Received: 8 February 2022 | Accepted: 10 May 2022 | Published online: 30 July 2022

DOI: 10.1002/agj2.21130

Agronomy Journal

ARTICLE

Climatology and Water Management

Eddy covariance quantification of corn water use and yield responses to irrigations on farm-scale fields

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Assigned to Associate Editor Chitranjan Kumar.

Abstract

Furrow irrigations dominate row-crop irrigation scenarios in many regions worldwide. In this study, corn (*Zea mays* L.) yield and evapotranspiration (ET) in an all-furrow irrigation (FI) were compared against irrigations applied through alternate furrows irrigation (SFI, skip-furrow irrigation) and rainfed (RF) systems on farm-scale fields in 2017 and 2019 {corn phases of a soybean [*Glycine max* (L.) Merr.]–corn rotation} in clay soil in the Lower Mississippi Delta region, United States. Evapotranspiration was monitored using the eddy covariance (EC) method. The average corn yield in the SFI was significantly (12.1 Mg ha^{-1}) higher (4.9%) than in the FI (11.7 Mg ha^{-1}). Corn yield in RF (10.2 Mg ha^{-1}) was significantly lower (10.7%) than in the FI. However, the leaf area index (LAI) in SFI was lower than in FI. Seasonal average ET was 556, 573, and 540 mm in FI, SFI, and RF, respectively. The average water use efficiencies (WUEs) were 0.021, 0.021, and 0.019 Mg ha^{-1} mm^{-1}, respectively (10.5 % lower in RF than FI and SFI). This investigation revealed that adapting the SFI irrigation regime in the corn cropping system could produce grain yields equal to or higher than corn grown under the conventional FI, saving ∼40% of irrigation water. The farm-scale studies conducted in this investigation gave better confidence to recommend SFI to replace conventional FI systems in the region for water conservation in corn cropping systems. Further investigations may be needed to evaluate the viability of SFI in other contrasting soils and climates and recommend the system for adoption by the farming community.

1 | INTRODUCTION

Water is critical for crop growth; therefore, when rainfall is insufficient to meet crop water demands, irrigations are essential for assuring optimum crop growth and harvested grain yield. Worldwide, the current rate of water extractions from aquifers for irrigations, in general, surpass their natural recharge rates threatening sustainable production outputs from irrigated agriculture (Mekonnen & Hoekstra, 2016; Scanlon et al., 2012; Wada et al., 2012). Applying less water or increasing the productivity of the applied water holds the key to reversing the declining irrigation water supplies in production agriculture. When there is a severe shortage of water,

Abbreviation: DAP, days after planting; EBC, energy balance closure; EC, eddy covariance; ET, evapotranspiration; FI, all-furrow irrigation; GDD, growing degree days; LAI, leaf area index; LMD, Lower Mississippi Delta; MRVAA, Mississippi River Valley alluvial aquifer; RF, rainfed; SFI, alternate-furrow irrigation; WUE, water use efficiency.

adopting alternate-furrow irrigation (SFI, skip-furrow irrigation) to replace the conventional surface flood irrigation in which water is normally applied through all the furrows in between ridges on which the row crop is planted, known as the furrow-irrigation system (FI, all-furrow or every-furrow irrigation), is a well-recognized practice across various cropping systems across the world (https://www.fao.org/3/s8684e/s8684e04.htm; Horst et al., 2007; Leininger et al., 2019). In the FI system, the furrow-applied water in the soil moves downward and laterally. In clay soils, the dominating lateral movement in the SFI system can help the water wet across the ridges for root uptake. There is also less chance for water logging from excess applied water in the SFI-applied soils. As such, following SFI can eventually lead to better soil aeration and water uptake by the plant for better crop growth and yield returns (Horst et al., 2007).

In many cropping systems worldwide, the water-saving potential and enhanced water use efficiencies (WUEs) of SFI over the conventional FI were reported. By adopting SFI, WUE increased by 23% over a conventional FI in cotton (*Gossypium* ssp.) lint yield production in Arizona, United States (Rahman and Shafi, 1977). The SFI studies on cotton in the Central Fergana Valley, Uzbekistan, reported ∼44% water saving with ∼11% cotton yield reductions but with 60% increases in water productivity than following the FI system (Horst et al., 2007). Practicing SFI systems in corn (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench] in small-plot studies in the southern high plains of the United States resulted in more efficient irrigation water use, while grain yield harvests were not significantly affected (Musick & Dusek, 1982). Leininger et al. (2019) reported enhanced lateral water suction from a nonirrigated furrow, which helped maintain yields in an SFI peanut (*Arachis hypogaea* L.) system over the FI system. A slight decline in the cotton lint yield with a 40% reduction in applied irrigation water has been reported using SFI (Khan et al., 1999). Kang et al. (2000) noted a reduction in water applications by ∼50%, while producing comparable yield in an SFI over the FI in an arid climate of northwestern China. They noticed a significant increase in root development, as reflected in the measured root weight and density, and plant height because of SFI. Siyal et al. (2016) reported a 50% reduction in applied water with a statistically insignificant yield reduction in okra [*Abelmoschus esculentus* (L.) Moench] yield (7.3%) because of SFI over the FI system.

The Lower Mississippi Delta (LMD) region in the southeastern United States is an important agricultural production region. In the recent past, irrigations for crops, mainly soybean, cotton, corn, and rice (*Oryza sativa* L.), are on the rise, causing a rapid depletion in the underlying Mississippi River Valley alluvial aquifer (MRVAA), which is its primary water source for irrigation water withdrawals (Yasarer et al., 2020). This has resulted in a 7-m drop in groundwater level in MRVAA between 1987 and 2014 (Ackerman, 1989; https://www.srs.fs.usda.gov/compass/2020/07/28/groundwater-recharge-in-the-lower-mississippi-river-alluvial-valley/). The FI system dominates the primary irrigation application method in the MRVAA region (Ouyang et al., 2016; Wood et al., 2017). The FI system, in general, is well known to have an average irrigation efficiency of ∼42% (Kandpal and Henry, 2016). However, the flat landscape, which cannot hold much surface water from draining off the fields, easily extractable groundwater supplies, and ease of application without any special technical skills rendered the FI system popular among farmers for crop irrigations in the MRVAA region (Leininger et al., 2019). Developing methods for enhancing irrigation WUEs in the FI system in this region has been the topic of research in many studies in the region in the past, for example, Leininger et al. (2019), Pinnamaneni, Anapalli, Fisher, et al. (2020), Pinnamaneni, Anapalli, Reddy, et al. (2020b), Anapalli et al. (2022), and Quintana-Ashwell et al. (2021). While considerable efforts have been made to investigate and demonstrate the water-saving potential of SFI vs. conventional FI method practiced in the area, not many farmers have adopted the method, possibly because of a lack of reports that demonstrated the feasibility of SFI at farmer's field level to build the confidence of assured grain yields while using less water. Evidently, all the studies referred to above are small-plot studies conducted to evolve agricultural technologies for farmer recommendations. In this context, before developing irrigation recommendations for farmer adaptations, confirming the small-plot-based results further in farm-scale plots in multiple climates and soils was recommended (Schmidt et al., 2018; Anapalli et al., 2022).

