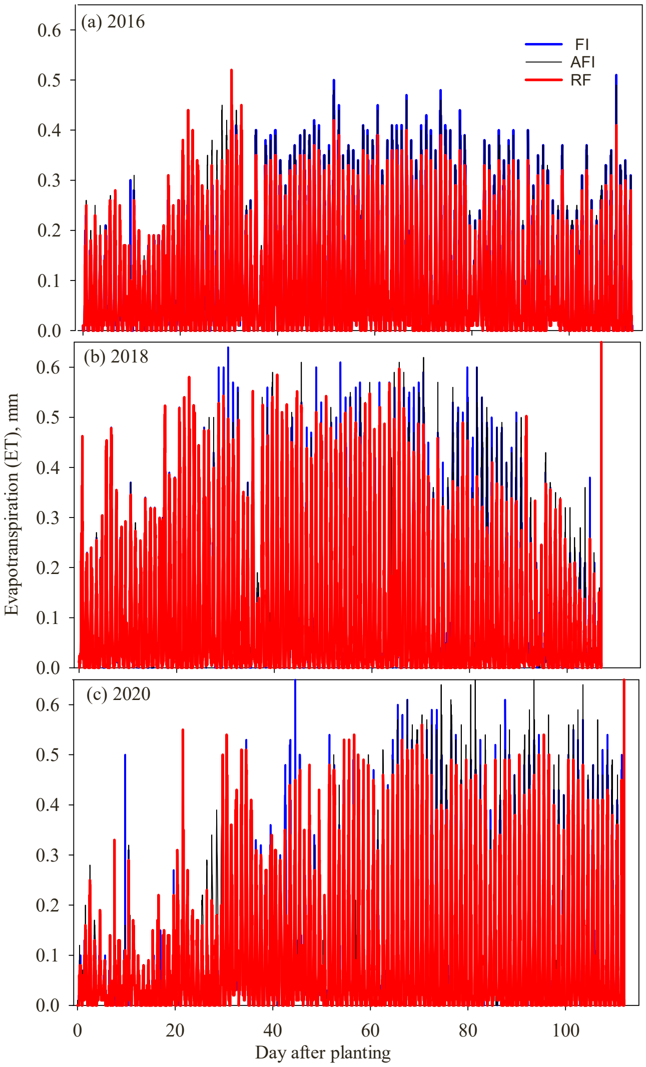

Fig. 5. Half hourly soybean evapotranspiration (ET) measured in the all furrow irrigation (FI), alternate furrow irrigation (AFI), and rainfed (RF) treatments in 2016, 2018, and 2020.

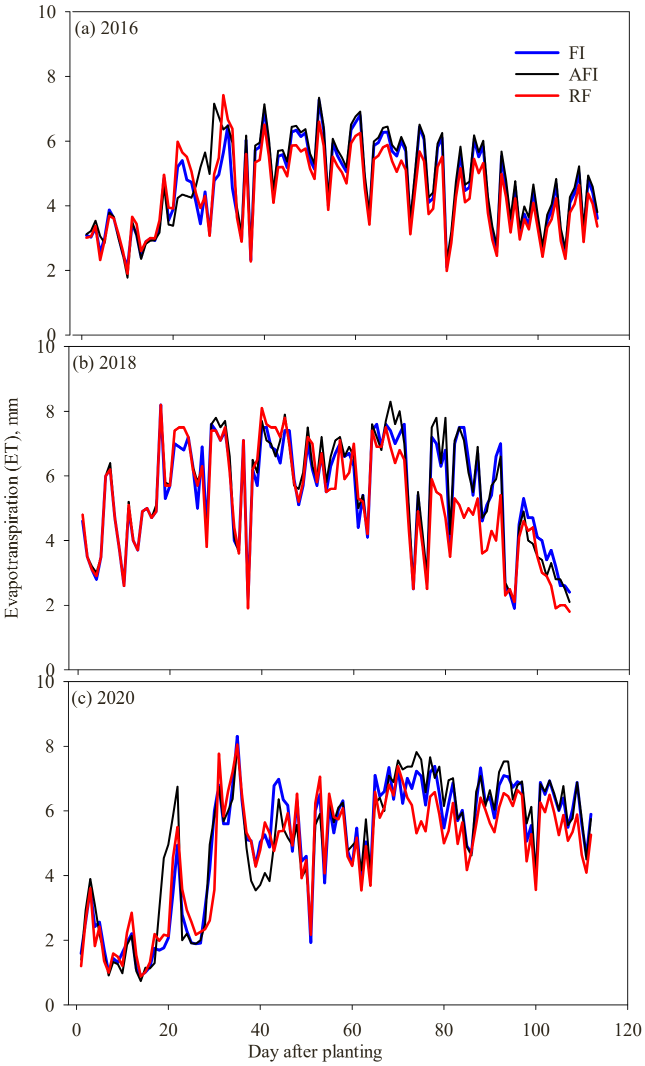

Fig. 6. Daily soybean evapotranspiration (ET) measured in the all furrow irrigation (FI), alternate furrow irrigation (AFI), and rainfed (RF) treatments in 2016, 2018, and 2020.

