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Quantifying evapotranspiration and crop coefficients for cotton (*Gossypium hirsutum* L.) using an eddy covariance approach

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ABSTRACT

Accurate quantification of consumptive water requirements (ET_c, evapotranspiration) of cropping systems is a critical prerequisite for sustainable irrigation water management applications. For applying the ET_c for irrigation scheduling across soils and climates other than the location in which it was measured, it is also critical to develop crop coefficients (K_c) that link a reference crop evapotranspiration computed from local weather data to ET_c. A systematic study for deriving K_c for cotton (*Gossypium hirsutum* L.) - representing its growth stages from planting to harvest - in humid climates is lacking in the literature. In this study, we used an eddy covariance (EC) method to quantify ET_c from irrigated cotton (*Gossypium hirsutum* L.) in a 250 ha field with a Tunica clay soil, in 2017 and 2018. In the EC experiment, an open-path infrared gas analyzer and a sonic 3-D anemometer were deployed in the constant flux layer above the cotton canopy for collecting crop-canopy water flux data. Using the measured ET_c, K_c were derived for alfalfa (K_{cr}) and grass (K_{co}) reference crop ET computed from weather data. Cotton cv. Delta Pine Land 1522 was planted in the first week of May and harvested in the second week of September in both the years. Lint yield was 1269 kg ha^{-1} in 2017 and 1569 kg ha^{-1} in 2018. Measured monthly averaged daily ET_c ranged between 2.5 mm in May/September to 4 mm in July in 2017, and between 2.9 mm in May and 4.4 mm in August in 2018. Maximum daily ET_c in 2017 and 2018 crop seasons were 5.6 and 6.7 mm, respectively. Seasonal total ET_c was 367 mm and 439 mm (on average 402 mm), respectively. Alfalfa (ET_r) and grass reference crop ET (ET_o) computed were 664 and 546 mm, respectively. Averaged across the two years, average daily K_{cr} ranged between 0.45 in May to 0.80 in August, and K_{co} ranged from 0.54 in May and 0.99 in August. On average, seasonal ET_r was 18 % more than ET_o. Seasonal ET_r and ET_o were, respectively, 39 % and 22 % more than ET_c. The K_c data developed will be useful for irrigation scheduling in cotton grown in similar climates and soils.

1. Introduction

Currently, more than 80–90 % of the freshwater resources available globally is used for irrigating crops for producing food, fiber, and energy for the burgeoning population (FAOSTAT, 2006; Morison et al., 2008; Wada and Bierkens, 2014). Groundwater withdrawals from aquifers for crop irrigations above their natural recharge capacities lead to aquifer declines that are threatening the sustainability of irrigated agriculture across the globe (Gleick, 1993; de Fraiture and Wichelns, 2010; Dalin et al., 2017). The ongoing pressure on agriculture for more food production calls for more judicial use of the limited ground water resources available for irrigations (Bruinsma, 2003; Rijsberman, 2006; Saseendran et al., 2014a, b, 2015; Distefano and Kelly, 2017). In this evolving scenario, for enhancing water productivity in irrigated agriculture, it is critical that irrigation we apply is based on accurate information on location-specific ET_c demands (Shiklomanov, 2000). The ET_c at specific locations is dynamic and depends mainly on the weather, crop type and variety, and soil properties among many other crop characteristics (Farahani et al., 2008; Li et al., 2008; Irmak et al., 2012, 2013, 2014; Anapalli et al., 2018b, 2019).

When crop growth and productivity mainly depend on the water available for meeting their ET_c demands, about 1% of the water absorbed by the plant from the soil is only used in its metabolic activities (Rosenberg et al., 1983; Allen et al., 1998; Morison et al., 2008). Most of the water absorbed gets evaporated from plant-soil-residue surfaces by absorbing heat from the surroundings (the latent heat of evaporation), thereby indirectly cooling the crop-environment to safe limits within which most of the metabolic activities take place. The crop

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environmental demand for water for meeting this ET demand is normally quantified at a potential rate of ET demand of the atmosphere (potential evapotranspiration, PET) and calculated from weather data (Penman, 1948). The PET definition assumes a crop that does not exert any resistance to water flow from the soil-crop canopy surface, that is, evaporation of water is only limited by the energy available for converting the state of water from liquid to vapor. However, in nature, many crop-environmental factors resist water loss at PET rate through plant stomatal control and other soil-residue related resistances to evaporation losses, so the concept of PET by itself restricts its applications in estimating ET_c or irrigation water requirements.

For calculations of PET, Monteith (1965) offered a single layer – an extended grass covered soil – Penman-Monteith (P-M) combination equation. This concept was extended to partial canopy-soil by Shuttleworth and Wallace (S-W) (1985), further extended to include the effects of surface residue on soil evaporation by Farahani and Ahuja (1996). Calculation of PET, for a crop in a natural environment, by means of the original P-M and the S-W equations, requires crop growth information on a daily or hourly basis, besides the weather data, to compute aerodynamic and canopy resistances. The values of these resistances differ with the plant species, varieties, and cultivars; climate, soil water, and nutrient status; and crop-management practices that are difficult to quantify accurately for water management applications. Therefore, for irrigation water management, Doorenbos and Pruit (1977) offered a two-step approach to ET_c: ET is initially calculated for a single reference crop (ET_{ref}) - a hypothetical crop - with known canopy-soil resistances and then modified with experimentally (real-world) obtained crop coefficients (K_c) to estimate ET_c of the crop of interest

$$Kc = \frac{ETc}{ET\text{ref}} \tag{1}$$

Allen et al. (1998) standardized the computation of a hypothetical grass reference crop, $ET_{o,}$ defined with given soil-plant-aerodynamic resistances and published K_{co} for a variety of field and tree crops. Fully irrigated short grass (0.12 m tall), K_{co} and alfalfa (0.50 m tall), K_{cr}, with full canopy cover are two mainly accepted reference crops. The ASCE-EWRI (2005) presented ET_r computation methods and K_c values for a variety of plants and conditions. When Allen et al. (1998) provide K_{co} for many crops, including cotton, those values were reported to be inadequate in calculating optimum irrigation water requirements for optimum crop production: Irmak et al. (2013) reported significant differences between the Allen et al. (1998) and measured K_{co} using lysimeters for soybean in south-central Nebraska's soil, climate, and management practices; In a lysimetric study with cotton in the Mediterranean region of Northern Syria, Farahani et al. (2008) reported 24 % lower mid-season cotton K_{co} than Allen et al. (1998) tabulated values; in various studies using either EC or lysimeters with various field crops, Karam et al. (2007); Farg et al. (2012); Payero and Irmak (2013), and Sánchez et al. (2015) also reported significantly lower K_{co} in experiments, compared to Allen et al. (1998), in various climates across the world. Considering these findings, we conclude that, in general, there is a need for developing location specific, crop-soil-climate specific K_c for crops and their cultivars for limited irrigation water management.

For limited water irrigation management in water scarce environments, Allen et al. (1998) also proposed a dual K_c approach for ET_c estimation - a basal crop coefficient (K_{cb}) representing the plant-transpiration contribution to ET_c and a K_s representing the soil surface evaporation during the initial growth of a crop with partial canopy covered dry soil surfaces. However, in the humid climate of the Mississippi Delta, with plenty of spring rainfall during the initial growth period of the crop, plant growth is not normally affected by dry soil surface, so a single K_c is still preferred for optimum growth benefits of the crops (Anapalli et al., 2016a, b).

For quantifying ET exchanges from cropping systems and computing K_c of crops, the eddy covariance (EC) is a cutting-edge, sound micrometeorological theory-based method (Parent and Anctil, 2012; Shurpali et al., 2013; Tallec et al., 2013; Uddin et al., 2013; Baldocchi, 2003; Anapalli et al., 2018a, 2018b, 2019). In the EC method, normally, net ecosystem exchanges of CO_2 (NEE) and water vapor (ET) are estimated by tracking and measuring the turbulent transport of eddies carrying CO_2 and water vapor in the plant canopy boundary layer of the atmosphere. Numerous methods with varying complexity were reported in the literature for quantifying ET: field lysimeters, Bowen ratio modeling, water balance, residual energy balance, and EC (Wilson et al., 2001; Anapalli et al., 2018a, b, 2019). Among these methods, with the current efficient and cost-effective electronic technologies available for frequent crop-soil-water-air data collection, storage, onsite-computing, and communication, the EC method emerged a scientifically sound and easy to install and maintain technology for quantifying ET in cropping systems.

