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Eddy covariance quantification of soybean (*Glycine max* L.,) crop coefficients in a farmer's field in a humid climate

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Abstract

For sustainable irrigated agriculture, scheduling irrigations based on accurate estimates of crop water requirements (ET_c, crop evapotranspiration) are critical. ET_c was estimated as a product of a reference crop evapotranspiration computed from weather data and a crop coefficient (K_c) in weather-based irrigation scheduling. In this investigation, an eddy covariance (EC) method was used for quantifying soybean (*cv. Asgro 46X4*) K_c in a farmer's field under a humid climate. ET_c quantified using the EC method was used for developing K_c for alfalfa (K_{cr}) and grass (K_{co}) reference crops computed from measured weather data. Experiments were conducted during three crop seasons (2017–2019) in a 500-ha furrow-irrigated soybean field—planted in silt loam soil in late April to early May and harvested in September. Harvested soybean yields were 4771, 5783, and 4909 kg ha^{-1}, consuming 584, 640, and 593 mm ET_c (average 605 mm), respectively, in 2017, 2018, and 2019. Monthly averaged daily ET_c across the crop seasons varied between 2.1 mm in May 2019 to 6.2 mm in June 2018. Seasonally averaged daily ET_c across the three crop seasons varied between 4.3 and 5.2 mm with an average of 4.8 mm. Across the crop seasons, ET_c was 22% less and 2% greater than computed grass (ET_o) and alfalfa (ET_r) reference crop evapotranspiration. Monthly averaged daily K_{co} varied between 0.79 and 1.18, and K_{cr} ranged between 0.65 and 0.97. The K_c established can help develop soybean irrigation schedules, across climates and soils, based on ET_o or ET_r computed from real-time weather data.

Introduction

For meeting the demand for agricultural produce, from a burgeoning human population, by 2050, irrigated food production must increase by 60% when the potential for rising water withdrawal is limited to only 10% (FAO 2017). Water productivity must be improved through irrigation water management practices to overcome this disparity in freshwater availability for agricultural production. As the surface water resources available for irrigations are often limited, groundwater stored in underground aquifers is withdrawn for agricultural use beyond natural recharge rates. Consequently, most aquifers have declined to levels that threaten the sustainability of irrigated agriculture (Clark and Hart 2009; Dalin et al. 2017).

The Lower Mississippi Delta (LMD), with a humid climate, is one of the most productive regions for crops in the United States of America (Kottek et al. 2006; Clark and Hart 2009). Typically, precipitation received in a humid climate is adequate for meeting the crop evapotranspiration (ET_c) loss of water from landscapes (Kottek et al. 2006). However, due to the uneven temporal distribution of precipitation, irrigating when soil water does not meet crop water demand is necessary for optimizing production. In the LMD, the sustainability of the shallow Mississippi River Valley Alluvial Aquifer (MRVAA) is in question as agricultural withdrawal from the aquifer exceeds its recharge (Clark and Hart 2009; Powers 2007; Heatherly 2014; Runkle et al. 2017). Approximately 60% of the row crops produced in the mid-southern USA are irrigated, leading to irreparable harm to MRVAA. Hence, sustainable withdrawal from the MRVAA will only be achieved if the application of irrigation is based on real-time crop water demand.

A crop demand for water arises from the need to maintain turgor pressure in leaf cells for inducing cell-wall

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expansion for maximizing leaf area for light harvesting in photosynthesis and supporting metabolic functions that are fundamental for growth and development (Robinson et al. 2013). Nonetheless, the amount of water required for maintaining cell turgor and metabolism is negligible compared to the amount of water the plant loses, passively, to the atmosphere through the evapotranspiration process (Morison 2008). The crop consumptive water requirement is expressed in terms of the ET_c alone, and the current weather controls it (Doorenbos and Pruit 1977; Allen et al. 1998; Schulze and Hall 1982; Way et al. 2014).

The dependence of ETc on the weather rendered it possible to estimate it from measured weather data. Penman (1948) offered a method for determining the potential rate of evapotranspiration (PET) from air temperature (T_a), solar radiation (R_g), wind speed, and relative humidity. This PET concept assumed unlimited water available at a vegetation surface that entirely covered the soil. For a more realistic estimate of ETc, Monteith (1965) offered a 'Penman–Monteith (P–M) combination equation' by redefining the generic vegetative cover of Penman (1948) with an extended grass-covered soil. Shuttleworth and Wallace (1985) extended the Monteith (1965) equations to coexist a partial canopy and ground in cropping systems. For computing ETc using these methods, crop-growth data are also required for computing aerodynamic and crop canopy resistances to water vapor transport from cropping systems besides the weather data. These resistances are influenced by the interacting effects of climate, soil water and nutrients, crop varieties, and crop management that are difficult to measure for real-time irrigation scheduling applications. In this direction, Doorenbos and Pruitt (1977) developed a two-step approach for estimating ETc. In the first step, evapotranspiration was computed for a hypothetical reference crop with predefined soil-crop-canopy-air resistances. In the second step, this reference evapotranspiration (ETo, potential evapotranspiration for a grass reference crop, and ETr is potential evapotranspiration for an alfalfa reference crop) is modified with an experimentally determined crop coefficient (K_c) that linked the reference crop evapotranspiration to the ET_c of a specific crop. The K_c is defined as

$$K_{co} = \frac{ET_c}{ET_o}, \tag{1}$$

$$K_{cr} = \frac{ET_c}{ET_r}, \tag{2}$$

where K_{co} is the crop coefficient for a short grass (0.12 m tall; Allen et al. 1998) reference crop and K_{cr} is the crop coefficient for tall grass or alfalfa reference crop (ASCE-EWRI 2005).

The K_c modifies the evapotranspiration computed for a hypothetical reference crop for crop variety, crop height, soil characteristics, aerodynamic properties, crop-growth stages, and leaf and stomata characteristics affecting aerodynamic resistance to water vapor flow (Allen et al. 1998). The K_c is also affected by the irrigation method, rate, and frequency as they change plant water availability in the soil (Doorenbos and Pruitt 1977; Allen et al. 1998).

The K_c values for various crops were reported in Allen et al. (1998). However, today's use of these data in irrigation scheduling is limited as they were developed over three or more decades ago under growing conditions, technology, and management practices that deviated considerably from the present (Allen et al. 1998; 2007). Substantial differences between Allen et al. (1998) K_c data and those computed later for various crops across climates and soils were reported (Irmak et al. 2013; Farahani et al. 2008; Anapalli et al. 2020; Karam et al. 2007; Farg et al. 2012; Payero and Irmak 2013; Sanchez et al. 2015). Meanwhile, the eddy covariance (EC) quantification of ETc based on sound micro-meteorological theory has become famous for irrigation water management applications (Baldocchi et al. 2003,2020; Uddin et al. 2013; Tallec et al. 2013; Shurpali et al. 2013; Way et al. 2014; Anapalli et al. 2018, 2019). In the EC method, the momentum, energy, and mass (CO_2 and water or ETc) transfer between the earth and its atmosphere are estimated by measuring and modeling turbulent transport of these properties in eddies generated in wind streams in the surface layer of the earth-atmosphere. The EC instrumentation, which is more flexible in their installation and maintenance, portability, costs, accuracy, and repeatability of measurements representing the crop environment, makes it a viable method in the twenty-first century.