Sufficient knowledge of the water requirements of the crop (evapotranspiration [ET]) and its variations with climate and soils is a prerequisite for research investigations for enhancing WUE in agriculture (Hatfield & Dold, 2019; Anapalli et al., 2020, 2022). Farm-scale plots are also essential for quantifying ET in cropping systems for computing WUE of alternative water treatments for comparison and selection of the optimum irrigation level for optimum production (Burba &

Core Ideas

- Corn yield and water use responses to irrigations in a humid climate have been quantified using EC systems.
- SFI produced corn yields equal or better than FI in farm-scale experiments.
- These studies give confidence to recommending SFI over conventional FI for sustainable irrigation water management.

Anderson, 2005; Moorhead et al., 2019; Anapalli, Fisher, Reddy, Krutz, et al., 2019; Anapalli, Fisher, Reddy, Rajan, et al., 2019; Anapalli et al., 2022). In field-crop irrigation water management research, it is essential to have large-scale plots for minimizing plot interactions that usually occur in conventional small-plot studies because of the three-dimensional movement of applied water across the soil–plant–atmosphere pathways (Heilman et al., 1976).

Compared with traditional lysimetric and water balance methods, the relatively modern eddy covariance (EC) technology-based method is a cutting-edge-science based method that is easy and less time-consuming to set up for quantifying ET from cropping systems (Baldocchi, 2003; Moorhead et al., 2019; Fong et al., 2020; Anapalli, Fisher, Reddy, Rajan, et al., 2019; Anapalli et al., 2020). In farm-scale field experiments, Runkle et al. (2017), Fong et al. (2020), Anapalli, Fisher, Reddy, Krutz, et al. (2019) Anapalli, Fisher, Reddy, Rajan, et al. (2019), and Anapalli et al. (2020, 2022) quantified ET and WUE in corn, soybean, and cotton cropping systems in the LMD region using the EC method. The advantages of the EC method lie in its innovative science theory-based sensors, which can be installed easily and quickly for timely measurements. The objective of this study was to compare (a) corn yield and (b) consumptive water use (ET), measured using the EC method, responses to FI, SFI, and RF irrigation treatments at farm scale.

2 | MATERIALS AND METHODS

2.1 | Corn experiments

Experiments were conducted in farm-size (∼10 ha) fields in 2017 and 2019 at the crop research facility of the Crop Production Systems Research Unit, USDA–ARS, Stoneville, MS, USA (33˚39′ N, 90˚59′ W, 42 m asl) located in the LMD region. The EC towers were located centrally in these fields to achieve the maximum possible fetch for the sensors installed on the towers to monitor air turbulence and physical properties (vertical component of wind and water vapor mixing ratio). The sensors for quantifying fluxes of water and energy from the cropping systems require a fetch ratio (ratio of the height of sensor placements above the crop canopy to the horizontal distance from the perimeter of the field to the tower) of ∼1:100 around the towers (Burba & Anderson, 2005; Nicolini et al., 2017).

The farm-size fields used in this investigation constrained having replicated experiments for each treatment. However, FI, SFI, and RF treatments were applied randomly to the plots across the years (2017 and 2019; corn phases of a soybean–corn experiment conducted from 2016 to 2021). The experiment was repeated in 2021, but because of COVID-19-related shortage in fertilizer availability, we could not apply fertilizer on time to collect data good enough for comparison with other years and present in this paper. Thus, the 2 yr of the experiments constituted two treatment blocks in which the FI, SFI, and RF were randomly applied to fields. This layout helped treat the experimental design as a randomized complete block with two replications for statistical significance analysis (Casler, 2015). The fields were maintained at about a 1% slope to facilitate irrigation or rainwater drain out of the field without causing waterlogging conditions.

The irrigations in this study were applied at the head of the furrows by supplying water through lay-flat polyethylene pipes. The FI and SFI plots were irrigated on the same day. Irrigation was stopped when the water in the furrow reached the bottom end. Soil water contents at 8 and 30 cm were measured and recorded every 30 min and stored along with the EC data. Three Stevens HydraProbe (Stevens Water Monitoring Systems Inc.) were used for soil water monitoring on either side of the ridges and in the middle of the furrow replicated thrice. Irrigations were applied when a break in rainfall allowed the top 30-cm soil layer to lose 35–40% of the plant available water. In the FI treatment, irrigations were closed when ∼80% of the furrows were completely wet from the head to tail. Irrigation water applied was monitored using a flow meter. The SFI treatment aimed to let the crops get approximately half as much water as applied in the FI treatment. This was achieved by applying water through alternate furrows and stopping when ∼70% of the rows had water run from head to toe. In this experiment, applied water in the SFIs was, on average, ∼60% of the irrigations applied in the FI treatment. On average, 30 and 18 mm of water were applied per irrigation in the FI and SFI treatments, respectively. In other small-plot experiments at the same location Pinnamaneni, Anapalli, Fisher, et al. (2020) and Pinnamaneni, Anapalli, Reddy, et al. (2020) followed a similar procedure, as adopted in this experiment: water applied in the SFI was approximately half as much as the water applied in the FI treatments. Two irrigations were applied each in 2017 and 2019 (Figure 1). The crop water consumption in the RF was purely rainfall dependent. The soil across the farm fields was uniform to a depth of ∼45 cm. Textural analysis was conducted on soil samples collected before planting in 2017 down to 45 cm depth. The texture class identified was clay (Table 1) (Sharkey clay: clayey over loamy, montmorillonitic, non-acid, thermic Vertic Halaquepet). Organic content in the soil layers varied between 1.7% in the top 0–15 cm to 1.3% in the 30–45 cm layer, and pH varied between 6.6 and 6.3.