in 2016, 2018, and 2020, respectively (Table 2). Soybean phenology depends on the number of growing degree days (GDD) above a base temperature, 10 °C, the plant is subjected to starting from the seedling emergence (Desclaux and Roumet, 1996). The cumulative GDDs from planting to the R8 stage in the three crop seasons were 1871, 1893, and 1814. The crop reached the full seed stage (R6), determining the yield potential in each crop season, on 109, 102, and 99 DAP, respectively. The full maturity stage (R8, the harvest stage), after which the seed weight does not change, was achieved on 126, 117, and 125 DAP in the three years. Across the three crop seasons, the crop duration differed by 9 days. It is possible, the differences in growth duration had occurred from across the year variations in the soil-water-weather parameters interacting with the genotype that resulted in early crop maturity in 2018 (117 days) when it took 126 days to mature in 2016.

3.3. LAI

Measured LAI differed considerably across the FI, AFI, and RF irrigation treatments. However, differences between FI and AFI treatments were low compared to the differences between FI and AFI differences from RF (Fig. 4). In general, the measured LAI under the FI treatment remained higher than those measured under the AFI and RF treatments. This means that applied irrigation water helped the plant alleviate adverse soil water stress effects on leaf expansion plant growth and grow better vegetatively, producing more leaf area. However, taller plants with increased leaf growth were reported not to translate to a proportional increase in grain yield returns in soybean (Eck et al., 1988). Like soil water deficit stress, excess water in the soil (less oxygen) also compromises yield in soybeans owing to root-tip decay (Sugimoto et al., 1988, 1989).

During the 2016 crop season, under the FI, AFI, and RF treatments, the measured seasonal maximum LAI were 6.8, 6.2, and 4.8, respectively. Seasonal maximum LAI measured during the 2018 season were 6.2, 6.2, and 4.9 in the FI, AFI, and RF treatments. During the 2020 crop season, the LAI recorded were 6.5, 6.5, and 4.6. The lower LAI observed in the RF treatments translated into significant grain yield reductions across the three crop seasons, as described below.

3.4. Evapotranspiration

Using these methodologies, developed based on sound micrometeorological theories, the computed 30-minute energy balance closure in the three crop seasons across three irrigation levels varied between 91% and 97%, with an average of 94%. Moorhead et al. (2019) obtained 64% and 67% closure in energy balance without applying any corrections for fluxes. With this closure level, they found that at a daily time scale, the

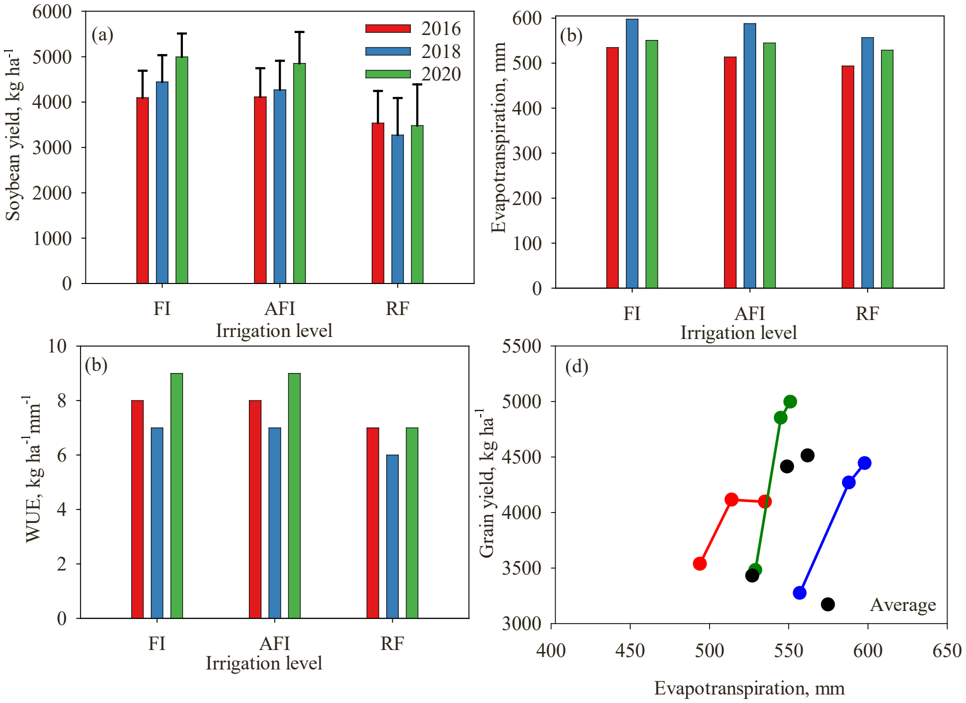

Fig. 7. (a) Grain yield, (b) evapotranspiration (ET) and (c) WUE response to irrigations, and (d) grain yield response to evapotranspiration, quantified in the all-furrow irrigations (FI), alternate- furrow irrigation (AFI) and rainfed (RF) treatments in 2016, 2018, and 2020.