An important agricultural production region in the USA, the Mississippi (MS) Delta, uses groundwater from the MS River Valley Alluvial Aquifer (MSRVAA) for meeting its irrigation water needs (Heatherly, 2014; Powers, 2007). Typically, over 60 % of all the crops grown in this region are irrigated. Currently, water is drawn from the thin MSRVAA, outside its natural recharge capacities, resulting in significant aquifer depletions, threatening the sustainability of irrigated agriculture in this region (Clark and Hart, 2009: Runkle et al., 2017). Developing and disseminating irrigation schedules based on location-specific crop ET_c demands and water supply scenarios can help in conserving the MSRVAA for sustainable irrigated agricultural production (Anapalli et al., 2018a. 2018b).

In this study, we quantified ET_c of cotton using an EC approach and then used that information for developing K_c for Allen et al. (1998) grass and ASCE-EWRI (2005) alfalfa reference crop ET data.

2. Materials and methods

2.1. Cotton experiment

The experiments for this study were conducted in 2017 and 2018 on a commercial producer's 250-ha field located about 1 km from the USDA Agricultural Research Service Crop Production Systems Research Unit's farm at Stoneville, Mississippi, USA (33° 42′ N, 90° 55′ W, ∼32 m elevation above sea level). The data collected in 2017 in this study had been used by Anapalli et al. (2019) for comparing water use efficiencies of Soybean and corn with those of cotton. In this study, we used the data collected during both 2017 and 2018 for developing an average crop Kc for cotton for irrigation scheduling applications. The soil type was a Tunica clay (clayey over loamy, montmorillonitic, non-acid, thermic Vertic Halaquepet) with a depth of about 1.2 m and land-formed to maintain a 1% slope. The field was tilled at least three times per season to break clay pans, bury crop residue, and kill weeds. This was followed by another tillage operation to form ridges for planting crops and furrows to facilitate furrow irrigations. In both 2017 and 2018, cotton cv. 'Delta Pine Land 152' was planted at an average density of 103,740 seeds per ha on ridges with a 77-cm row spacing. The crop was planted on May 2, 2017, and May 10, 2018, and fertilizer was applied at a rate of 140 kg N ha^{-1}. As needed in the region, the plant growth regulator Mepiquat chloride was applied 3–4 times per year after the First Square growth-stage to control plant height and excessive vegetative growth. The site is characterized by a sub-tropical humid climate with warm summers and mild winters, receiving on average about 1300 mm yr^{-1} of rainfall. May to August is the core cotton-growing season during which, on average, about 30 % (390 mm) of the annual rainfall was received (Anapalli et al., 2016a, 2016b).

The crops were furrow irrigated, with water delivered through polyethylene pipes at the top of the furrows. Roughly 30 mm of water was provided at each irrigation event. Irrigations were scheduled based on soil water content, applied when plant available water in the soil fell

Table 1
Observed major phenological growth stages of cotton in 2017 and 2018. DAE is the days after emergence. DOY is the day of the year.

Phenological growth stages	2017			2018		
	Day	DOY	DAE	Day	DOY	DAE
Planting	May 2	122	–	May 10	130	–
Emergence	May 14	134	0	May 19	139	0
First square	June 20	170	36	June 22	167	33
First flower	July 12	193	59	July 15	191	57
First boll	July 30	211	77	August 5	212	78
Open boll	Aug. 28	240	106	Aug 30	234	100
Harvest	Sept. 23	266	132	Sept 26	263	129

below about 60 % of its maximum value as measured. Three irrigations each occurred in both 2017 and 2018 resulting in a seasonal total of 90 mm of water each year. Plant heights were monitored every week for positioning the flux senors constantly in the constant flux layer (turbulance) above the plant canopy. Leaf area index (LAI) was measured every other week using an AccuPAR LP-80 Ceptometer (Decagon Devices Inc., Pullman, WA USA). Cotton phenological growth stages were recorded following Oosterhuis (1990) (Table 1). Being an indeterminate plant species, phenological stages of cotton often overlapped, so each phenological stage was measured when roughly 50 % of the plants exceeded that particular stage, irrespective of many plants have already reached the next stage. Crops were harvested 26 and 29 days after open boll stage, respectively, in 2017 and 2018. All crop-growth measurements were repeated over 15–20 random locations across the fields. Seed cotton was harvested using 12-row, mechanical cotton pickers.

2.2. Eddy covariance quantification of ET_c

In the EC measurements, speed of vertical eddy transport and sonic temperature were measured using a Gill New Wind Master sonic anemometer (Gill Instruments, Lymington, UK) and vapor density in the eddies using a LI-7500-RS open-path infrared gas analyzer (IRGA; LI-

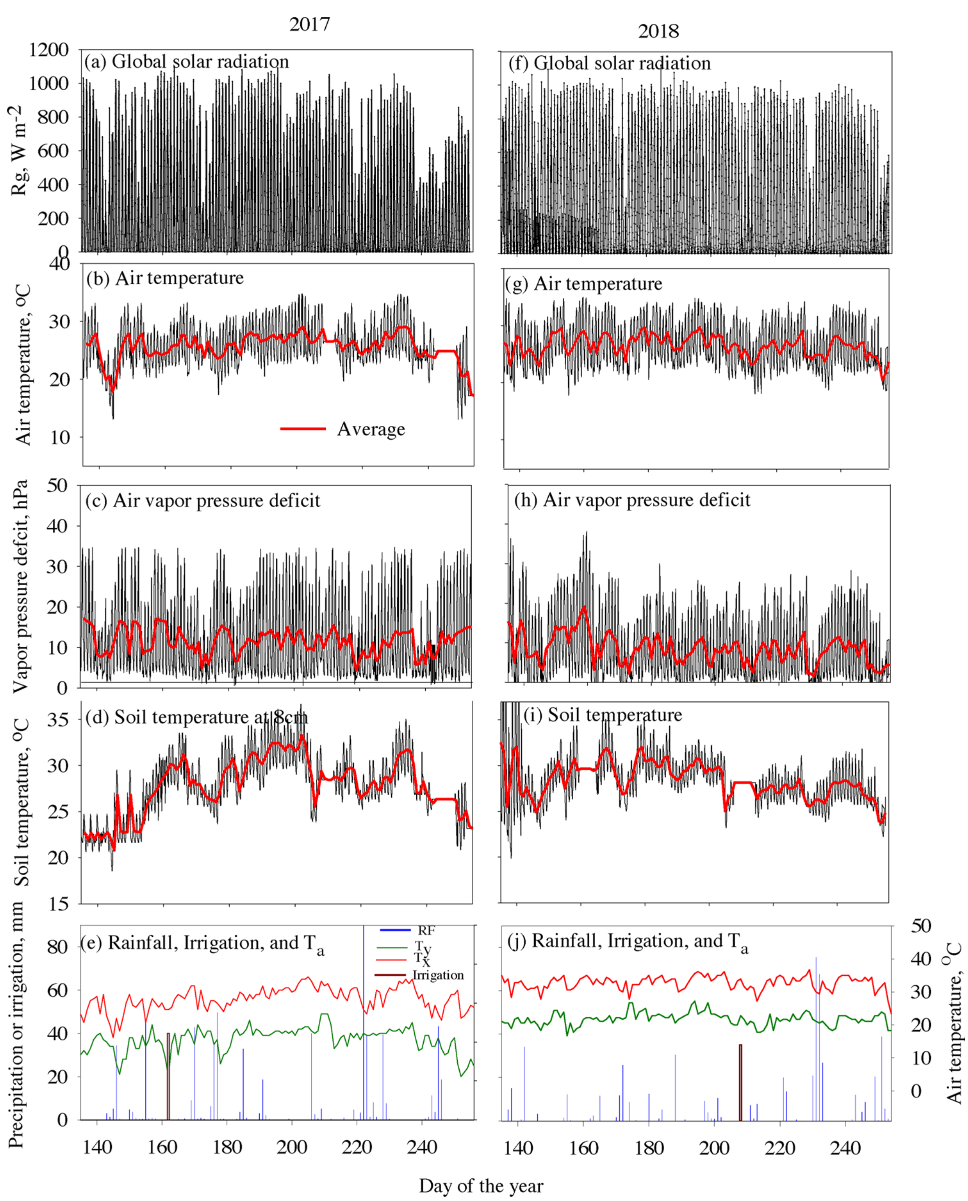

Fig. 1. Measured global solar radiation, maximum and minimum air temperatures, air vapor pressure deficit (VPD), soil temperature at 8 cm depth, rainfall, and irrigations during the growing seasons in 2017 and 2018. T_x and T_y represent maximum and minimum air temperatures, respectively. T_a represent is air temperature, RF represent rainfall.