Conventional tillage practices prevalent in the LMD region were followed. The main tillage operations consisted of two tillage passes of disk harrow or chisel plow to kill weeds and create raised beds (ridges) for planting corn and furrows to facilitate furrow irrigation. A pike harrow pass was used for smooth seedbed planting. Pre- and postemergence herbicides were applied as needed to control weeds. Crop cultivators with

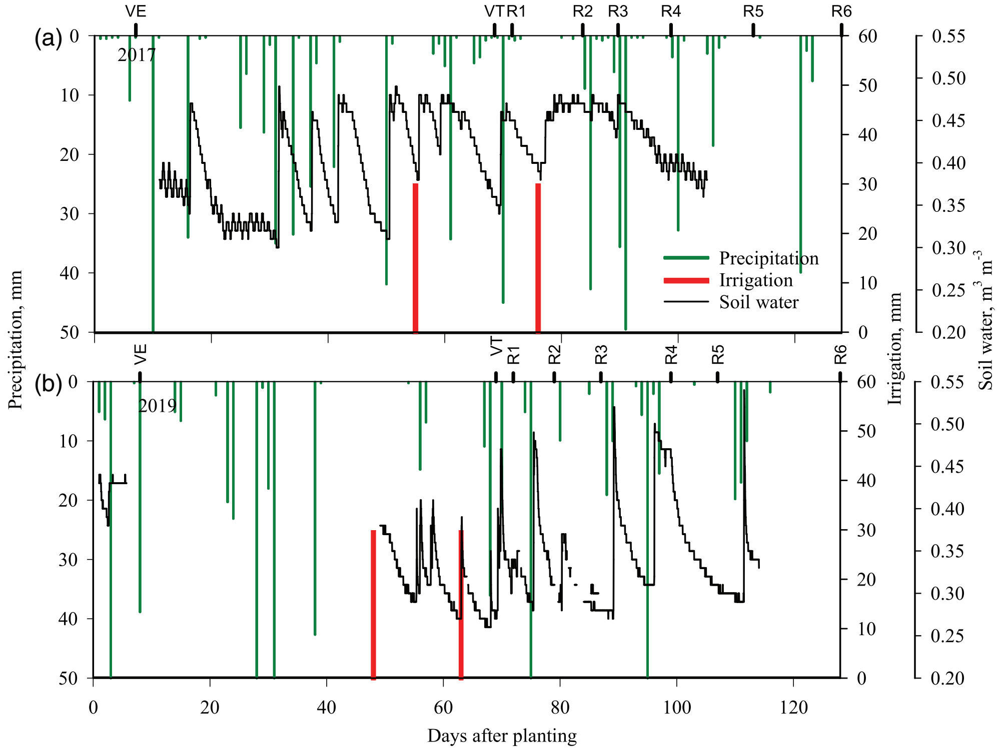

FIGURE 1 Soil water at 15 cm depth, and irrigations applied in the all-furrow irrigation (FI) treatment in (a) 2017 and (b) 2019. Precipitation (rainfall) recorded at the location is shown. Approximately 60% of irrigation amounts applied in FI were applied in the alternate-furrow irrigation (SFI) treatment. No irrigations were applied in the rainfed treatment

TABLE 1 Average soil physical and chemical properties at planting under all-furrow irrigations (FI), alternate-furrow irrigations (SFI), and rainfed (RF) treatments at Stoneville, MS

					Mehlich-3 extractable nutrients						
Soil depth	Soil texture	pH	Organic matter	Cation exchange capacity	P	K	Ca	Mg	Zn	S	Cu
cm			%	Meq 100 g^{-1}	mg kg^{-1}						
0–15	Clay	6.6	1.7	23.5	21	203	2,240	673	2.3	5.5	4.0
15–30	Clay	6.3	1.3	18.5	23	238	2,711	571	2.5	10.2	2.3
30–45	Clay	6.5	1.3	20.9	27	241	2,192	689	1.7	7.9	2.6

shallow sweep passes were resorted to, thus controlling weeds after corn emergence.

2.2 | Corn growth and development

The corn cultivar Terral REV 24BHR99 was planted on 97-cm spaced ridges of ∼180 m in a north–south orientation at a seeding rate of ∼70,000 seeds ha^{-1}. Intrarow plant spacing on the ridges were ∼14 cm. The fertilizer applied was urea ammonium nitrate injected into the ridge base at ∼224 kg N ha^{-1} after corn seedling emergence. Major corn phenological growth stages were noted using a nondestructive, visual method (Table 2). Agronomists relate the plant phenological development with an accumulation of growing degree days (GDD) above a crop-specific base temperature where plant growth ceases completely. A base temperature of 8 ˚C was used for computing the GDD of corn (Neild and Seeley, 1977). An AccuPAR LP-80 Ceptometer (Decagon Devices Inc.) was used for measuring leaf area index (LAI) at biweekly intervals. Plant heights were also monitored for positioning EC sensors above the plant canopy. Each irrigation field was divided into three sections, and all plant-related measurements were repeated in those sections. For spatial analysis, corn seeds were harvested, weighed, and geo-referenced using a GPS-enabled combine with grain yield monitor (Case IH 5140). Corn yield data recorded were adjusted to 15% moisture content. All harvests were conducted approximately 1–2 wk after the full seed maturity stage (R6).

TABLE 2 Observed phenological growth stages of corn in 2017 and 2019

Phenological growth stages	2017 DAP	2017 GDD	2019 DAP	2019 GDD	Plant height	Avg. eddy covariance sensor height
	d	˚C	d	˚C	m	m
Emergence (VE)	7	87	8	84	0.0	2.0
Tasseling (VT)	69	933	69	1,030	2.3	5.3
Silking (R1)	71	969	72	1,088	2.4	5.4
Blister (R2)	83	1,174	79	1,216	2.4	5.4
Milk (R3)	89	1,284	87	1,380	2.4	5.4
Dough (R4)	98	1,435	99	1,624	2.4	5.4
Dent (R5)	112	1,709	107	1,768	2.4	5.4
Physiological Maturity (R6)	121	1,896	115	1,920	2.4	5.4

Note. GDD, computed growing degree days using an 8 ˚C base temperature; DAP, days after planting. Phenology remained constant across all-furrow and alternate-furrow irrigations and rainfed treatments in both years, so only one set of data was provided. Planting in 2017 and 2019 was on 21 March and 2 April, respectively.

2.3 | Corn ET measurements using the EC method

Air temperature (computed using the sonic method) and three-dimensional wind speed for computing the vertical speed of propagation of eddies were measured using a Gill new WindMaster 3-D sonic anemometer (Gill Instruments). Water vapor density in the eddies was measured using an LI-7500-RS infrared gas analyzer (LI-COR Inc.). The sensors were installed on a telescopic height-adjustable mast (EC tower) in each farm's center to measure turbulence data for quantifying ET (water flux) from the soil–crop canopy system. Operating a built-in hydraulic pump on the tower, the sensors (anemometer and gas analyzer) were constantly kept within the constant flux layer above the frictional sublayer above the crop canopy, which roughly starts from approximately twice the plant canopy height. The sonic anemometer and gas analyzer data were recorded at 10-Hz intervals on a datalogger.