Anapalli et al. (2018) reported ET_c of soybean grown in the soybean phase of a corn–soybean (also with cotton and rice) rotation experiments in the Mississippi Delta region to recommend farmers for irrigation water management. In that study, they grew soybean (cv. Dyna Grow 31RY45, a mid-maturity group IV cultivar) in clay soil in experimental fields. As there was only a partial season's data available for that study, they could derive only weekly K_c values. However, for real-life applications, daily K_c is preferred for irrigation scheduling applications at any given time during the life cycle of a crop. Farmers in the area also expressed concerns on the real-life applicability of data derived under ideal experimental conditions in a predominantly clay soil using a cultivar at its verge of replacement with more modern verities, as above, for irrigation management in their fields. Many farmers in the region follow soybean monocropping in place of soybean in rotation with other crops. Hence, in this study, a modern soybean variety 'Asgro 46X6' was grown in a 500 ha plot (a farmer's field) with predominant silt loam (Dubb's silt loam: fine-silty, mixed, active, thermic Typic Hapludalfs) soil for three years in a row for estimating ET_c and K_c. Specifically, first, soybean ETc was quantified using eddy covariance data collected in three crop seasons (2017–2019) in this investigation. We then used these data for developing K_c for grass (Allen et al. 1998) and alfalfa (ASCE-EWRI 2005) reference crops for irrigation water management.

Materials and methods

Soybean experiments

The experiments were conducted in a farmer's field of over 500 ha in size located near the USDA Crop Production Systems Research Unit's (CPSRU) farm at Stoneville, Mississippi, USA (33° 39′ N, 90° 59′ W, ~ 42 m elevation above sea level). The experimental site has a humid subtropical climate characterized by mild winters and warm summers (Kottek et al. 2006). The average annual rainfall at the location is about 1300 mm, with 30% of it received during the major crop-growing seasons of the soybean, that is, May to August (Kebede et al. 2014; Anapalli et al. 2016a, b). The uneven distribution in rainfall in this region often makes it necessary to provide crops grown during this season with supplemental irrigations for profitable yield returns. The farm's dominant soil type is a poorly drained Dubbs silt loam (fine-silty, mixed, active, thermic Typic Hapludalfs) to a depth of about 1.2 m. The crop field is land-formed to a 1% slope. The crop is continuous (ever year) soybean under conventional tillage practices: deep tillage—once in 3–4 years to break claypans and overturn soils, one to three passes of shallow tillage every season for burying crop residue and killing weeds, followed by another tillage to generate furrows for irrigation applications and ridges for planting soybean. Soybean (*cv.* Asgro 46×6) seeds were planted on ridges on April 21, April 28, and May 01 in 2017, 2018, and 2019, respectively, on north–south rows at 77-cm row spacing and an average seeding rate of 407,550 seeds per ha. Seedlings emerged, respectively, on 7, 9, and 7 days after planting, and the crop reached physiological maturity stages on 132, 128, and 131 days (average 130 days) after seedling emergence from the soil (DAE).

The crops were furrow (surface or ground) irrigated. Water was applied through polyethylene pipes at the elevated end of crop rows to maintain water content in a 50-cm soil layer at a level above 65% of maximum plant available water (irrigated when water in the soil layer fell below this threshold amount). Due to the nature of the furrow-irrigation method, in which water was applied at the head of furrows and allowed to run until they reached the furrows' end, irrigation amounts were not predetermined. Irrigation applied should be sufficient to run from the head of the furrow to its end, and once the water reaches the end of the furrow, irrigation water supply to that furrow was stopped. Each irrigation applied was about 60 mm. Irrigations were applied thrice in 2017 (on 51, 59, and 98 DAE), twice in 2018 (on 29 and 82 DAE), and thrice in 2019 (on 83, 108, and 115 DAE) (Fig. 1). Soil water and temperature at 15, 30, and 50 cm depths were monitored using Stevens HydraProbe (Stevens Water Monitoring Systems, Inc., Portland, OR USA). The sensors were installed, three each in the north and south-facing sides of ridges on which soybean was planted in rows and three sensors in the furrow between the ridge-rows.

An AccuPAR LP-80 Ceptometer (Decagon Devices, Inc., Pullman, WA, USA) was used to estimate the leaf area index (LAI) of the soybean crop at approximately 2 weeks intervals. Soybean plant heights were monitored weekly for adjusting the sensor heights above the canopy for micrometeorological measurements. Soybean phenological stages were recorded following Fehr and Caviness (1977) with Hodges and French (1985) modifications (Table 1). The soybean crop variety (*Asgro 46X6*) belonged to the maturity group IV (4.6) with indeterminant growth characteristics; as such, its phenological growth stages did not occur uniformly. So, each phenological stage was noted when approximately 50% of the plants exceeded that stage; nevertheless, many plants reached the next stage by then. Soybean grains from the whole farm area (over 500 ha) were harvested in about 2 weeks after reaching physiological maturity and weighed using harvest combines (Table 1). Grain weights were adjusted to 13% moisture content.

Eddy covariance measurements for quantifying ET_c

The EC measuring system used consisted of a Gill New Wind Master sonic anemometer (Gill Instruments, Lymington, UK) for measuring the speed of vertical eddy transport and sonic temperature and an LI-7500-RS open-path infrared gas analyzer (LI-COR Inc., Nebraska, USA) for measuring water vapor density in the eddies. These sensors were installed on a telescopic, height-adjustable mast (EC tower), centrally located in the 500-ha soybean farm. This way, the above sensors' fetch deployed on the towers were over 200 m in all directions. Using the EC tower's height adjusting facility, the sensors were mounted continuously at twice the canopy height above the plant canopy. Height of the tower till the crop reached 60-cm height was constant at 1.2-m above ground. The tactical placement of the EC sensors continuously above about twice the crop height helped measure 3-D wind speed and water vapor concentration in the eddies, roughly, in the constant-flux layer above the plant canopy (Burba 2005). Measurements were at 10 Hz on a data logger.

Additional micrometeorological data associated with the crop canopy environment were also collected for use in the