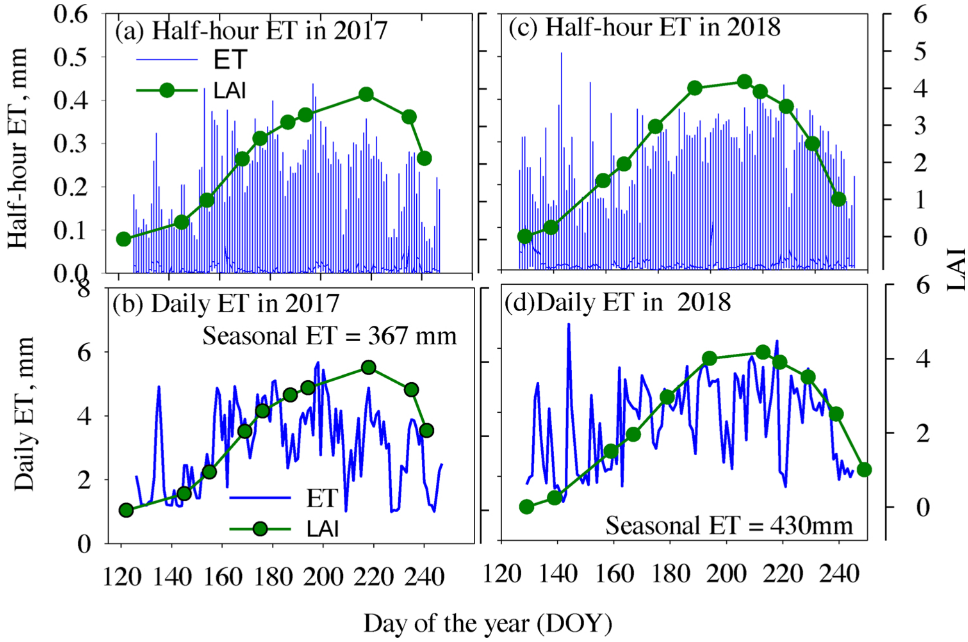

Fig. 2. LAI measured during the crop season (lines with dark circles in panels a-d) and ET measured using eddy covariance method (a) half hourly in 2017 (Anapalli et al., 2019, with permission to reproduce), (b) half hourly in 2018, (c) daily in 2017 (Anapalli et al., 2019, with permission to reproduce), and (d) daily in 2018.

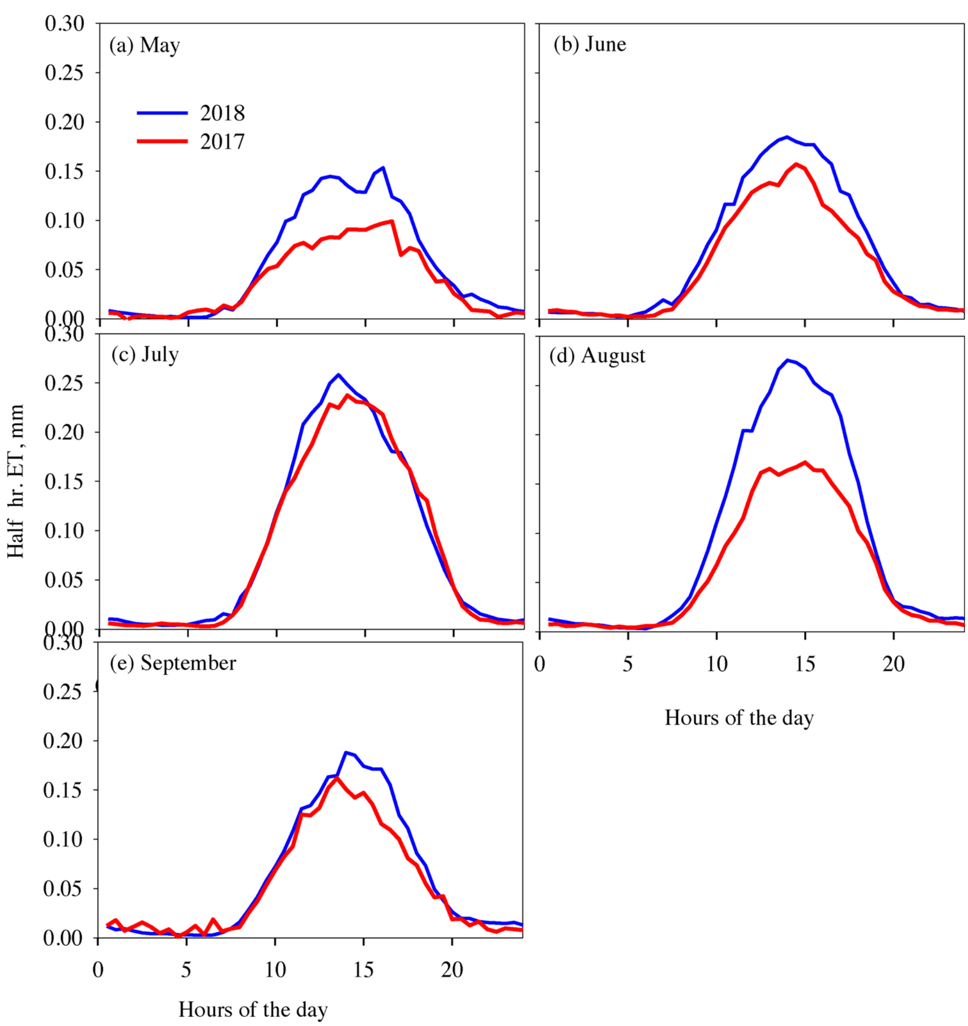

Fig. 3. Comparison between diurnal patterns of half hourly values of eddy covariance ETc in May, June, July, August, and September in 2017 and 2018.