Microclimate and radiation–energy balance in the crop environment were monitored at 1-min intervals. They were averaged at half-hour intervals for computing energy balance in the soil–crop canopy system: (a) incoming and outgoing solar radiation (shortwave), and incoming and outgoing earth radiation (longwave) using a CNR4 net radiometer (Kipp & Zonen B.V.); (b) air temperature and relative humidity using HMP 155 sensors (Vaisala); (c) rainfall using a TR 525 tipping bucket rain gauge (Texas Electronics); (d) soil heat flux using six self-calibrating HP01SC soil heat flux plates (Hukseflux Thermal Sensors B.V.) at 8 cm depth in the soil; and (e) soil temperature and water above the heat flux plates using Stevens HydraProbe (Stevens Water Monitoring Systems, Inc.).

The EddyPro v6.1.0 software provisioned in the SmartFlux system (LI-COR, Inc.) connected to the datalogger and mounted on the EC tower was used for processing the raw turbulence data collected using EC sensors at 10-Hz intervals. The latent heat of evaporation (LE) and ancillary microclimate data were output from this system at 30-min intervals. Further postprocessing of this data for quality control and removing improbable fluxes for water flux computations, the Tovi software (LI-COR, Inc.) based on the OzFlux method (Isaac et al., 2017) was used. In Tovi, the Mauder and Foken (2006) method was adopted for removing epochs with poor air turbulence because of calm wind conditions. The energy balance residual correction method recommended by De Roo et al. (2018) was used for latent and sensible heat flux corrections for energy imbalance in the system (Figure 2). The marginal distribution sampling technique (Reichstein et al., 2005) was used to fill gaps in the computed fluxes and measured microclimate data. Finally, the latent heat of evaporation flux outputs (W m^{-2}) were converted to ET, expressed in depth of water (mm), following thermodynamic principles (the conversion factor was 0.00073 mm per W m^{-2}).

2.4 | Yield data analysis

Corn grain yield data recorded by the combine were evaluated for normality, and outliers in the data were removed following the Sudduth et al. (2012) procedure. The Glimmix procedure in the statistical software SAS v9.4 was used for analyzing the yield data. Irrigation treatments were considered as fixed effects. Years of yield data collected (2017 and 2019) were considered random factors in the repeated measure model statement. A spatial–temporal covariance structure, type = SP(POW)(c-list) selected based on the lowest Akaike's Information Criteria, was used for spatial yield data having longitude and latitude associated with each data point (Littell et al., 2007). Mean differences at alpha = .05 were evaluated using the Tukey–Kramer test.

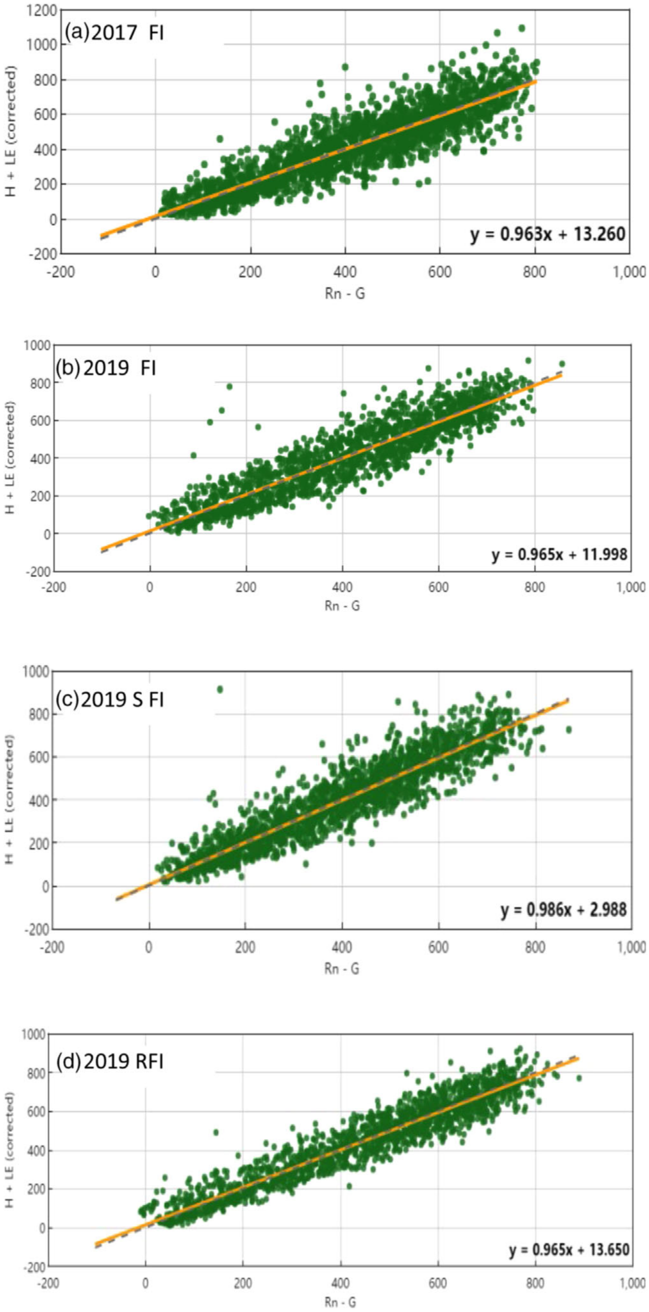

FIGURE 2 Energy balance closure in the measured energy fluxes from the corn cropping system in the all-furrow irrigation (FI) in 2017 and FI, alternate-furrow irrigation (SFI), and rainfed (RF) treatments in 2019. LE, latent heat of evaporation; H, sensible heat flux