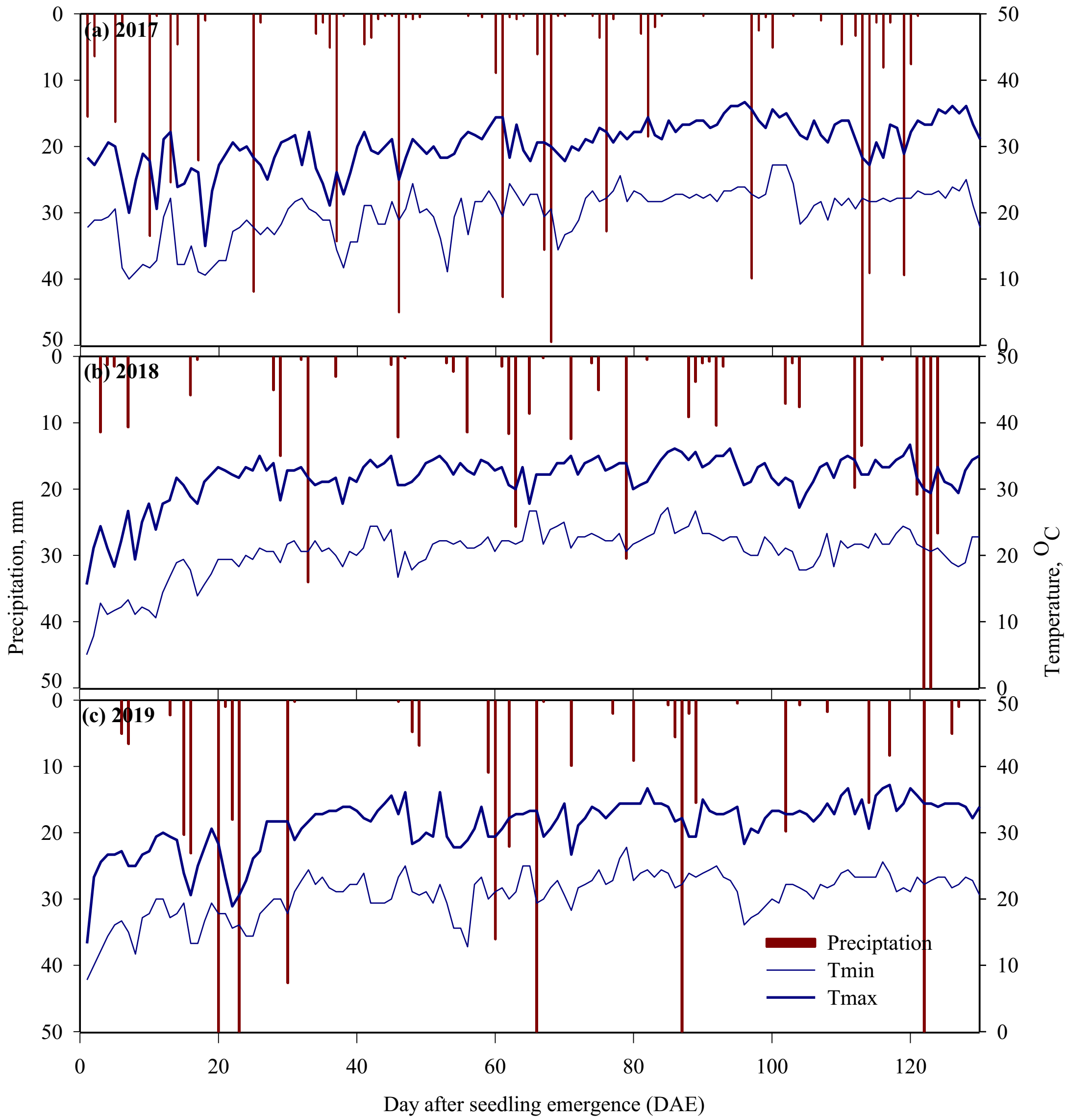


Fig. 1 Daily maximum and minimum air temperatures and rainfall were received at the experiment site during the 2017, 2018, and 2019 soybean seasons

analysis, interpretation, and data-gap filling of the EC flux data: 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; air temperature (T_a) and relative humidity (HMP 155, Vaisala, Helsinki, Finland); soil water content and temperature in the 8-cm soil layer above the heat flux plates using Stevens HydraProbe (Stevens Water Monitoring Systems, Inc.), precipitation using a tipping bucket rain gauge (TR 525, Texas Electronics). Micrometeorological data were sampled at 1-min intervals and averaged every 30 min.

The EddyPro v 6.1.0 (LI-COR Inc., Lincoln, NE, USA) software was used to process the EC data for computing the fluxes of water in terms of latent heat of water evaporation (LE, Wm^{-2}), for estimating ET_c. The processed LE flux and micrometeorological data were averaged or accumulated at 30-min intervals. Post-processing of the Eddy covariance data was performed in the Tovi™ software. (LI-COR Inc, Lincoln, NE, USA). Quality control was performed on the data following the OzFlux methodology (Isaac et al. 2017) to remove implausible flux values arising out of weather disturbances, especially rainfall. Fluxes measured during active rainfall events were also removed from the analysis. Flux measurements during periods without well-developed turbulence or weak stationarity were removed following Mauder and Foken (2006). Net Ecosystem Exchange (NEE) was determined from CO_2 flux by adding in the storage

Table 1 Non-destructively detected key soybean (c.v. Asgrow 46X6) phenological growth stages in 2017, 2018, and 2019, in a study conducted in a silt loam soil in a 500-ha producer's field in Stoneville, Mississippi

Phenology	2017		2018		2019	
	Date	DAE	Date	DAE	Date	DAE
Planting	April 21	–	April 28	–	May 01	–
Emergence (VE)	April 28	0	May 07	0	May 08	0
Beginning bloom (R1)	May 28	30	June 9	33	June 13	36
Full bloom (R2)	June 20	53	June 19	43	June 17	40
Beginning pod (R3)	June 27	60	June 22	46	June 22	45
Full pod (R4)	July 05	68	June 28	52	July 01	54
Beginning seed (R5)	July 15	78	July 09	63	July 11	64
Full seed (R6)	July 30	93	July 26	80	July 26	79
Beginning maturity (R7)	Aug 25	119	Aug 15	100	Aug 18	102
Full maturity (R8)	Sept. 07	132	Sept 12	128	Sept. 14	131
Harvest	Sept. 18	143	Oct 04	151	Sept. 30	145
Grain yield, kg ha^{-1}	4771		5783		4909	
Growing degree days (°C)	2004		2160		2134	

DAE is the day after seedling emergence

term determined using the one-point storage (Myers and Hollinger 2004) using the EddyPro software (Fratini and Mauder. 2014). The sensible and latent heat fluxes were also corrected following the energy balance residual correction proposed by De Roo et al. 2018, which is parametrized based on a large eddy simulation study. Gap filling was then done on the quality controlled and corrected fluxes following the marginal distribution sampling techniques proposed by Reichstein et al. (2005). For computing ET_c in mm from LE fluxes in W m^{-2}, a constant conversion factor of 0.00073 was used.

The EC method has been widely accepted as an innovative, science-based method for quantifying momentum, mass, and energy transfer between the plant canopies and the atmosphere (Foken et al. 2006; Mauder et al. 2007). In the EC system, ET_c is quantified by measuring the covariance between the water vapor density in an eddy-air stream and its velocity/speed of vertical eddy transport within the horizontal wind flow. Significant steps of assumptions in computing and modeling are required for solving the EC theory for quantifying vertical fluxes of ET_c. Confidence in the quantified fluxes using this method depends on how accurately the energy fluxes into the plant canopies balance the energy fluxes out of the system, known as energy balance closure (EBC). Using the Tovi™ software for processing the EC data described above, achieved EBC of 96, 97, and 94%, respectively, in 2017, 2018, 2019 crop seasons, that is, the EBC at these levels indicate that the soybean ET_c computed in this study has an error between 3 and 6%. As an example, the EBC scenario for the 2017 crop season is presented in Fig. 2. The fluxes calculated with EBC at these levels can provide a reasonable level of accuracy required for irrigation water management applications (Anderson and Wang 2014; Liu et al. 2017; Gao et al. 2017; Anapalli et al. 2018, 2019, 2020).

Computing ET_o, ET_r, K_{co}, and K_{cr}

The ET_o and ET_r values were calculated from weather data collected at a 2 m height from the ground by the Mid-South Agricultural Weather Service, Delta Research and Extension Center, Stoneville, Mississippi, weather station located within a two-mile radial distance from the experimental field. The Allen et al. (1998) and ASCE-EWRI (2005)

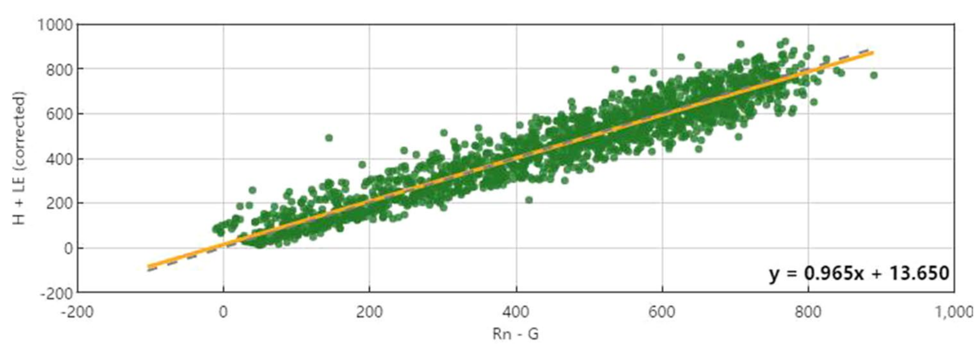


Fig. 2 Energy balance closure in eddy covariance measurements during the 2017 crop season. Values are 30-min averages, and all units are in W m^{-2} s^{-1}. H, LE, and G are sensible, latent, and ground heat fluxes, respectively. Rn is the net solar radiation. The slope of the linear regression between H + LE and Rn-G, represents the energy balance closure

computation procedures were used for computing ET_o and ET_r. Half hour ET_c derived from the EC method above were accumulated over 24 h and used to calculate daily $K_{co,}$ and K_{cr} values Eqs. (1) and (2).