Table 3
Monthly and seasonally averaged daily evapotranspiration (ET) measured using the eddy covariance method in every furrow (FI), alternate furrow irrigations (AFI), and rainfed (RF) treatments.

Irrigation level	Daily evapotranspiration (ET), mm				
	May	June.	July	Aug.	Seasonal
			2016		
FI	3.3	5.1	5.3	4.1	4.4
AFI	3.2	5.5	5.4	4.3	4.6
RF	3.4	5.1	4.9	3.8	4.3
			2018		
FI	4.2	6.2	6.0	5.3	5.4
AFI	4.3	6.4	6.3	5.2	5.5
RF	4.2	6.4	5.8	4.2	5.2
			2020		
FI	2.1	5.2	6.1	6.2	4.9
AFI	2.4	4.9	6.3	6.3	5.0
RF	2.3	5.1	5.6	5.6	4.7
			Average		
FI	3.2	5.5	5.8	5.2	4.9
AFI	3.3	5.6	6.0	5.3	5.0
RF	3.3	5.5	5.4	4.5	4.7

error in ET estimation compared to those measured using large-scale field-lysimeters were between 10% and 15%. In our study, we did not have lysimeter measurements for comparing the EC estimated ET to compare against for accuracy, but the average 94% energy balance closure can reasonably provide a better level of accuracy in ET estimates for use in water management applications.

Across the three crop seasons, both half-hourly and daily soybean ET estimates in the AFI treatment were marginally higher than the ET measured in the FI treatment (Figs. 2, 5, 6, 7b). However, ET in the RF treatments was substantially lower than ET in both FI and AFI. Across the different months (May, June, July, and August) of the three crop seasons (2016, 2018, and 2020), measured ET in the FI treatment varied between 2.1 and 6.1 mm. Measured daily ET in the AFI treatment varied between 2.4 and 6.3 mm, and between 2.3 and 5.8 in the RF treatment (Table 3). Seasonal average daily ET averaged across the three seasons were 4.9, 5.0, and 4.7 mm, respectively, in FI, AFI, and RF. Seasonal (emergence to R7) ET varied between 514 and 555 mm in FI, 535 and 598 mm in the AFI, and 494 and 557 in the RF treatments (Table 5, Fig. 2). Averaged across three seasons, seasonal ET in the three treatments were 539, 562, and 527 mm, respectively (Table 5). Averaged across the three crop seasons, seasonal rainfall was 494 mm, and total water applied (rainfall + irrigation) in FI and AFI were 573 mm and 534 mm, respectively.

Table 4
Least square means and 95% confidence interval values of soybean yield for irrigation treatments. The same letters within a column are not statistically different from each other at $p < 0.05$.

Irrigation treatments	Soybean yield ± Standard error Kg ha^{-1}	% yield reduction
All furrow irrigation(FI)	4507 ± 14b	-
Alternate furrow Irrigation (AFI)	4413 ± 17b	2
Rainfed (RF)	3422 ± 19a	24
P-value	<0.0001	

As above, the measured LAI under the FI treatment was slightly higher than that measured in AFI, however, the potential contribution of the higher leaf area available for transpiring more water (T, transpiration component of ET) did not translate into higher ET from this treatment. It is possible the higher LAI under the FI closed the canopy over the bare soil between rows faster and better than the AFI with less LAI. This, possibly, lead to less direct evaporation (E, bare-soil evaporation component of ET) from the soil surface, resulting in less total water loss (ET = E + T) (Figs. 2, 4, 5 & 6). The frequent rainfall events combined with the added water from the irrigation events maintained the soil surface wet for keeping E at a higher rate in the AFI treatment with less canopy closure.

3.5. Grain yield and WUE

Spatial average yields across the three crop seasons in the FI, AFI,

Table 5
Soybean grain yields measured across FI, AFI, and RF treatments in 2016, 2018, and 2020.