3 | RESULTS AND DISCUSSION

3.1 | Weather conditions

Following the Köppen–Geiger climate classification, the LMD area has a humid subtropical climate, warm summers, and mild winters (Kottek et al., 2006). Based on the 1960–2015 weather data recorded at the location, this region receives ∼1,300 mm of rainfall in a year (Anapalli et al., 2016). Both 2017 and 2019 received above-normal rainfalls of 1,468 and 2,098 mm, respectively. On average, ∼35% of the annual rainfall was received during the summer crop growth season (April through September). Typically, corn in the region was planted around the last week of March depending on the rainless window available for planting and related operations to drive the planter in the field. The crop was planted on 21 Mar. 2017 and on 2 Apr. 2019 when the soil was relatively dry without substantial rainfall (Figure 1; Table 2). During 2017 and 2019, the crop duration (from planting to physiological maturity) was 127 and 128 d, respectively, and rainfall totaled 560 and 557 mm (Table 3). The crop in 2017 experienced 59 rainy days (rainfall with more than 1 mm recorded) and 47 rainy days in 2019 (Figure 1). In 2017, the maximum number of continuous rainless days was 14, while in 2019, it was 17. The highest rainfall recorded in the 2017 crop season was 69 mm on 5 April, and in the 2019 crop season was 158 mm on 9 June. In 2017, the first irrigation was given 13 d before tasseling stage (VT), during a 14-d dry-spell period (20 June through 4 July). Second irrigation (5 d after silking stage, R1) when the rain-free period was 13 d (11–23 July) (Figure 1). In 2019, the first irrigation was given 3 wk before VT, when the longest continuous rainless period was 17 d (11–24 May). Second irrigation was given, 3 d before VT, when a 9-d rainless spell occurred from 8 to 17 June (Figure 1). These dry spells left the soil in the top 30 cm depth with losses of 35–40% of the plant available water, the criteria used for initiating irrigations stated above.

Daily air temperatures below 8 ˚C and above 34 ˚C can unfavorably affect corn growth and development processes (Hatfield & Preuger, 2015; Hussain et al. et al., 2019; Priya et al., 2019). Daily minimum air temperature ranged between 6.9 and 24.4 ˚C on 9 April and 6 June, respectively, in 2017, and between 7.8 and 24.4 ˚C on 20 April and 22 May 2019. Maximum temperatures varied between 20.0 ˚C on 2 April and 35.0 ˚C on 21 July 2017 and between 16.4 ˚C on 14 April and 36.7 ˚C on 10 July 2019. There were 3 d between 34 (the upper threshold that affects growth) and 36.7 ˚C (the highest recorded) in 2019. As such, air temperatures below the lower or above the upper thresholds did not substantially affect corn growth in the experiment. Solar radiation recorded at the top of the crop canopy was highly variable because of cloudy, overcast skies typical in the humid climate of this region (Kottek et al., 2006) (Figure 3). During the 2017 crop season, daily solar radiation (total hemispherical radiation) recorded was 4.1 MJ m^{-2} on 9 April and 29.1 MJ m^{-2} on 27 May. In 2019, it varied between 4.0 and 28.6 MJ m^{-2} on 11 May and 13 June, respectively. The high variability observed in the measured solar radiation appears to be an important yield-limiting factor in crops raised in this region; however, further investigations are needed to confirm its role and quantify the extent of this limitation in crop production in the LMD

TABLE 3 Corn seasonal water use (evapotranspiration [ET]), rainfall and irrigation, corn yields, and water use efficiencies (WUE, grain yield/ET) measured across irrigation applied through every furrow (FI) and alternate furrow (SFI) irrigation and rainfed (RF) treatments in 2017 and 2019

Irrigation method	ET			Rainfall			Irrigation			Grain yield			WUE		
	2017	2019	Mean	2017	2019	Mean	2017	2019	Mean	2017	2019	Mean	2017	2019	Mean
	mm									Mg ha^{-1}			Mg ha^{-1} mm^{-1}		
FI	532	579	556	560	557	559	60	60	60	11.5	11.6	11.6	0.022	0.020	0.021
SFI	–	573	573	560	557	559	36	36	36	12.0	12.1	12.1	–	0.021	0.021
Change from FI, %	–	−1.0	3.1	0	0	0	−40	−40	−40	4.3	4.3	4.3	–	5.4	1.2
RF	–	540	540	560	557	559	0	0	0	10.4	10.0	10.2	–	0.019	0.019
Change from FI, %	–	−7.2	−3.0	0	0	0	−100	−100	−100	−10.6	−16.0	−13.7	–	−7.5	−10.5

Note. Long-term (1960–2019) mean rainfall for the season was 520 mm.

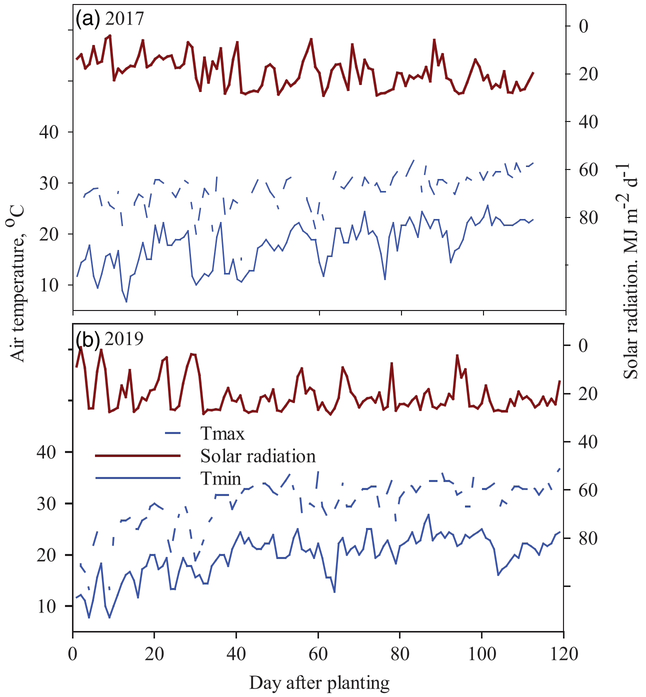

FIGURE 3 Measured daily air temperature maximum (Tmax), minimum (Tmin), and solar radiation during 2017 and 2019 corn growth seasons (planting to beginning physiological maturity stage)

for prescribing measures for better light-harvesting techniques in row-crop agriculture in the region.