To account for the differential photoperiod effect on soybean growth across locations and thereby facilitate transferability of information across sites, expressing K_{co} and K_{cr} also expressed in terms of growing degree days (GDD) (Ayars 2008; Lopez-Urrea 2009).

The GDD (°C) for soybean were calculated using a base temperature (*T base*) of 10 °C and an upper threshold of 30 °C (Desclaux and Roumet 1996):

$$\mathrm{GDD} = \left(\frac{T_x + T_y}{2}\right) - T_{\mathrm{base}}, \tag{3}$$

where, $(T_x + T_y)/2 < 10$ or $(T_x + T_y)/2 > 30$. GDD = 0.0.; where, T_x and T_y are daily maximum and minimum air temperatures.

Results and discussion

Weather

Virtually all the consumptive water requirements of crops grown under field conditions originate from ET_c (Rosenberg et al. 1983; Allen et al. 1998; Morison et al. 2008; Farahani et al. 2008). The loss of water to ET_c from a cropping system at any instance depends on the existing weather conditions. The main weather variables that control ET_c from a cropping system are solar radiation (R_g), air temperature (T_a), and air vapor pressure deficit (VPD) (Fig. 1). During the time, the precipitation also contributes to this by providing a water input source into the system for meeting the ETc. In 2017, daily maximum T_a (T_x) measured at 2-m above the crop canopy increased from 32 °C in May to a maximum seasonal value of 35 °C in August and then decreased to 29 °C during the crop harvest in September (Fig. 1). Daily T_x in 2018 increased from 32 °C in May to the highest seasonal value of 36 °C in July, which went down to 24 °C during harvest. In 2019, the monthly maximum T_x was 29 °C in May that increased marginally to 30 °C in August, and then declined to 26 °C at harvest in September. During the soybean season in 2017, recorded daily total global solar radiation (R_g) ranged from 5 M J m^{-2} s^{-1} in August due to excessive clouding and rain events to 32 M J m^{-2} s^{-1} in May on bright sunny days. Under similar atmospheric conditions, measured R_g ranged between 6 and 31 M J m^{-2} s^{-1} in 2018 and between 4 and 30 M J m^{-2} s^{-1} in 2019 crop seasons (data not shown).

Rainfall received during the crop season was 700 mm in 2017 (132 d), 540 mm in 2018 (128 days), and 560 mm in 2019 (131 days) (Fig. 1). Rainfalls received during the three crop seasons were reasonably uniform through the crop-growing period, with 63, 49, and 35 rainy days in 2017, 2018, and 2019, respectively (Fig. 1). In 2017, three irrigations of 60 mm each had been given to supplement the rainfall inputs for crop growth (Fig. 3). The soil clay textured soil had a field capacity of 0.38 cm^3 cm^{-3} (water content at 33 k Pa suction) and a permanent plant wilting point (water content at 1500 k Pa suction) of 0.27 cm^3 cm^{-3}. In 2017, irrigation events were on 51, 59, and 98 days after soybean seedling emergence (DAE) when the water in the 15 cm soil layer dropped to 0.29, 0.33, and 0.35 cm^3 cm^{-3}, respectively. During the rest of the crop season, soil water levels remained near or above field capacity for most of the time, maintaining enough water for optimum plant uptake and productivity—a requirement for deriving K_c representing optimum crop growth (Fig. 3). However, whenever it rained heavily, the soil water often went above field capacity until drained off the soil or lost to ETc in 2–3 days. In 2018, 50 mm of irrigation was applied on 29 and 82 DAE when soil water in 15 cm of soil was 0.31 and 0.33, respectively. This study's primary focus was to determine crop coefficients using Eqs. 1 and 2. The crops were not allowed to get water-stressed by depleting the soil water further down before irrigations were applied. In 2019, 50 mm of water per irrigation was applied on 83, 108, and 115 DAE when soil water in the 15 cm soil layer dropped to 0.32, 0.30, 0.31, respectively (Fig. 3).

Soybean growth and yield

Soybean seedlings emerged on April 28 (seven days after planting) in 2017, May 07 in 2018 (9 days after planting), and May 08 in 2019 (7 days after planting) (Table 1). Across all years, emergence was uniform, which facilitated uniform crop stand across the fetch zone of the EC tower. Establishing a uniform crop stand is an essential requirement for employing the eddy covariance theory for measuring water and CO_2 fluxes from cropping systems (Burba and Anderson 2005; Foken 2008). The soybean crops reached the R1 phenological stage of growth (Beginning bloom) 30, 33, and 36 DAE in 2017, 2018, and 2019, respectively. The crop reached physiological maturity in 130 days on average across the three crop seasons (132, 128, and 131 days in 2017, 2018, and 2019, respectively) (Table 1). So, for calculating seasonal water requirements, the crop was assumed to have a fixed crop duration of 130 days after emergence. Harvested crop yields were 4771, 5783, and 4909 kg ha^{-1} for 2017, 2018, and 2019, respectively. The maximum measured value of LAI was 4.8, 5.7, and 5.8 in 2017, 2018, and 2019, respectively (Fig. 4). The relatively lower amount of grain yield measured in 2017 corresponded with a lower LAI that year.