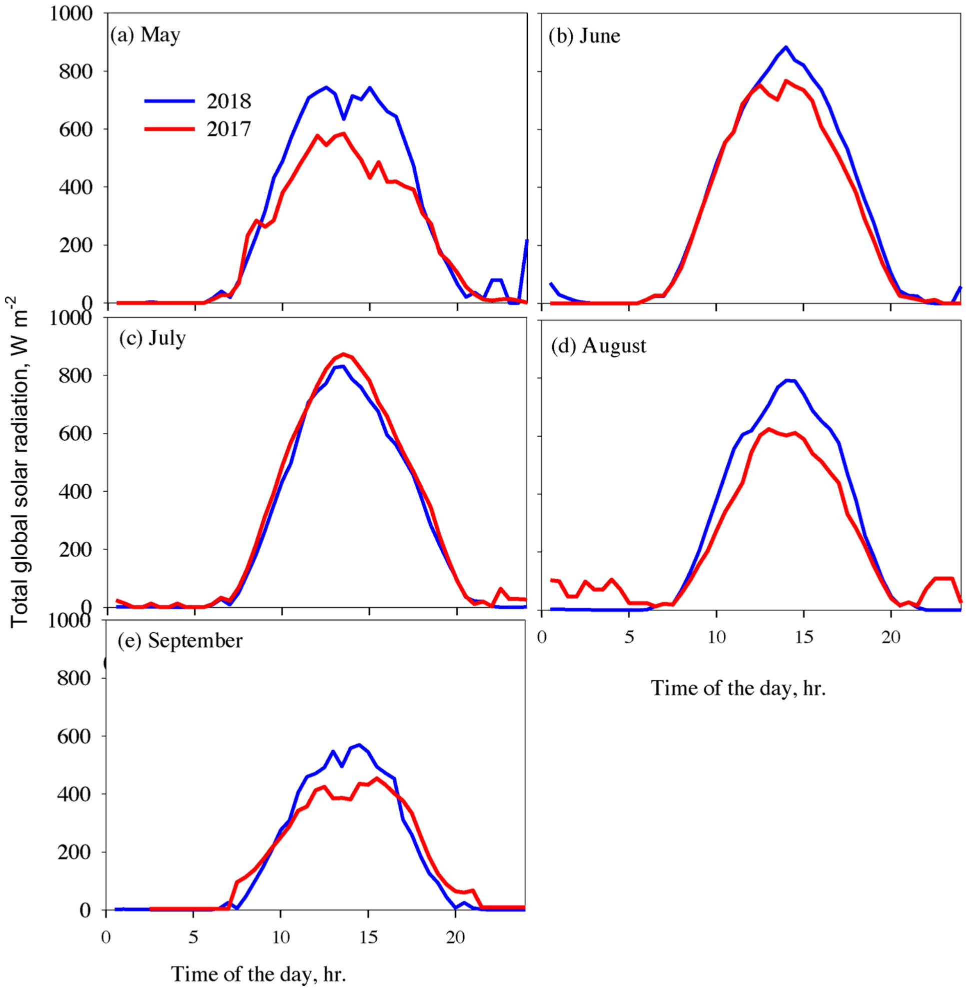

Fig. 4. Comparison of diurnal patterns of half hour averaged total global solar radiation in the months of May, June, July, August, and September (panels a-e) in 2017 and 2018.

COR Inc., NE USA), and recorded at 10 Hz on a LiCOR data logger. These sensors were mounted on a telescopic, height-adjustable tower (EC tower), and the sensor height was constantly maintained at twice the canopy height above the plant canopy, starting at an initial height of 1.2 m above ground at planting: this arrangement allowed us to maintain the EC sensors constantly in the constant-flux layer above the plant canopy, which was assumed to occur at about twice the crop height above the plant canopy (Burba and Anderson, 2005). The EC tower was established in the middle of the 250 ha cotton field, with less than 1% slope, resulting in the fetch of the sensors on the towers to be over 200 m in all directions.

The eddy flux data collected were processed using the EddyPro v 6.1.0 (LI-COR Inc., Lincoln, NE USA) software. The output of the EddyPro software runs and micrometeorological data collected were averaged or accumulated at 30-min intervals. These flux outputs carried quality-flags between 0 (highest quality) and 2 (lowest quality). Flux data with a quality flag of 2 and statistical outliers beyond ±3.5 standard deviations based on a 14-day running window were removed from further analysis (Wagle and Kakani, 2014; Anapalli et al., 2019). Also, latent heat (LE) and sensible heat (H) fluxes were cleaned to limit them within the reliable range from −200 to 800 W m^{-2} and −200 to 500 W m^{-2}, respectively (Anapalli et al., 2018b; Wagle et al., 2015; Sun et al., 2010). The gaps in the flux and micrometeorological data were filled using the REddyProc package available online from the Max Planck Institute for Biogeochemistry (https://www.bgcjena.mpg.de/bgi/index.php/Services/REddyProcWebRPackage). In brief, the gap filling using this package considered methods similar to Falge et al. (2001) but also considered the co-variation of fluxes with meteorological variables and the temporal auto-correlation of the fluxes (Reichstein et al., 2005). For identifying the path for analysis, three different conditions were identified: 1) Rg is missing, 2) Ta or VPD are missing, but Rg is available, 3) only the data of direct interest is missing, but the meteorological data are available for total solar radiation (Rg), air temperature (Ta), and vapor pressure deficit (VPD). Case 1): The missing value is replaced by the average value under similar meteorological conditions, i.e., with a look-up table (LUT), within a certain time window. Similar meteorological conditions are present when Rg does not deviate by more than 50 W m^{-2}, Ta by 2.5 °C, and VPD by 5.0 hPa. If no similar meteorological conditions are present within the starting time window of 7 days, the size of the window is increased to 14 days. Case 2): The same LUT approach is taken, but similar meteorological conditions can only be defined via Rg within a time window of 7 days. Case 3): The missing value is replaced by the average value at the same time of the day (1 h), i.e., by the mean diurnal course (MDC). In this case, the window size starts on the same day, thus it is a linear interpolation of available data at adjacent hours. If after these steps the values could not be filled, the procedure is repeated with increased window sizes until the value can be filled. In this study, we have first calculated half-hourly data from the above processed LE fluxes (Latent heat Energy) using latent heat of evaporation corrected for air temperature to compute ETc.

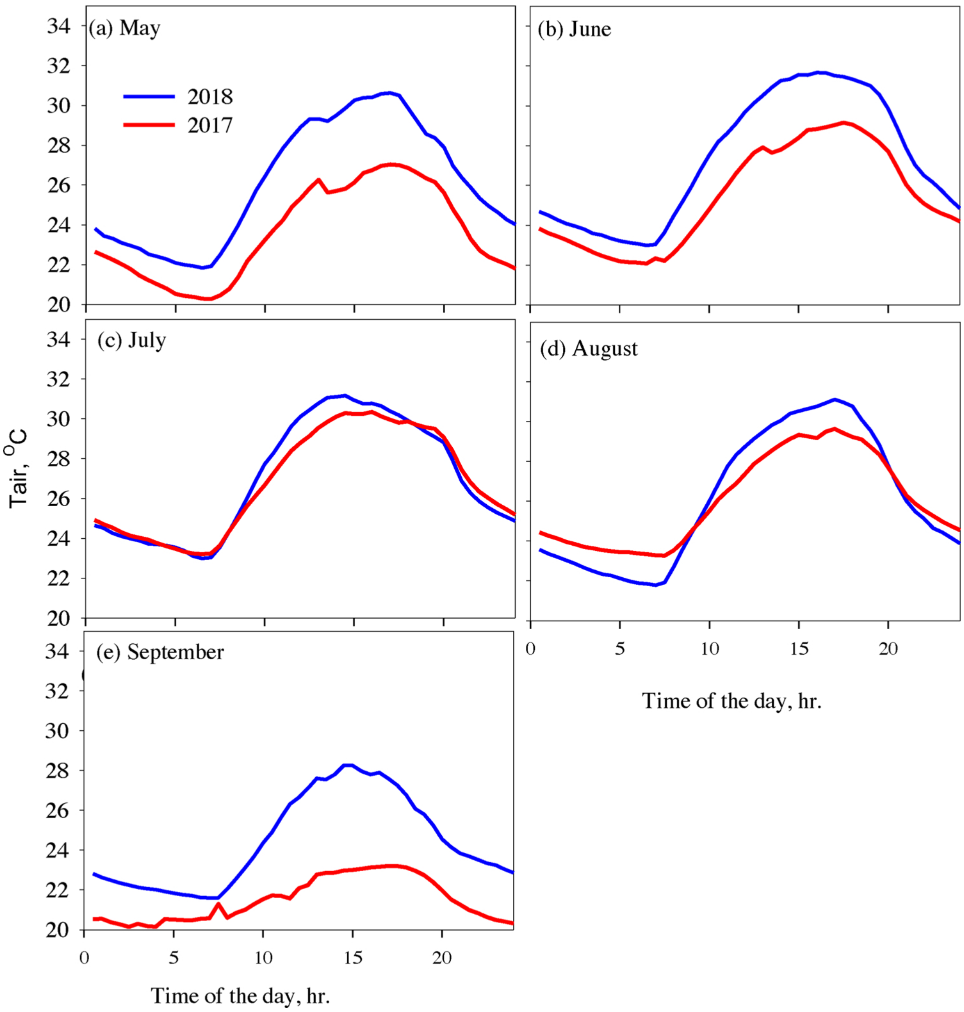

Fig. 5. Comparison between diurnal patterns of half hour average air temperatre (Tair) in May, June, July, August, and September (panels a-e) in 2017 and 2018.