3.2 | Corn growth and development response to irrigations

No noticeable differences in phenology were noticed across the three irrigation treatments across 2 yr in this study (Table 2). Prolonged absence of water inputs and consequent severe water stress was found to delay leaf initiation, tasseling, and flowering in corn (Farre & Faci, 2006; Traore et al., 2000). It is possible that the water stress induced in the crop in our experiments by the short periods of dry spells encountered in both crop seasons (2017 and 2019) was not strong enough to change the crop phenology appreciably across the FI, SFI, and RF treatments (Table 2). In 2017 and 2019, the corn seedlings emerged from the soil within 7 and 8 d, respectively (Table 2). In 2017, the crop was planted on 21 March; seedlings emerged from the soil after 7 d and reached physiological maturity 121 d after planting (DAP). In 2019, the crop was planted on 2 April, which emerged 8 DAP. In this experiment, in 2017 and 2019, corn reached physiological maturity accumulating growing-degree days of 1896 (121 DAP) and 1920 °C (115 DAP), respectively (Table 2). As such, the crop took 6 d less in 2019 than the number of days it reached physiological maturity because it accumulated substantially

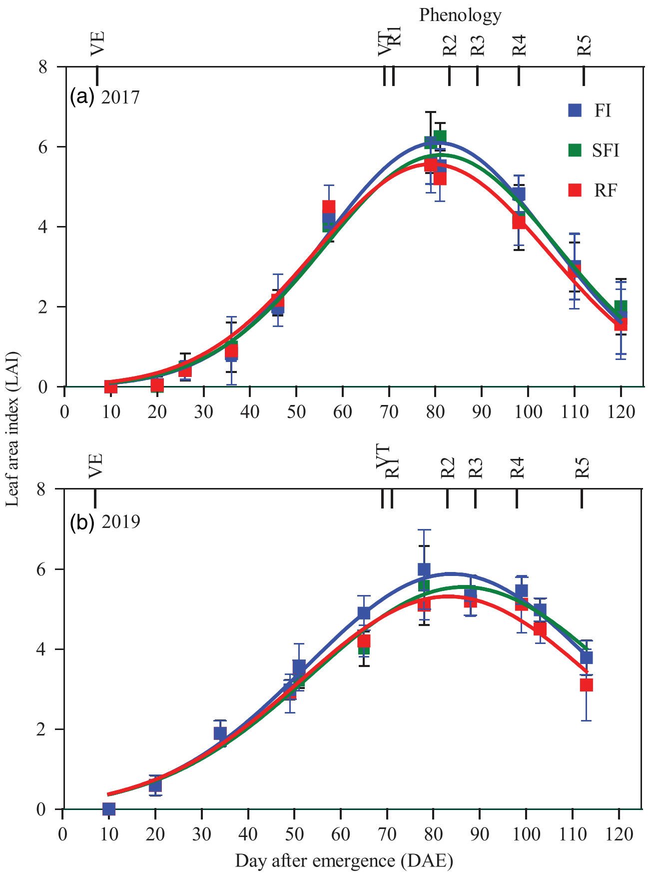

FIGURE 4 Measured corn leaf area index across all-furrow irrigation (FI), alternate-furrow irrigation (SFI), and rainfed (RF) treatments in (a) 2017 and (b) 2019. VE, VT, and R1 through R5 stages denote phenological growth stages presented in Table 2

more GDD because of higher air temperatures encountered from later planting (21 March vs. 2 April). From the GDD required to reach physiological maturity, it appears the difference in crop maturity, interestingly, in both the years, tasseling occurred at 69 DAP. The average maximum plant height was 2.3 m, attained at about the tasseling to the silking stage of the crop (Table 2).

Overall, the leaf expansion growth quantified as LAI measured under the FI treatment, which received higher irrigation water inputs than the SFI, remained marginally higher than LAI measured in the SFI and RF treatments (Figure 4). However, the measured LAI differences between the three irrigation treatments did not remain constant with time possibly because of the spatial variations of plant growth in the large-scale plots. The tendency for higher LAI seen in both FI and SFI treatments over that measured in the RF treatments shows that corn benefits from irrigation in the region as reflected in the leaf expansion growth, potentially translating to better photosynthesis and dry-matter production for enhanced grain yields. During the 2017 crop season, the maximum LAI recorded among measurements conducted in ~2-wk intervals in FI, SFI, and RF treatments were 6.2, 5.6, and 5.5, respectively. In 2019, the highest recorded LAI values were, respectively, 6.0, 5.6, and 5.2. The lower LAI values measured in 2019 were due to the 17-d-long absence of rains starting from 39 to 56 d after emergence, though we provided irrigation on the 10th day of this dry spell (Figure 4). The dry spell reduced vegetative growth in the growing season (Figure 4).

3.3 | Corn ET responses to irrigations

The extent of balance between all measured heat energy inputs with the energy stored and output from the system has been used to quantify the energy balance closure (EBC) in EC flux measurements (Widmoser & Michel, 2021; Anapalli, Fisher, et al., 2018; X. Liu et al., 2017; Leuning et al., 2012). The EBC is generally expressed as the slope of a linear regression between energy inputs and outputs from cropping systems and expressed in percentage. In the EC literature, levels of EBC reported varied between 70 and 90% (Anapalli, Fisher, et al., 2018). Various sound micrometeorological theory-based solutions to maximize EBC in energy flux quantification procedures using the EC systems have been proposed (Widmoser & Michel, 2021). In this study, the energy balance in the experiments was closed following De Roo et al. (2018), available in the Tovi software (LI-COR Inc.). The EBC obtained in the analysis of 30-min fluxes were 96% in FI treatment in 2017 and 97, 99, and 97% in FI, SFI, and RF treatments in 2019, which are accurate enough for water management applications (Moorhead et al., 2019) (Figure 2). Moorhead et al. (2019) reported ET quantified using an EC technique to fall between 85 to 90% of ET quantified using field lysimeters in a semiarid climate.

In our experiments in 2017, the ET was monitored only under the FI treatment because of technical difficulties with instrument deployment in other treatments. However, in 2019, we could simultaneously monitor ET in all three treatments. Seasonal (plant emergence to physiological maturity) ET in the FI treatment in 2017 was 532 mm and in 2019 was 572 mm (Table 3). Using a residual energy balance approach (not using EC system), Anapalli, Fisher, et al. (2018) reported seasonal ET of corn under FI treatment in 2016 in the same climate, but under a silt loam soil, to be ~ 593 mm. The actual ET loss of water from the cropping system to the atmosphere is dominantly controlled by the climate and soil hydraulic properties and the soil water status during the crop season. The ET estimate can also be affected by the method (energy balance vs. EC) used. So, a combination of all these variables contributed to the difference in corn ET between 2016 reported by Anapalli, Green, et al. (2018) and those measured under FI in 2017 and 2019 in this study.