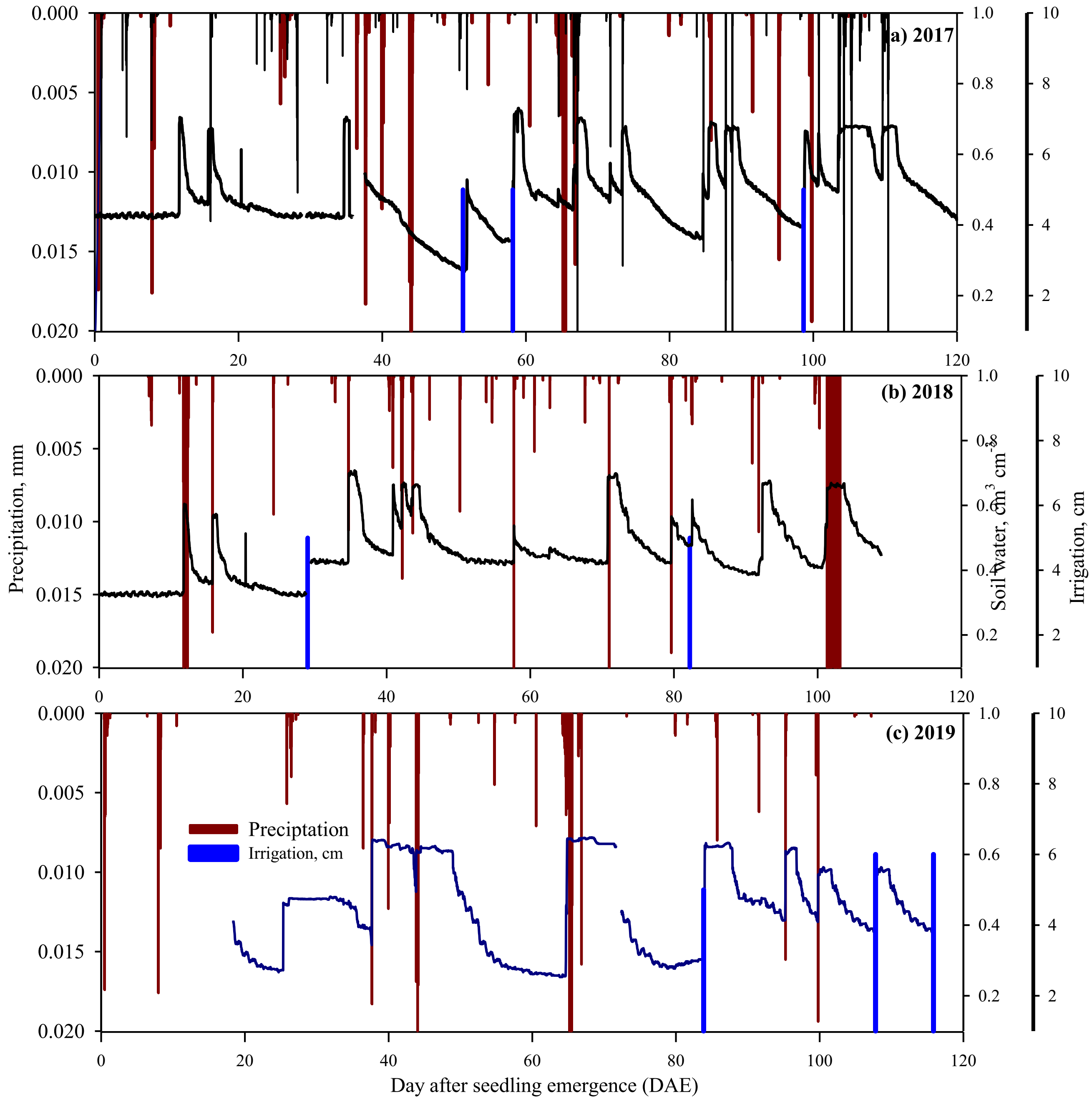


Fig. 3 Applied irrigations, half-hourly rainfall, and soil water content (15 cm soil depth) in soybean cropping system in 2017, 2018, and 2019

Soybean phenology depends on the number of GDD (°C) the plant is subjected to during its growth in a specific climate (Ayars 2008; López-Urrea et al. 2009). The total number of GDD from the day of emergence to physiological maturity was 2004, 2160, and 2134 in the 2017, 2018, 2019 crop seasons, respectively (Fig. 5; Table 1). On average, the number of GDD from planting to harvest for the average duration of the crop (130 days as above) was 2099.

Seasonal variations in diurnal ET_c

The core crop-growth season across the three years of this experiment was in May, June, July, and August (Table 1). The monthly averaged diurnal pattern of half-hourly ET_c across the crop seasons in these four months matched well with each other, but daily peak values differed considerably (Fig. 6). Monthly averaged daily peak values were 0.16,

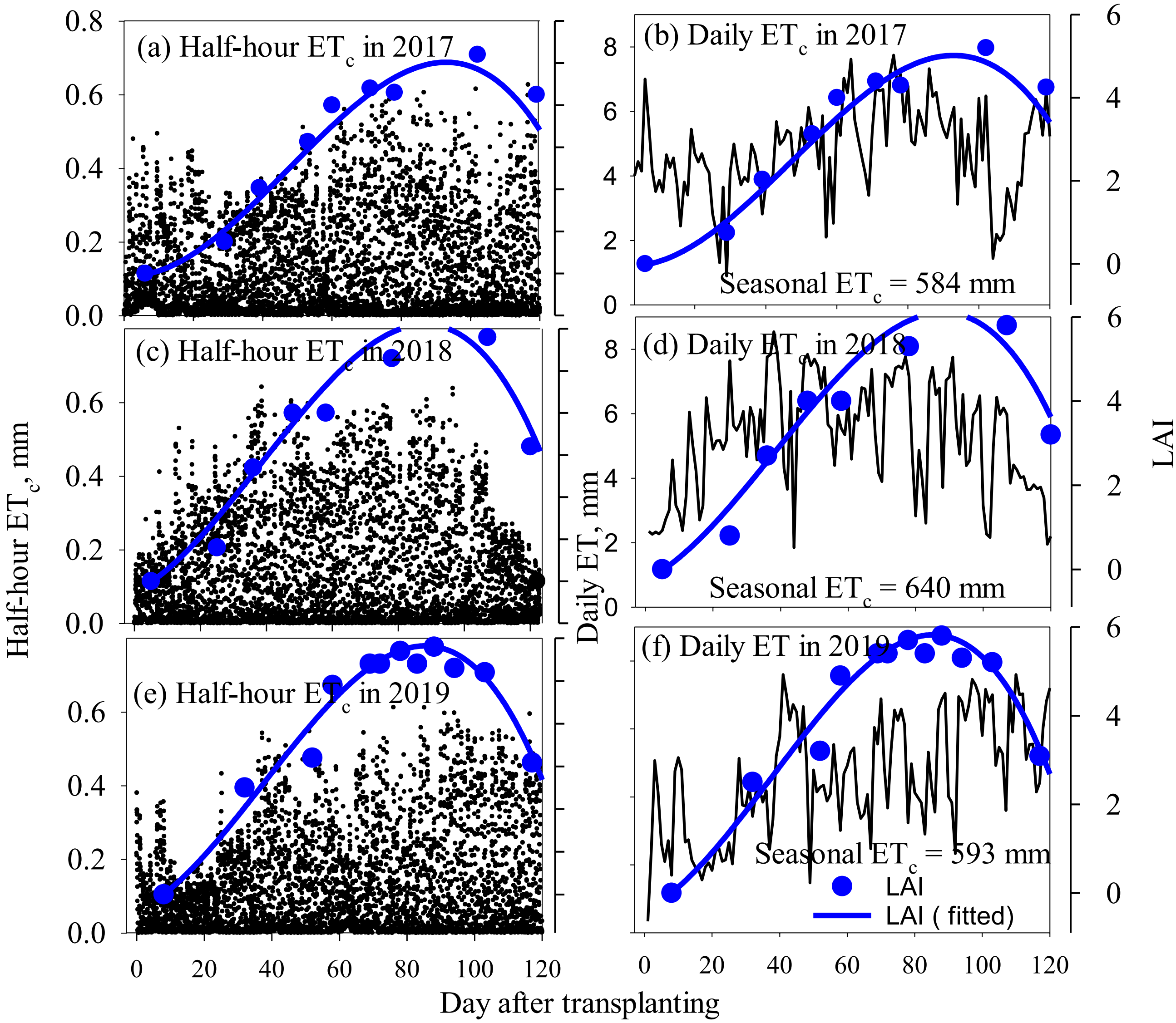
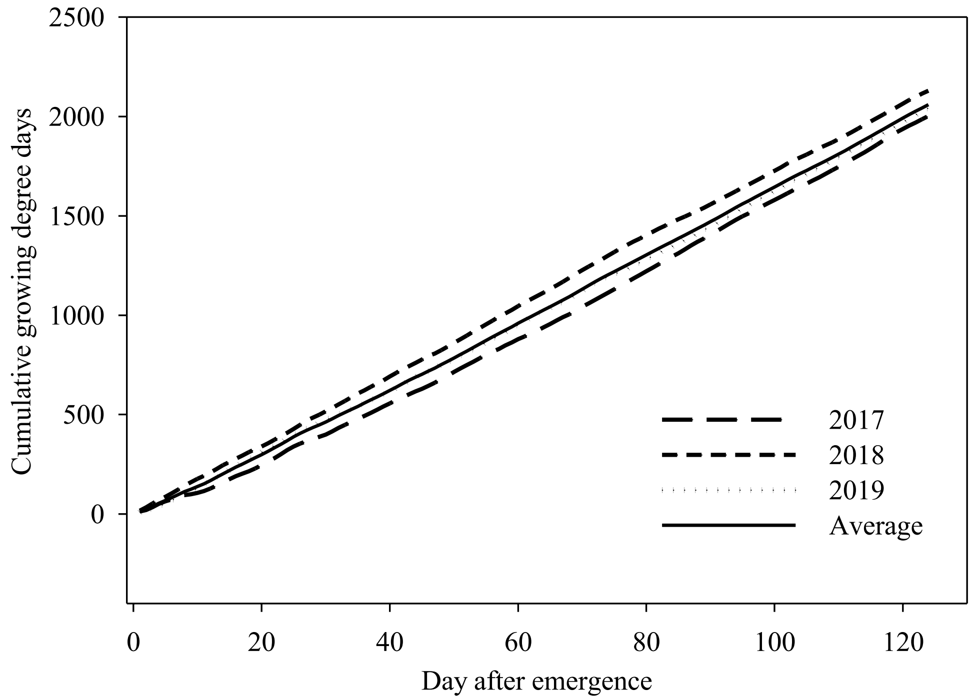