2.3. Micrometeorological measurements

For use in the analysis, interpretation, and data-gap filling flux data, ancillary data related to the crop canopy micrometerological processes were also collected: air temperature (Ta) and relative humidity (HMP 155, Vaisala, Helsinki, Finland); net solar radiation (NR-LITE2, Kipp & Zonen B.V., Delft, The Netherlands), soil heat flux using six self-calibrating soil heat flux plates (HP01SC, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) at 8-cm below the soil surface; soil water content and temperature in the 8-cm soil layer above the heat flux plates using Stevens HydraProbe (Stevens Water Monitoring Systems, Inc., Portland, OR USA), precipitation using a tipping bucket rain gauge (TR 525, Texas Electronics, Dallas, TX USA). These instruments other than soil sensors were maintained at 2 m above the crop canopy along with the EC sensors. Data were sampled at 1-minute intervals and were averaged every thirty minutes and used in the analysis.

2.4. Alfalfa and Grass reference crop ET and K_c

K_c for cotton was computed using Eq. (1). The daily ET_o and ET_r were computed using the Allen et al. (1998) and ASCE-EWRI (2005) computation procedures, respectively. Weather data collected at 2-m height from a standard weather station, maintained by the Mississippi State University, within 1 km from the experiment location were used for estimating ET_o and ET_r and K_c. Half-hour ET_c from the EC system was accumulated over a 24 -h period for use in the calculation of daily K_c values.

3. Results and discussion

3.1. Weather

In crop fields, about 99 % of the water taken up by plant roots is lost to the air as water vapor through the stomatal opening in the plant epidermal cells, the process known as transpiration. Water is also lost due to direct evaporation from soil, residue, and plant surfaces, and the combined loss of water to air from a crop-soil-residue system is termed ET (Rosenberg et al., 1983; Allen et al., 1998; Morison et al., 2008; Farahani et al., 2008; Irmak et al., 2014). Hence, the rate and amount of loss of water from a cropping system (ET_c) depends on the physical state of the atmosphere (weather) defined, mainly, in terms of solar radiation (Rs), air temperature (Ta), air vapor pressure deficit (VPD), soil temperature (Ts), and water availability in terms of rainfall and irrigation water applied (Fig. 1). In addition to the genetic traits of the crop varieties planted, all realized weather in the field during the crop growth season determines the crop growth and yield. During the cotton growing season in 2017, half-hr average global solar radiation (Rg) ranged from 1120 W m^{-2} in July to 298 W m^{-2} in August (Fig. 1a). In September 2018, they ranged between 1116 W m^{-2} in July to 252 W m^{-2} (Fig. 1f).

In 2017, Ta increased from 26 °C at planting in May to 29 °C in August, declining to 17 °C at harvest in September (Fig. 1b). A cold wave in the second week of May brought Ta down to 13 °C, the spell lasted about a week. In 2018, Ta recorded at the experiment site was 28 °C at planting in May, which increased to 30 °C in August and further

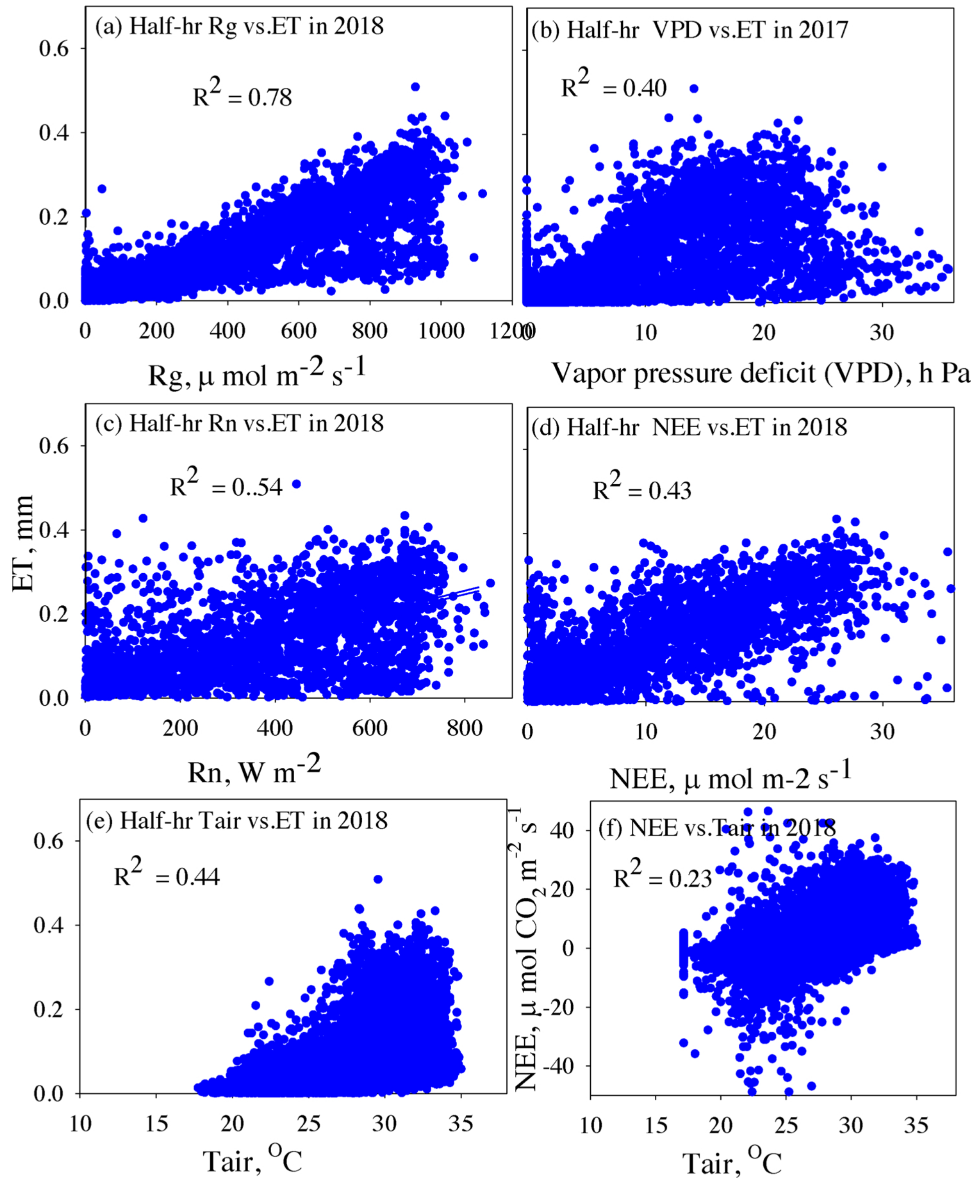

Fig. 6. Extent of variations in eddy covariance measured half hourly ET explained by the measured variations in (a) Total global solar radiation, Rg, (b) air vapor pressure deficit, VPD, (c) net solar radiation, Rn, (d) net ecosystem exchange of CO_2, NEE, and (e) air temperature, Tair in 2017. The extent of variations in net ecosystem exchange explained by variations in Tair is also provided in (f).

declined to 24 °C at harvest in September (Fig. 1g). In 2017, daily maximum Ta (Tx) varied from 32 °C in May to a seasonal maximum value of 35 °C in August and 29 °C at harvest in September. Daily Tx in 2018 ranged from 32 °C in May to the seasonal maximum of 36 °C in July, which went down to 24 °C at harvest. Half-hour average maximum daily air VPD during the growing season in 2017 varied between 11–34 hPa (Fig. 1c). In 2018, half hour average VPD varied between 9–38 hPa during the crop season (Fig. 1h). The temperature at 8 cm soil-depth increased from 24 °C to 36 °C in August and decreased to 27 °C at harvest in September (Fig. 1d, i). Rainfall received during the crop growth period in 2017 (132 days from May 2 to September 23) and 2018 (129 days from May 10 to September 23) were 719 mm and 542 mm, respectively (Fig. 1e, j). These rainfalls were fairly uniform through the crop growing period, enabling the crop to grow without substantial water stress by providing just 30 mm irrigation, three times in each of the two years. The number of rainy days during the crop growth period in 2017 was 63 days and in 2018 was 49 days.