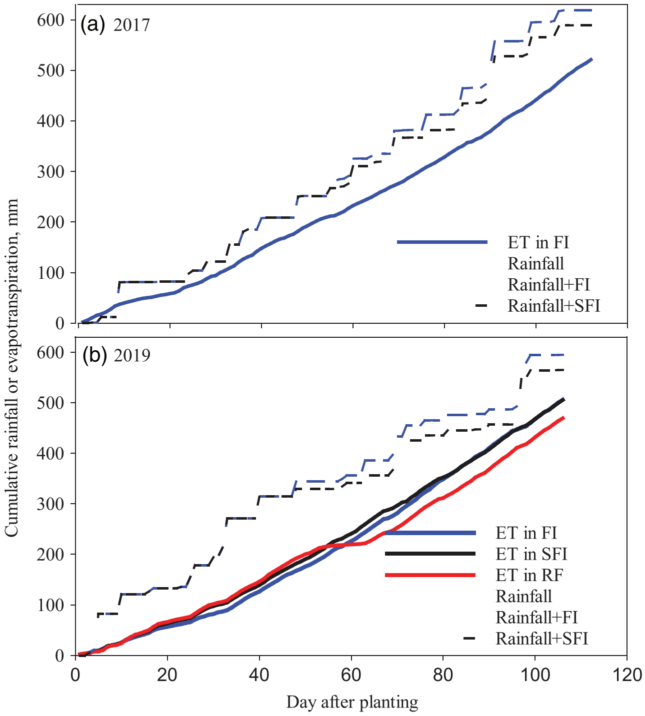

FIGURE 5 Seasonal cumulative rainfall, irrigations, and evapotranspiration (ET) measured in the all-furrow (FI) and alternate-furrow irrigation (SFI) irrigations, and rainfed (RF) treatments in (a) 2017 and (b) 2019

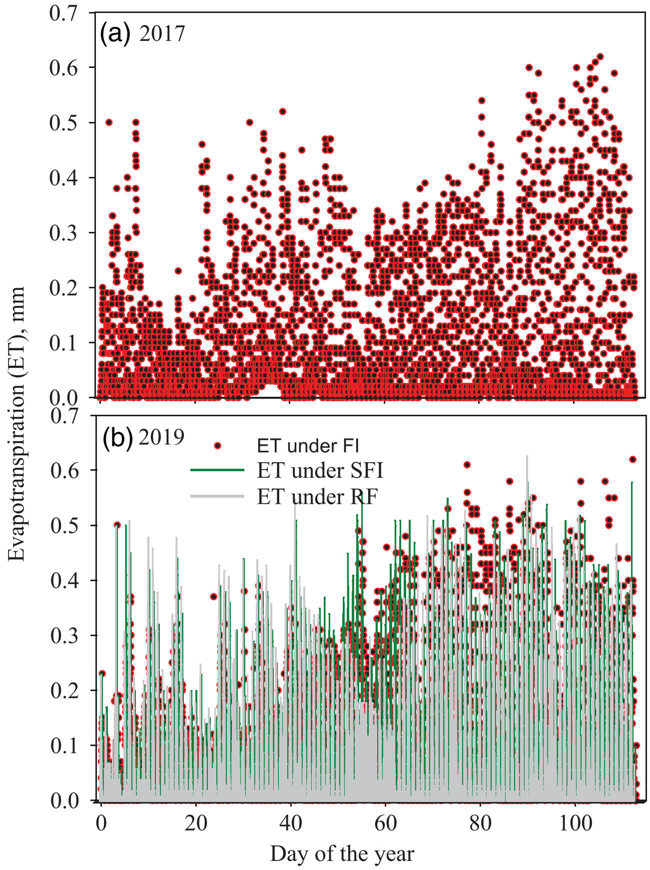

FIGURE 6 Half hourly corn evapotranspiration (ET) measured in the all-furrow (FI) and alternate-furrow irrigations (SFI), and rainfed (RF) treatments in (a) 2017 and (b) 2019

In 2019, ET quantified in SFI and RF treatments were 573 and 540 mm, respectively (Table 3; Figure 5). The differences in realized ET between the treatments were not substantial: ET under SFI and RF were only 1 and 7% less than measured under the FI. The observed rainfall in the 2019 season was 557 mm, sufficient to meet the ET at or close to the measured rate of 540 mm. Rainfall and irrigation together amounted to 587 mm water input in the SFI in 2019 when the measured ET was 573 mm (Table 3; Figure 5), so the measured ET in SFI was correct. Additionally, stored water in the soil profile can meet the crop's ET demands.

The measured half-hourly and daily ET under the three treatments varied considerably among different days of the corn season, mainly because of differences in the amount of solar radiation received resulting from various levels of cloudy, overcast sky conditions, air temperature, rainfall, and soil water status (Figures 1, 3, 6, and 7). Daily ET under FI in 2017 and 2019 ranged between 1 and 8 mm, but the day after seedling emergence, these values varied considerably (Figure 7). In 2019, ET measured under SFI treatments varied between 0.6 and 7 mm and between about 0.4 and 8 mm under the RF treatments. In this year, from 56 to 62 DAP, measured ET in the RF (no irrigation) treatment were as low as 0.6 mm d^{-1} while it remained above 3.0 mm in the FI and SFI treatments (Figure 7). The reason for the low ET measured in the RF (no irrigation) was due to a negligible amount of rainfall received during 40 through 68 DAP (only 21.9 mm rainfall received during the 28 d) at the location and consequent low water availability in the soil root zone for plant uptake to meet crop ET demands. During this period, both FI and SFI plots received two irrigations each (Figure 1). Monthly averaged daily ET across a season in the FI treatment ranged from 3.3 mm d^{-1} in March to 5.3 mm d^{-1} in August 2017 and from 3.0 mm d^{-1} in April to 5.9 mm d^{-1} in August 2019. In 2019, SFI varied between 3.1 mm d^{-1} in April and 5.8 mm d^{-1} in July, while, in RF, minimum ET was 3.3 mm d^{-1} in April to 4.9 mm d^{-1} in July (Table 4). The maximum difference in average daily ET between different irrigation treatments was 1 mm d^{-1}, as observed between FI and RF in July 2019 (5.9 mm d^{-1} under FI and 4.9 mm d^{-1} under RF) (Table 4).