Fig. 4 Soybean leaf area index (LAI), and half-hourly and daily evapotranspiration (ET_c) measured using the eddy covariance method during the 2017, 2018, and 2019 crop seasons. The continuous blue lines are cubic polynomial curves fitted to the leaf area index (LAI) values in blue color

0.22, and 0.26 mm per half-hour in 2017, 2018, and 2019, respectively. The highest non-averaged, half-hourly amounts in those three seasons were 0.49, 0.48, and 0.38 mm for 2017, 2018, and 2019, respectively (Fig. 6, non-averaged values not shown). Across 2017, 2018, and 2019, highest values of ET_c in June were, respectively, 0.57, 0.58, and 0.51 mm, in July were 0.61, 0.54, and 0.61, and in August were 0.63, 0.57, and 0.59 mm. The highest monthly averaged half-hour ET_c in June across three crop seasons were 0.27, 0.39, and 0.32; in July were 0.26, 0.38, and 036; and in August were 0.25, 0.35, and 0.37, respectively.

The half-hour averaged diurnal patterns of ET_c corresponded well with similar half-hour averaged diurnal patterns of global solar radiation measured in the soybean field (Figs. 6, 7). These ET_c values were close to zero until about 7:30 AM, then increased gradually with an increase in solar radiation after sunrise, and peaked to a maximum at about 1:30 PM, thereafter declined down to near zero values by about 9.00 PM. This pattern in ET_c corresponded well with the monthly averaged half-hourly values of T_a (Fig. 8). However, unlike R_g, the magnitude of T_a differed considerably between crop seasons. On average, throughout the day in May, the value of T_a in 2018 was the highest, followed by 2019, and lowest in 2017 (Fig. 8b). In June, as reflected in ET_c, T_a in 2019 was the highest, followed by 2018, and lowest in 2017 (Fig. 8c). In July, measured ET_c between crop seasons was not considerable, so T_a measured across the seasons (Fig. 8d). In August, estimated ET_c was lowest in

Fig. 5 Cumulative growing degree days (GDD, °C) from soybean seedling emergence until physiological maturity in 2017, 2018, and 2019



2018, followed by intertwined patterns in 2017 and 2019, and similar patterns were noticed both in R_g and T_a diurnal patterns in this month (Figs. 6e, 7e, 8e).

In general, evaporative losses became appreciable only after sunrise (about 6 AM), peaked between 1 and 2 PM, and decreased to near zero after sunset at 8 PM (Fig. 6). The largest ET_c was observed in July when crop growth was also highest, as reflected in higher measured LAI (Fig. 5.): In 2017 through 2019, LAI measured in July and August were above 5.0 (Fig. 4). Recorded averaged diurnal half-hourly R_g in July was about 880 W m^{-2} in the three crop seasons (Fig. 7d).

Daily and seasonal ET_c across the three crop seasons

Half-hourly ET_c measured across the three crop seasons, in general, was positively correlated with crop growth as reflected in the measured LAI across the crop-growth period (Fig. 4a, c, e). When these half-hourly values were accumulated over a daily period, the general pattern in ET_c followed the LAI curve; however, day to day, large fluctuations in ET_c values were observed (Fig. 4b, d, f). The ET_c measured in 2017 varied between 1.3 mm on May 21 to 7.7 mm on July 30, apparently due to extreme variations in the amount of solar radiation received on those days (Fig. 4a, daily Rg not shown). The amount of Rg received on May 21 was 5.7 MJ m^{-2}, and on July 30 was 29.3 MJ m^{-2}, and these values were, respectively, the smallest and largest amounts received per day in this season. The T_a recorded these days, respectively, 20.7 and 28.1 ^{O}C, were comparable to many other days in the season with lower ET_c rates. In general, the large variations in ET_c across the season were due to the amount of R_g, T_a, and soil wetting/drying due to rainfall events (Figs. 1, 3). We did not attempt a thorough analysis of the role of different weather variables on the daily rates of ET_c in this paper. Such large variations in ET_c across cotton crop season at the location were attributed to differences in measured daily weather (Anapalli et al. 2020). In this regard, a detailed analysis of the likely causes of variations in daily ET_c and its predictivity in the location's climate in a follow-up paper will be reported. Daily variations in ET_c across 2018 and 2019 were like those observed in the 2017 crop season. The highest ET_c of 7.6 mm in 2018 was on June 16, in response to 30.3 MJ m^{-2} of Rg received, and the minimum ET_c of 1.7 mm was measured on June 22 in response to 4 M J m^{-2} of Rg. During the 2019 crop season, the largest ET_c was 7.6 mm, and the smallest was 1.48 mm measured on June 27 and June 20, respectively, in response to solar radiation amounts of 28 and 8.0 M J m^{-2}.

The measured monthly average daily ET_c values in 2017 were 4.3 mm and ranged between 3.6 mm in May and 4.9 mm in June (Table 2). 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, 3, 4). Measured LAI increased with crop growth to values above 3.0 by 50 DAE (observed canopy closure) and then decreased with the onset of leaf senescence in August and September (Fig. 4). The higher ET_c in June was attributed to more solar radiation received in response to less clouding, as reflected