3.2. Cotton performance in the experiments

Cotton seeds were sown on May 2 in 2017 and May 10 in 2018, and both these days were preceded with enough rainfall, 78 mm in the 2-week period before planting in 2017 and 113 mm in 2-week period in 2018, for the seeds to imbibe sufficient moisture, sprout, and emerge from the soil and establish fairly uniform crop stands, thereby establishing a uniform crop-stand across the fetch area for the EC flux instruments (Anapalli et al., 2018b, 2019; Burba and Anderson, 2005; Foken, 2008). Cotton seeds emerged from the soil after 12 days in 2017 and after 9 days in 2018 (Table 1). The three-day delay for seedling emergence in 2017 was due to lower soil temperatures (22 °C) at sowing compared to 2018 (28 °C), measured at 8-cm soil depth. The plants reached the first square, first flower, first boll, and first cracked-open boll in 36, 59, 77, and 106 days after emergence (DAE) in 2017, and 33, 57, 78, and 100 DAE in 2018. These phenological stages within a season, in both the years, exhibited considerable overlap with each other, owing to the indeterminate growth habits of the cotton plants. However, all the stages were recorded only when at least 50 % of the

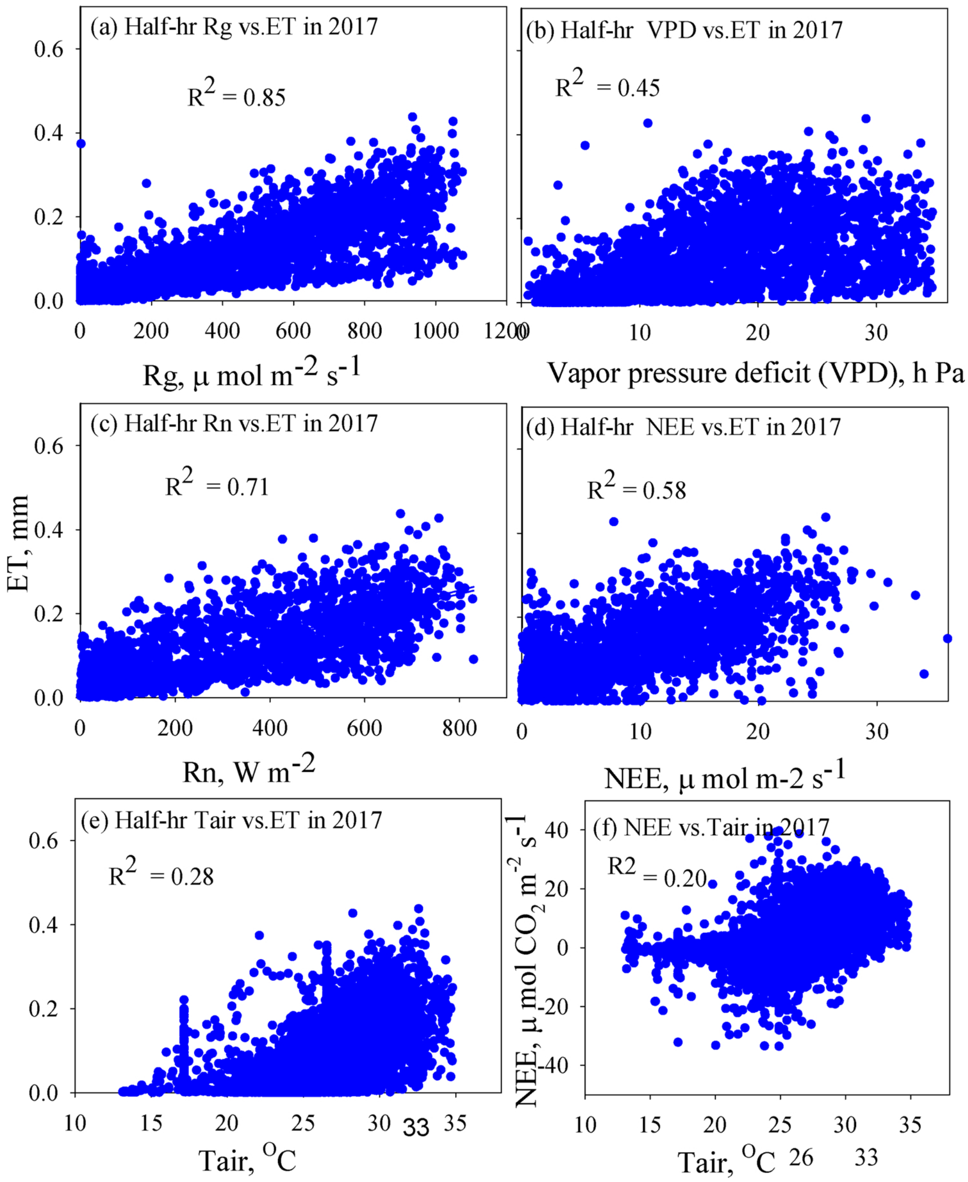

Fig. 7. Extent of variations in eddy covariance measured half hourly ET explained by the measured variations in (a) Total global solar radiation, Rg, (b) air vapor pressure deficit, VPD, (c) net solar radiation, Rn, (d) net ecosystem exchange of CO_2, NEE, and (e) air temperature, Tair in 2018. The extent of variations in net ecosystem exchange explained by variations in Tair is also provided in (f).

Table 2
Monthly averaged daily evapotranspiration (ET), seasonally averaged daily ET, and seasonal total ET measured using the EC method, and weather-based ET computed for alfalfa (ET_r) and grass (ET_o) reference crops in 2017 and 2018.

ET method	Monthly averaged daily evapotranspiration mm					Seasonal averaged ET, mm	Seasonal total ET, mm
	May	June	July	Aug	Sept.		
			2017				
Average ET_c	2.5	2.9	4.0	2.9	2.5	3.0	367
Average ET_r	5.3	5.5	5.8	4.8	5.4	5.4	649
Average ET_o	4.2	4.5	4.9	3.9	4.4	4.4	530
			2018				
Average ET_c	2.3	3.2	4.1	4.4	3.1	3.4	430
Average ET_r	5.7	6.0	5.6	5.5	4.6	5.5	678
Average ET_o	4.7	5.1	4.7	4.5	3.7	4.5	562
			Average				
Average ET_c	2.4	3.1	4.1	3.7	2.8	3.2	402
Average ET_r	5.5	5.75	5.7	5.2	5.0	5.5	664
Average ET_o	4.45	4.8	4.8	4.2	4.1	4.5	546

Table 3
Comparison between average daily and seasonal evapotranspiration (ET_c) measured in 2017 and 2018, using the eddy covariance technique and evapotranspiration computed from weather data for alfalfa (ET_r) and grass (ET_o) reference crops, and crop coefficients for alfalfa (K_{cr}) and grass (K_{co}) reference crops.

Comparisons based on average monthly or seasonal values	May	June	July	Aug.	September	Seasonal
	Relative differences, %					
			2017			
$(ET_r-ET_c)/ET_c*100$	53	47	31	40	54	44
$(ET_o-ET_c)/ET_c*100$	68	55	23	34	76	25
$(ET_r-ET_o)/ET_o*100$	26	22	18	23	23	18
$(K_{cr}-K_{co})/K_{co}*100$	16	17	16	21	22	18
			2018			
$(ET_r-ET_c)/ET_c*100$	60	47	27	20	33	35
$(ET_o-ET_c)/ET_c*100$	42	32	11	2	13	18
$(ET_r-ET_o)/ET_o*100$	18	15	16	18	20	17
$(K_{cr}-K_{co})/K_{co}*100$	18	17	18	18	20	18
			Average			
$(ET_r-ET_c)/ET_c*100$	56	47	29	29	44	39
$(ET_o-ET_c)/ET_c*100$	37	30	13	11	25	22
$(ET_r-ET_o)/ET_o*100$	19	17	16	18	19	18
$(K_{cr}-K_{co})/K_{co}*100$	17	17	17	20	21	18

Table 4
Monthly and seasonally averaged daily crop coefficients computed for alfalfa (K_{cr}) and grass (K_{co}) reference crops in 2017 and 2018.