	Yield, kg ha^{-1}				ET, mm				Rainfall + Irrigation, mm				WUE, kg ha^{-1} mm^{-1}			
Year	2016	2018	2020	Mean	2016	2018	2020	Mean	2016	2018	2020	Mean	2016	2018	2020	Mean
FI	4098	4445	4977	4507	514	558	545	539	553	606	562	573	8	7	9	8
AFI	4116	4270	4853	4413	535	598	551	562	523	561	517	534	8	7	9	8
Change from FI	0%	-4%	-2%	-2%	-21	-40	-6	-23	15	45	45	34	0	0	0	0
RF	3538	3275	3482	3422	494	557	529	527	493	516	472	494	7	6	7	7
Change from FI	-14%	-26%	-30%	-24%	-4	-0	-3	-2	60	90	90	90	1	2	2	1

FI = irrigation applied through every furrow; AFI = irrigation applied through alternate furrows; RF = rainfed, WUE = water use efficiency, grain yield/ET.

and RF were 4507, 4413, and 3422 kg ha^{-1}, respectively (Table 4, Fig. 7a). Though significantly different at $p < 0.05$, yield in the AFI treatment was only 94 kg ha^{-1} less than FI, that means, only a 2% decrease in grain yield compared to FI. In irrigation trials in a silt loam soil in the LMD, Pinnamaneni et al. (2020a, 2020b) demonstrated that comparable yield and economic returns from cotton and soybean are possible when irrigations were applied through conventional, all furrows, and half as much water were applied through alternate furrows. In a semiarid climate in Nebraska, USA, Graterol et al. (1993) reported similar soybean grain yields across FI and AFI irrigation experiments. In this experiment, in AFI treatments, irrigation water applied was only about half the irrigation water applied in the FI treatment. In our experiments, grain yield in RF treatment was significantly lower than grain yields harvested in FI and AFI treatments, averaged across 2016, 2018, and 2020 crop seasons by 1085 and 991 kg ha^{-1}, respectively.

Averaged across the three years, grain yield harvested in RF was 24% lower than grain yield in FI treatment (Tables 4 and 5, Fig. 7a). Across the three crop seasons, the grain yields in AFI were less than FI by 0% in 2016 to 4% in 2018. Grain yield reduction in RF treatment compared to FI varied between 14% in 2016 and 30% in 2020. The consistent, significant reduction in soybean yields in RF treatment shows the importance of irrigating soybean in the LMD to increase net returns from soybean cropping systems. In small plot studies in the LMD, Leininger et al. (2019) reported increased yield returns from the practice of applying irrigations through AFI. They reported that FI treatments could lead to over-irrigation-related yield losses in peanut production systems in the LMD. Our study, in farm-scale plots over multiple years, demonstrated the importance of adopting the AFI system for water conservation in soybean cropping systems in the LMD.

WUE, defined as the amount of grain yield per amount of water consumed by the plant, in meeting the ET demands, in FI and AFI were similar in magnitude but higher than the values obtained for the RF treatment. Averaged across the three crop seasons, WUE in RF was lower than AFI and FI by 1 kg ha^{-1} mm $^{-1}$ (Table 5, Fig. 7c). In small-plot studies, in the semiarid climate of Nebraska, USA, Graterol et al. (1993) obtained a WUE of 7 kg ha^{-1} mm $^{-1}$ under FI irrigation and 6 kg ha^{-1} mm $^{-1}$ under AFI irrigation. In our study, WUE between the AFI and FI treatments coincided. During the three crop seasons, WUE varied between 7 and 9 kg ha^{-1} mm $^{-1}$ under the FI and AFI treatments, and 6 and 7 kg ha^{-1} mm $^{-1}$ under RF. In summary, the AFI treatment needs only about half the irrigation water required for the FI; however, both treatments resulted in similar water use efficiencies and comparable grain yield returns.

4. Conclusions

Conventional furrow (surface flood) irrigations have the lowest irrigation efficiency among various irrigation methods (sprinkler and drip irrigations have better irrigation efficiencies) available to farmers in the Lower Mississippi Delta region. While the irrigation efficiency is low, it is also true that the irrigations applied to crops through furrow irrigations exceed the crop water demands. It is unequivocal that the shallow MRVAA underlying this region is declining from exploitation, far exceeding the natural recharge rates of this aquifer. Using eddy covariance-based sensors in large farm-scale fields, we quantified water used by the crops in all-furrow (FI), alternate-furrow (AFI) irrigations, and rainfed (unirrigated) treatments. Soybean irrigated through FI and AFI supplied enough water for the optimum production of the crop. Consequently, soybean grain yields were similar in AFI and FI. The RF consumed less water; however, it yielded significantly lower as well. This large farm-scale study in the LMD region indicated that crops can be irrigated through AFI saving about half the irrigation water while producing comparable grain yields. This farm-scale study is being continued for quantifying similar irrigation responses of corn, cotton, and rice crops across major soils and climates in the region for developing decision support information for sustainable water management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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