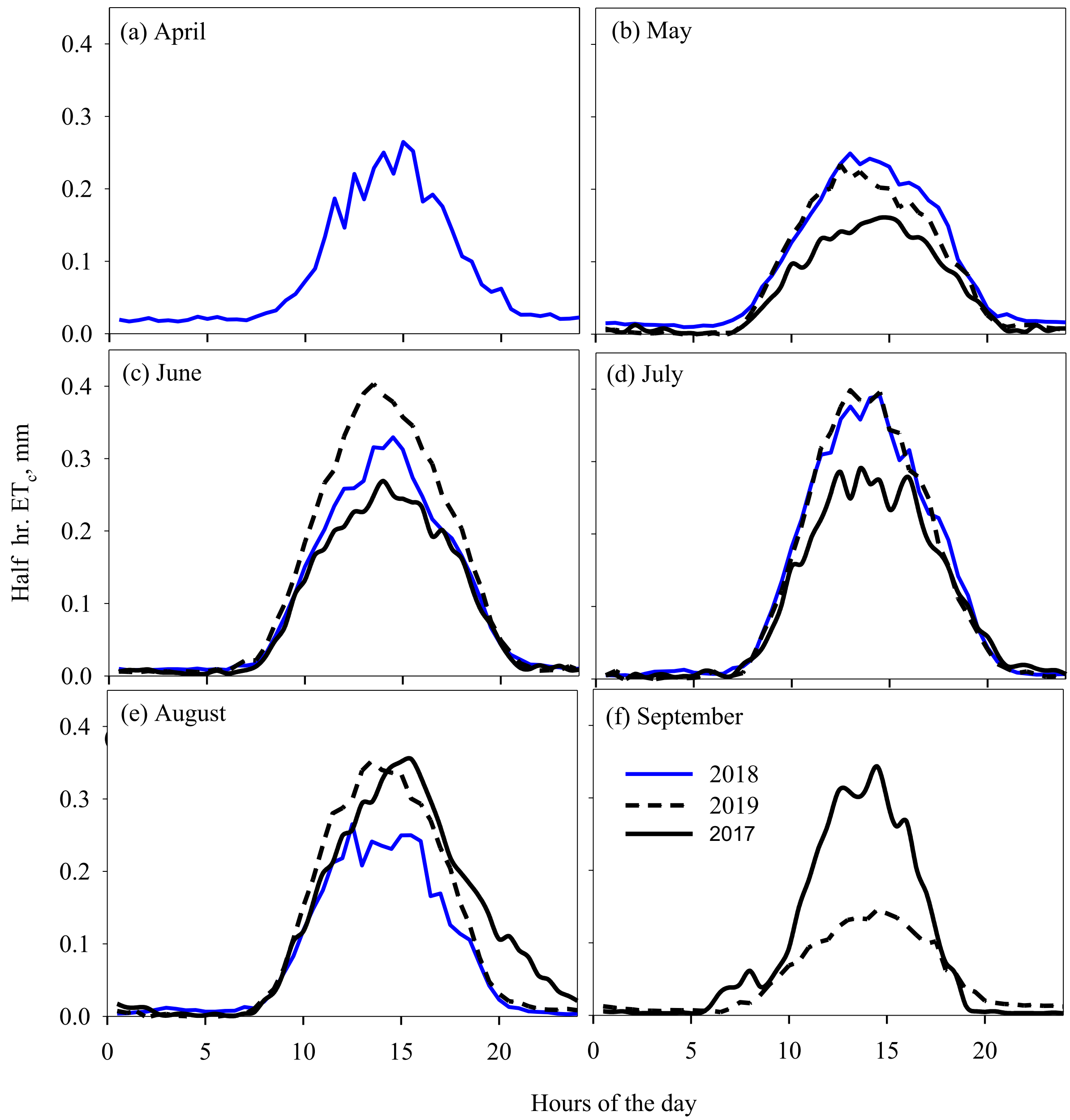


Fig. 6 Comparison between monthly averaged diurnal patterns of half-hourly soybean evapotranspiration (ET_c) 2017, 2018, and 2019 crop seasons

in the relatively fewer rainfall events this month this year (Figs. 1, 3).

Monthly averaged daily ET_c during the crop season in 2018 ranged between 2.4 mm in September and 6.2 mm in June with a seasonal average of 5.2 mm (Table 2). In 2019, ET_c ranged between 2.1 mm in May and 5.9 mm in August and September, with a seasonal average of 4.6 mm. Across the three crop seasons, the monthly average daily ET_c varied between 4.1 mm in May and 5.4 mm in July, and the average seasonal daily ET_c was 4.5 mm (Table 2). The total seasonal, on average, 130 DAE, ET_c in 2017, 2018, 2019 were 584, 640, and 593 mm, respectively, with an average of 605 mm (Table 2). The enhanced ET_c in 2018 compared to 2017 and 2019 was due to higher T_a as reflected in the higher number of cumulative degree days in 2018, and higher R_g received (Fig. 4, R_g not shown).

Seasonally averaged daily ET_o was 4.4 mm with monthly values ranging from 4.0 to 4.9 mm in 2017, 4.8 mm with monthly values between 3.5 to 5.1 mm in 2018, and 4.9 mm with monthly values ranging between 4.6 and 5.4 mm in 2019. Similarly, in 2017, 2018, and 2019, the seasonally averaged daily ETr was 5.4 mm

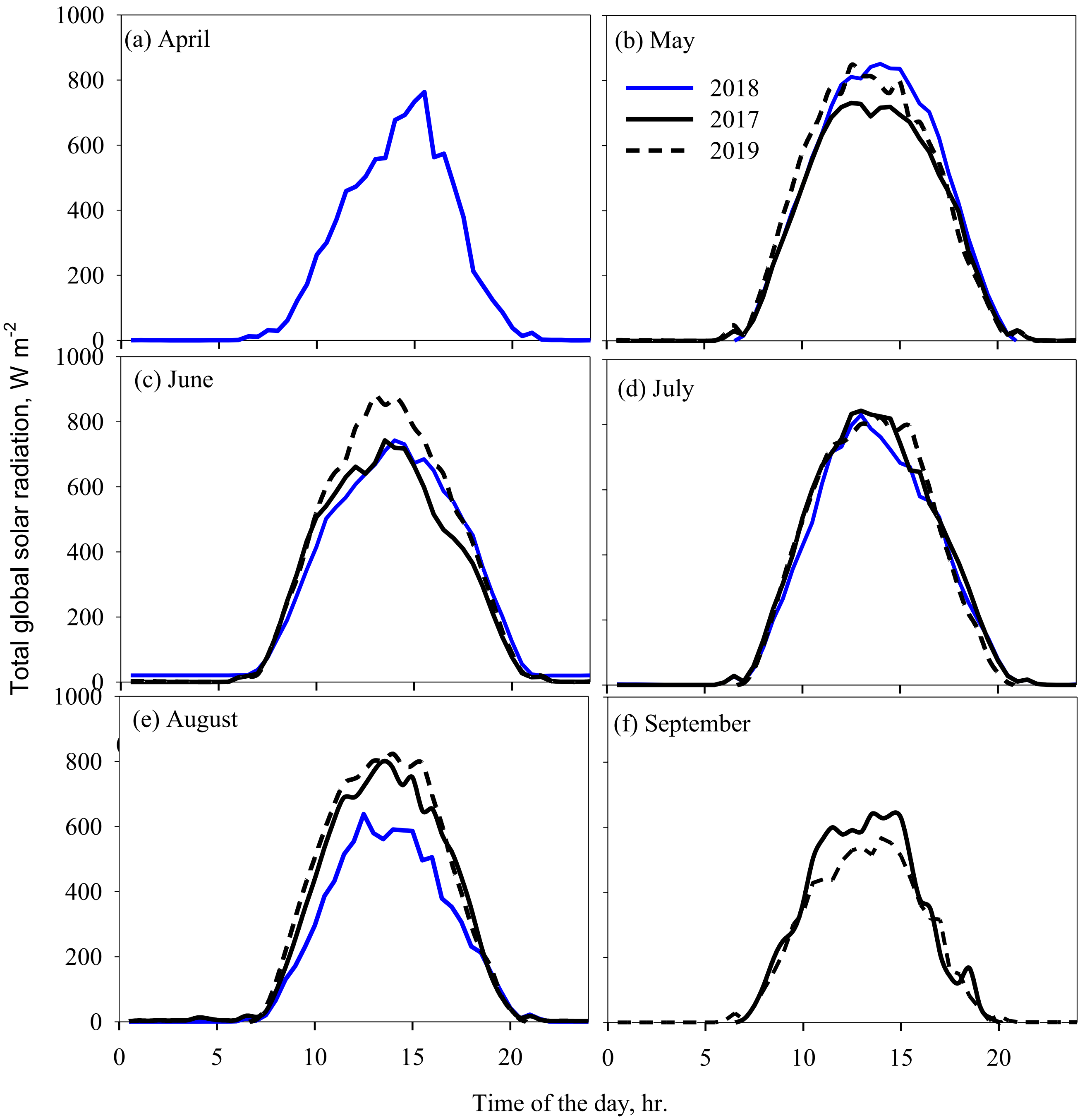


Fig. 7 Comparison between monthly averaged diurnal patterns of half-hourly global solar radiation (R_g) measured under standard conditions in 2017, 2018, and 2019 soybean crop seasons