Crop coefficient	Monthly averaged daily crop coefficients (K_c)					
	May	June	July	August	September	Seasonal average
			2017			
Average K_{cr}	0.47	0.55	0.71	0.70	0.59	0.63
Average $_{Kco}$	0.56	0.66	0.85	0.89	0.76	0.77
			2018			
Average K_{cr}	0.42	0.55	0.74	0.81	0.70	0.60
Average $_{Kco}$	0.51	0.66	0.90	0.99	0.87	0.81
			Average			
Average K_{cr}	0.45	0.55	0.73	0.76	0.65	0.62
Average K_{co}	0.54	0.66	0.88	0.94	0.82	0.79

plants exceeded that stage from visual observation. Crops were harvested on 132 and 129 DAE in 2017 and 2018, respectively. Harvested cotton lint yield in 2017 was 1269 kg ha^{-1} and in 2018 was 1569 kg ha^{-1}. Maximum LAI measured was 3.9 and 4.1 in 2017 and 2018, respectively, at around the first flower stage (Fig. 2). However, these LAI measurements did not reflect the growth potential of the cotton variety used in both the years for, as practiced in the region, the plant growth regulator Mepiquat chloride was applied to stimulate boll formation by controlling biomass spent on increasing plant height and excessive vegetative growth; it was applied when the crop reached around LAI 2.5 that coincide with the first-flower stage of the crop.

3.3. Checking energy balance closure (EBC) in the flux measurements

The EC method has hitherto achieved wide acceptance as a cutting-edge science-based method for quantifying mass, energy, and momentum transfer between the soil-plant canopies and the atmosphere (Foken et al., 2006; Mauder et al., 2007). In the EC system, ET is quantified by measuring the covariance between the speed of vertical eddy transport within the horizontal wind-flow and the water vapor density in the eddy-air stream. A considerable amount of computing and modeling is required for solving the EC theory for quantifying ET. So, in order to have confidence in the derived flux data, it is important to check if the energy fluxes out of the system balance the heat inputs into the system, known as EBC. We computed the EBC using a linear regression between half-hourly heat input, $R_n - G_o - S_{bm} - S_{ph}$, and turbulent out-fluxes, H + LE, at 30-minute intervals, where R_n is net solar radiation, G_o is soil heat flux, and S_{bm} and S_{ph} are energy stored in the biomass and energy used in photosynthesis, respectively (Liu et al., 2017; Gao et al., 2017; Anapalli et al., 2018a, 2019). These terms were computed following Anapalli et al. (2018b, 2019). The EBC obtained in 2017 and 2018, respectively, were 84 % and 76 % (slope of the regression line between energy inputs and outputs expressed as percentages). EBC reported in the literature differed considerably between studies, and varied from 70 to 100 % (Gao et al., 2017; Leuning et al., 2012; Anderson and Wang, 2014; Liu et al., 2017). Many attempts to close the energy balance did not result in a complete EBC. From an analysis of data from sugarcane fields in Hawaii, USA, Anderson and Wang (2004) reported better EBC between 90 and 92 %, when computed on a daily basis. Following this procedure, we arrived at EBC of 92 and 89 %, respectively, in 2017 and 2018. EBC at 92 and 89 % in 2017 and 2018 show that the cotton ET estimated in this study can potentially have errors between 8 and 11 %.

3.4. Diurnal variations in ET_c

Diurnal patterns of ET_c in both 2017 and 2018 were similar to the measured diurnal patterns of Rg (Figs. 3, 4). In general, evaporative loss of water started around sunrise (about 6:00 AM), peaked between 1 and 2 PM, and then deceased to near zero values after sunset at around 8:00 PM (Fig. 3). The highest value of ET_c was observed in July when crop growth also was highest, as reflected in higher measured LAI (Fig. 2): in both 2017 and 2018, LAI measured in July and August were above 3.5 (Fig. 2). Measured Rg in July was around 880 W m^{-2} in both years (Fig. 4). In 2018, peak Rg measured was slightly higher at 890 W m^{-2}. In general, ET_c in 2018 was higher than in 2017, though the LAI measured showed slightly lower values in 2018 (Fig. 2). This enhanced ET_c in 2018 appears more due to increased Rg received at the crop surface, possibly owing to occurrences of lesser cloud cover in the sky compared to 2017 or some other factors not measured in this experiment. This enhanced ET_c cannot be attributed to enhanced LAI in 2018 (Fig. 2). Compared to 2017, the measured enhanced ET_c in 2018 was well reflected in the enhanced air temperatures (Fig. 5). Daily peak values of monthly averaged diurnal ET_c were 0.10, 0.16, 0.24, 0.17, and 0.16 mm per half-hour in the months of May, June, July, August, and September, respectively, in 2017, and 0.14, 018, 0.25, 0.28, 0.19 mm per half-hour in 2018 (Fig. 2 a, c; 3).

3.5. ET_c at daily to seasonal scales

Measured ET_c exhibited a high amount of variations across days during the crop seasons in both 2017 and 2018 (Fig. 2). These day-to-day variations in the amount of ET_c were mainly due to the realized within-season weather variabilities (Fig. 1). Another important factor causing these variations was the frequent rainfall and subsequent soil wetting and drying cycles (Figs. 1e, j; 2 b, d). In both years, half-hourly ET_c time-series showed highest correlation with Rg (R^2 = 0.85 in 2017 and 0.78 in 2018) and least correlation with Tair (R^2 = 0.28 in 2017 and 0.44 in 2018) (Figs. 6, 7).

In 2017, monthly averaged daily ET_c values ranged between 2.5 mm in May and 4.0 mm in July. Average daily ET_c during the whole crop-growth period was 3.0 mm (Table 2). Measured ET_c in both June and August was 2.9 mm. These variations in ET_c were mainly due to both the growth patterns of the crop within the seasons and the realized variabilities in weather (Figs. 1–4). Measured LAI increased with crop growth to values above 3.0 (observed canopy closure), eventually decreasing with the onset of leaf senescence in August, culminating into total senescence in September (Fig. 2). Recorded Rg at the location in both 2017 and 2018 followed the cotton LAI growth pattern. Owing to the apparent movement of the sun north and south with seasons, Rg increased from the cooler spring season in May to warmer summer

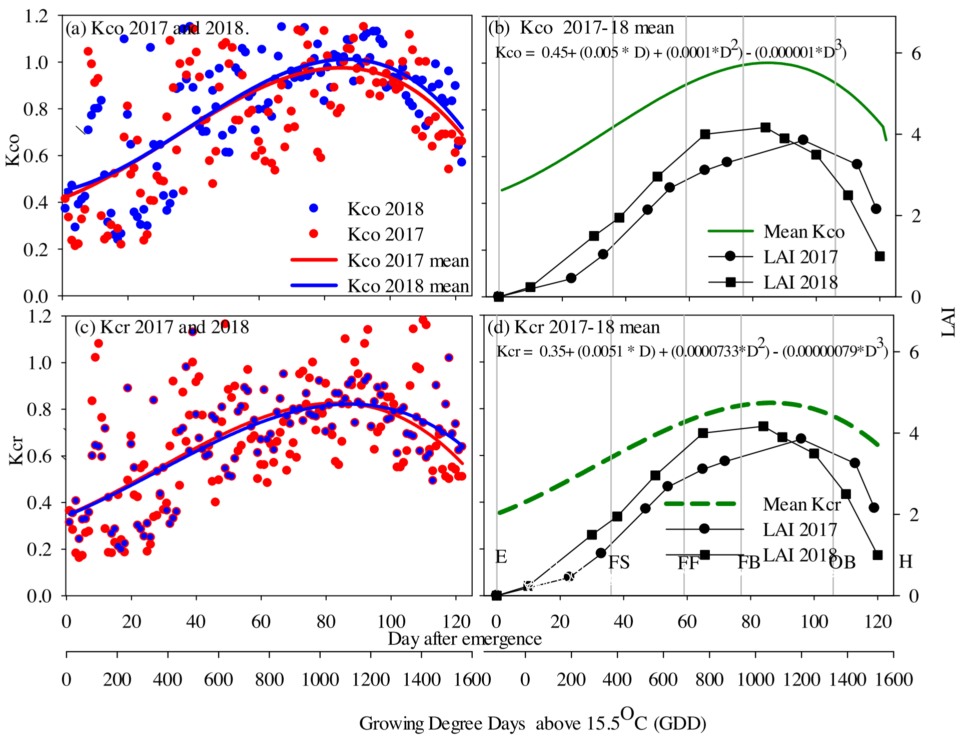

Fig. 8. (a) Daily crp coefficient for grass reference crop ET (K_{co}), (b) K_{co} across 2017 and 2018, (c) daily crop coefficient computed for alfalfa reference crop ET (K_{cr}), and (d) K_{cr} averaged across 2017 and 2018. Measured cotton LAI in 2017 and 2018 are also shown in panels (b) and (d). Symboles E, FS, FF, FB, OB, and H represent major phenological growth stages of cotton (vertical lines in Fig. 9, panels b, d), respectively, emergence, first square, first flower, first boll, and first cracked boll in 2018. D in the regression equations is days after cotton seedling emergence.