Following the trend in daily ET measured in FI and SFI treatments as described above (average, 5.8 mm d^{-1} under the SFI vs. 5.6 mm d^{-1} in the FI treatment), SFI treatment had significantly higher grain yield than under the FI treatment (Table 5). Averaged across the two seasons, corn yield was 5.2% higher under SFI than FI (12.1 vs. 11.6 Mg ha^{-1}). However, LAI measured under the FI was slightly higher than under SFI than RF. As discussed above, the highest LAI

TABLE 4 Monthly and seasonally averaged daily evapotranspiration (ET) measured using the eddy covariance method in all-furrow (FI) and alternate-furrow irrigations (SFI) and rainfed (RF) treatments in 2017 and 2019 at Stoneville, MS

Irrigation treatment	Daily ET						
	Mar.	Apr.	May	June	July	Aug.	Mean
	mm						
2017							
FI	3.3	3.8	4.7	5.3	4.1	4.2	4.2
SFI	–	–	–	–	–	–	–
RF	–	–	–	–	–	–	–
2019							
FI	–	3.0	3.3	5.9	5.9	4.1	4.4
SFI	–	3.1	3.3	5.4	5.8	3.7	4.3
RF	–	3.3	3.5	4.8	4.9	3.8	4.1
Daily average by month							
FI	3.3	3.2	4.0	5.6	5.0	4.2	4.4
SFI	–	3.1	3.3	5.4	5.8	3.7	4.3
RF	–	3.3	3.5	4.8	4.9	3.8	4.1

TABLE 5 Corn yield harvested in the all-furrow (FI) and alternate-furrow (SFI) irrigation and rainfed (RF) treatments in 2017 and 2019

Irrigation treatments	Corn yield		
	2017	2019	Mean ± 95% CI
FI, Mg ha^{-1}	11.5	11.8	11.7 ± 0.03 b
SFI, Mg ha^{-1}	12.0	12.1	12.1 ± 0.04 a
Change because of SFI, %	4.9	5.5	5.2
RF, Mg ha^{-1}	10.4	10.0	10.2 ± 0.09 c
Change because of RF, %	−15.4	−21.0	−18.6

Note. The least-square means and 95% CI are also shown. The same letters following standard error values within a column are not statistically different at $p < .05$.

measured under the FI treatment was 6.2 in 2017 and 6.0 in 2019 (Figure 4). Some studies reported the disadvantages of having LAI above 5.9, such as decreased light penetration in the corn canopy, which can affect photosynthesis, and reduced grain yield returns (G. Liu et al., 2020). Excess soil water with insufficient oxygen for root respiration can also reduce grain yield returns in corn (Muktar et al., 1990; Purvis & Williamson, 1972; Ritter & Beer, 1969). This study recorded many unusually high wetting events during the 2017 and 2019 crop seasons (Figure 1). It appears the higher LAI, on the order of 6.0 and above, has caused a yield decline under the FI treatment. In 2017 and 2019, SFI returned higher grain yield returns than FI; as such, the SFI appears a better irrigation strategy for grain yield returns in the region. However, rainfed (not irrigated) treatment resulted in, on average, an 18.6 % grain yield decline compared with the SFI treatment. In summary, grain yields measured under different irrigation treatments were significantly different, and irrigating corn under SFI can be a better option for stabilizing yield returns from the crop (Table 5). Average grain yields under FI, SFI, and RF were 11.7, 12.1, and 10.2 Mg ha^{-1}, respectively.

Average WUE, grain yield per amount of water consumed in ET, was 0.021, 0.021, and 0.019 Mg ha^{-1} mm^{-1} under SFI, FI, and RF, respectively. Gain in WUE by switching from FI to SFI was 5.4 % in 2019; the WUE loss for switching from FI to RF was 7.5% (Table 3). On average, WUE loss by switching from FI to RF treatment was 10.5%. Averaged across 2017 and 2019 seasons, 1.2% gain in WUE by switching from FI to SFI was noticed in addition to the 40% saving in irrigation water and 4.3% gain in grain yield returns. Because conducted in farm-scale fields, conclusions derived from this study can be recommended to farmers for adaptation for sustainable irrigation water management in their farming systems.

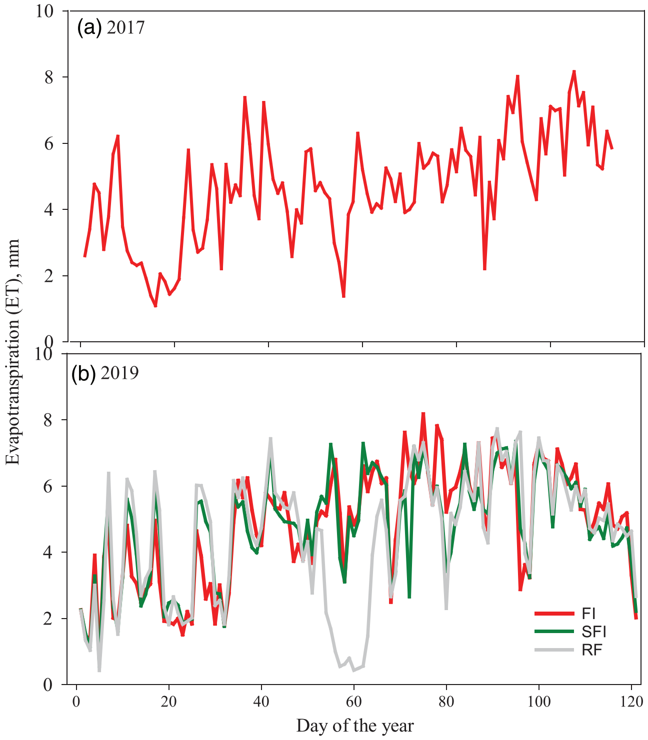

FIGURE 7 Daily corn evapotranspiration (ET) measured in the all-furrow (FI) and alternate-furrow irrigations (SFI), and rainfed (RF) treatments in (a) 2017 and (b) 2019

4 | CONCLUSIONS

This study quantified and compared corn yield, water use, and WUE response to FI, SFI, and RF systems in farm-sized experiments in clay soil in the LMD region of the United States. In this pioneering effort, corn consumptive water use (ET) was monitored using the state-of-the-science EC instrumentation. In the region's humid climate, the measured corn ET did not differ appreciably across the three irrigation treatments. In the SFI, the average corn harvested was ∼4.3% higher than FI. Grain yield harvested in the RF was ∼13.7% lower than the FI, emphasizing the importance of irrigating corn in the region for stabilizing yield returns for farmers. The farm-scale study reported in this paper confirmed that switching from FI to SFI in corn cropping systems on clay soil in the LMD region can reduce water use by ∼40% without compromising WUE and grain yields. Therefore, based on the results obtained in this study, we recommend switching from FI and RF to SFI for better water conservation and yield returns in irrigated corn production systems in clay soils in this region.

ACKNOWLEDGMENTS

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

AUTHOR CONTRIBUTIONS

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

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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How to cite this article: Anapalli, S. S., Pinnamaneni, S. R., Reddy, K. N., & Singh, G. (2022). Eddy covariance quantification of corn water use and yield responses to irrigations on farm-scale fields. *Agronomy Journal*, *114,* 2445–2457. https://doi.org/10.1002/agj2.21130