months of June, July, and August, and declined with time in the cooler fall season in September (Fig. 4). In 2017, the total seasonal (127 days) ET_c was 367 mm, with a seasonal average daily ET_c of 3.0 mm (Table 2). In 2018, measured monthly averaged daily ET_c varied between 2.3 mm in May and 4.4 mm in August (Table 2). Average ET_c for May, June, and September was 5.3, 5.5, and 5.4 mm, respectively, with a seasonal average daily ET_c of 3.4 mm. The enhanced ET_c in 2018 compared to 2017 was due to higher Ta, Ts, and Rg (Fig. 1a, b, d, i).

In general, seasonal and monthly averaged daily ET_r and ET_o did not differ substantially between 2017 and 2018 (Table 2). Seasonal averaged daily ET_r was 5.4 mm (monthly values ranged from 4.8 to 5.8 mm) in 2017 and 5.5 mm (monthly values ranged from 4.6 to 6.0 mm) in 2018. Similarly, seasonally averaged daily ET_o was 4.4 mm (monthly averages were between 3.9 and 4.9 mm) in 2017, and 4.5 mm (monthly averages were between 3.7 and 5.1 mm) in 2018.

Measured seasonal (130 days) ET_c was 367 mm in 2017 and 430 mm in 2018 (Fig. 2b, d). The two-year average seasonal total ET_c, ET_r, and ET_o was 402, 664, and 546 mm, respectively (Table 2). On a seasonal basis, the measured ET_c was 39 % less than ET_r (between months it varied between 29 and 56 %) and 22 % less than ET_o (between months it varied between 11 and 37 %) (Table 3). The seasonal values of ET_r were more than ET_o by 18 % in 2017 and 17 % in 2018.

3.6. Measured k_c for cotton

Use of a K_c value from literature, and a reference crop ET calculated from commonly measured weather data at a location of interest, provide a simple but reasonably accurate method of obtaining crop irrigation water requirements for scheduling irrigations for conserving limited water resources (Hunsaker, 1999; Farahani et al., 2008). When Allen et al. (1998) published K_c values for a variety of cereal and tree crops across the world, the applicability of those values in computing irrigation water requirements across locations, soils, and climates was reported to lead to different degrees of error in computed irrigation schedules (Howell et al., 2004; Karam et al., 2007; Farahani et al., 2008; Farg et al., 2012; Payero and Irmak, 2013; Irmak et al., 2013).

On a seasonal scale, averaged across 2017 and 2018, ET_r values were 18 % higher than ET_o, and the computed K_{cr} values were also 18 % higher than K_{co} (Table 4, Fig. 8). Calculated K_{cr} in both 2017 and 2018 ranged between 0.19 and 0.99 (Fig. 8a, c). In general, both K_{cr} and K_{co} increased with increasing leaf expansion growth (increase in LAI) (Fig. 8a, c). In general, the K_c curves in 2017 and 2018 followed a similar pattern and overlapped substantially when plotted against both days after planting (DAP) and growing degree days above 15.5 °C (GDD). Therefore, to obtain a general K_c curve for cotton at the location, we merged the two-year data, and an average K_c curve was constructed for K_{cr} and K_{co} (Fig. 8b, d).

Two-year average K_{cr} was 0.36, 0.59, 0.74, 0.82, 0.77, and 0.63, respectively, at the emergence, first square, first flower, first boll, first open boll, and harvest stages of cotton, respectively (Fig. 8d). K_{co} at similar stages of cotton growth was 0.46, 0.71, 0.89, 0.99, 0.91, and 0.73, respectively (Fig. 8b). The K_{cr} and K_{co} during the early vegetative growth stages of a cotton plant, that is, from seedling emergence to first square growth stage, is lower than other stages and followed the LAI pattern. During this stage, LAI varied from 0 to 2, with bare soil exposed to the atmosphere for evaporative loss of water from the system. As such, soil evaporation was a major contributor to ET_c which was modified by intermittent wet and dry events following rainfall and irrigations and water stored in the surface soil (Fig. 2b, d). With increase in LAI with crop-growth, the contribution of soil evaporation to ET_c declined and transpiration from the crop dominated the water flux out of the system. With deeper roots and enhanced LAI leading to a closed canopy during the mid-season, ET_c also peaked with similar increase reflected in the calculated K_{co} and K_{cr} values. At the end of the crop season, leaf senescence sets in, which again brings down the ET_c, so, K_{co} and K_{cr} as well (Allen et al., 1998).

Based on various sources of data, Allen et al. (1998) presented K_{co} of various field and orchard crops; however, K_{co} for cotton presented in this study represented only the middle and end growth stages of the crop, so making it very difficult for its use in irrigation scheduling for the whole crop-growth period (planting to physiological maturity of the crop). K_{co} representing the mid-season growth stage of cotton ranged from 0.9 to 1.2, about 24 % higher than the K_{co} values obtained in our study. In a lysimetric study with cotton in a Mediterranean region of northern Syria, Farahani et al. (2008) found the Allen et al. (1998) tabulated values to be 24 % higher than what they computed. Based on this finding, they expressed the need for caution in the blind application of Allen et al. (1998) tabulated values for managing limited water for irrigations. The K_{co} computed in this study was 24 % less than Allen et al. (1998) values.

However, based on lysimetric experiments, Ko et al. (2009) reported K_{co} between 0.2 and 1.5, greater than Allen et al. (1998) values, for cotton in a semiarid climate in Texas, USA. In this experiment, instead of computing ET_o for a hypothetical grass reference crop, a lysimeter was used for measuring ET_o, and these measured values were further used for deriving K_{co}. However, Allen et al. (1998) and ASCE-EWRI (2005) defined K_c for not real but hypothetical grass or alfalfa crops – these crops are characterized by given, constant, canopy and soil resistances to water vapor losses from these cropping systems. So, in this study, we used Allen et al. (1998) for ET_o and ASCE-EWRI (2005) for ET_r.

4. Conclusions

Water resources in aquifers across the globe are declining due to unsustainable water withdrawals for irrigated agriculture. For sustaining irrigated agriculture for producing sufficient food, fiber, and fuel for an increasing population, it is critical that irrigations are applied based on location-specific crop water demands for achievable production goals. Crop water demands vary across space and time during the crop season depending on the realized weather and other dynamic crop-soil-atmospheric conditions. In this study, we quantified ET_c of cotton (cv. Delta Pine Land 1522) across two cropping seasons (2017 and 2018) in silty clay soil in the humid climate of the Mississippi Delta. This information was used for generating K_c that linked actual, location specific, dynamic cotton ET_c demands with reference crop ET (grass or alfalfa reference crops) computed from weather data collected locally. Computed K_{co} varied between 0.5 and 0.99, and K_{cr} varied between 0.45 and 0.8. Seasonal consumptive use water requirements (ET_c) for cotton in the MS Delta was 367 mm in 2017 and 439 mm in 2018, with an average of 402 mm. Computed seasonal ET_r and ET_o were 664 and 546 mm, respectively. On average, computed ETr were 18 % more than ET_o. There is a need for collecting more data and extending the study presented here for deriving long-term climate averaged ET_c and K_c values for cotton, which can be used with better confidence across different climates and soils in the Mississippi Delta region for irrigation scheduling applications.

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.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106091.

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