(monthly between 4.9 and 5.9 mm), 5.8 mm (monthly averages between 4.4 and 6.0 mm), and 6.0 mm w(monthly values between 5.6 and 6.5 mm), respectively (Table 2). Averaged across 2017 through 2019, seasonal total ET_o, and ET_r were 588 (2% less than ET_c) and 716 mm (40% higher than ET_c), respectively (Table 2, 3). These seasonal total ET_o and ET_r values were 2% less than (-2% in Table 3) and 24% higher than seasonal average ET_c. The seasonal values of ET_r were higher than ET_o by 23, 21, and 22% (average 21%) in 2017, 2018, and 2019, respectively (Table 3). Based on a 3-year study in a semi-arid climate of North Platte (Nebraska, USA), Payero and Iramk (2013) reported ET_r values 32.3% higher than ET_o.

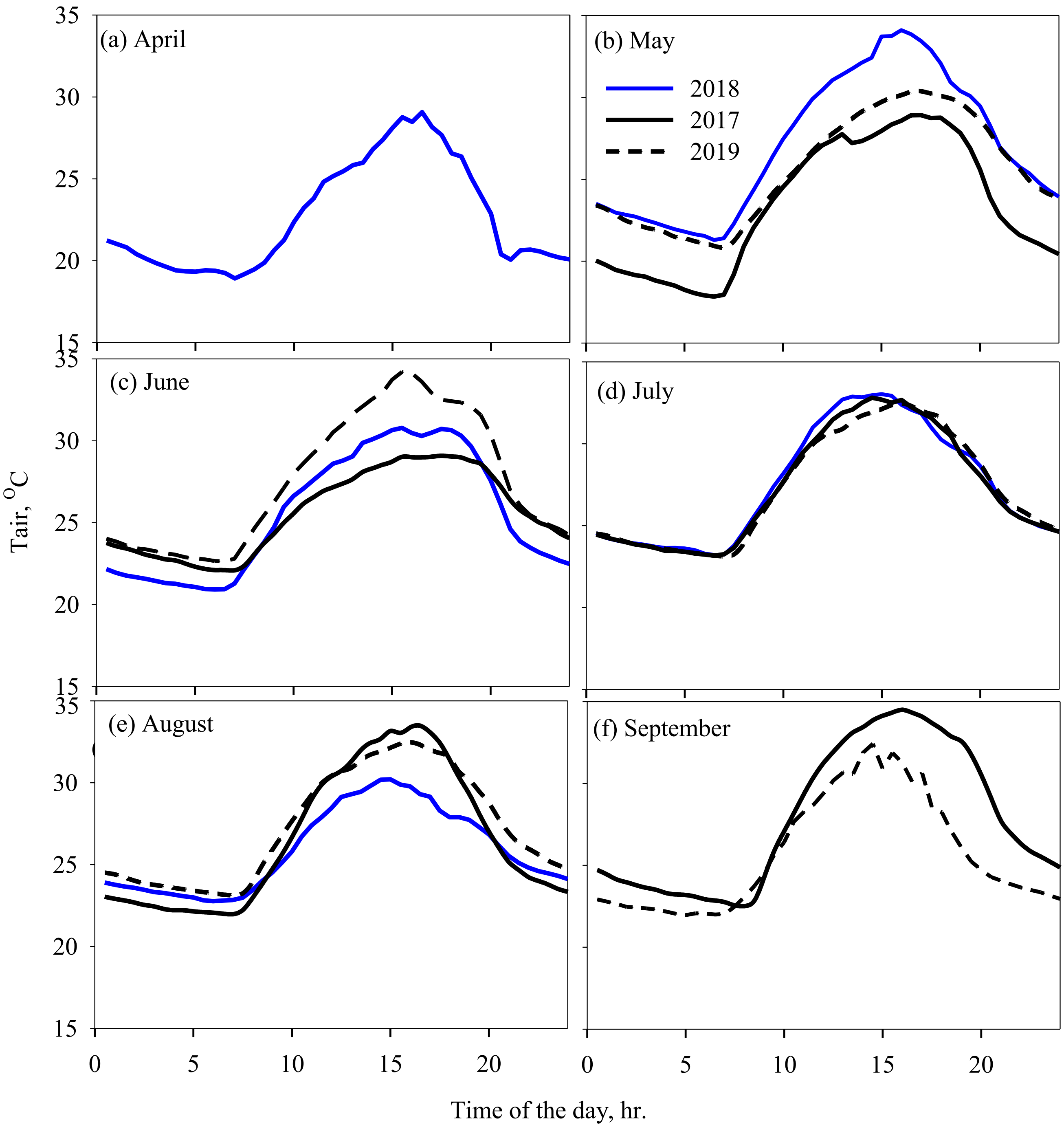


Fig. 8 Comparison between monthly averaged diurnal patterns of half-hourly air temperature (Tair) measured under standard conditions in 2017, 2018, and 2019 soybean crop seasons

Measured K_c for soybean

For scheduling crop irrigations, a crop-specific K_c from and a reference crop ET computed from measured weather da T_a can provide a reasonably accurate estimate of crop irrigation water requirements (Doorenbos and Pruitt 1977; Allen et al. 1998; Hunsaker et al. 2003; Farahani 2008). When Doorenbos and Pruitt (1977) and Allen et al. (1998) reported K_c values for a diversity of cereal, legume, and tree crops, applicability of those values in computing irrigation water requirements across locations, soils, and climates was a concern for long in the literature (Jagtap and Jones 1989; Howell et al. 2004, 2006; Karam et al. 2007; Farahani et al. 2008; Farg et al. 2012; Irmak et al. 2013;

Table 2 Monthly averaged daily soybean evapotranspiration (ET_c), seasonally averaged daily ET_c, and total seasonal ET_c measured using the EC method, and grass (ET_o) and alfalfa (ET_r) reference evapotranspiration computed from weather data in 2017, 2018, and 2019 soybean seasons

ET method	Monthly averaged daily evapotranspiration Mm					Seasonal averaged ET_c, mm	Total seasonal ET_c, mm
	May	June	July	Aug	Sept		
2017							
Average ET_c	3.6	4.9	4.3	4.2	–	4.3	584
Average ET_o	4.2	4.5	4.9	4.0	–	4.4	548
Average ET_r	5.3	5.5	5.9	4.9	–	5.4	674
2018							
Average ET_c	3.7	6.2	5.8	5.3	2.4	5.2	640
Average ET_o	5.0	5.1	4.6	4.5	3.5	4.8	588
Average ET_r	6.0	6.0	5.6	5.5	4.4	5.8	709
2019							
Average ET_c	2.1	4.4	4.7	5.9	5.9	4.6	593
Average ET_o	5.0	4.6	4.9	4.8	5.4	4.9	629
Average ET_r	6.2	5.6	6.0	5.8	6.5	6.0	766
2017–2019							
Average ET_c	4.1	4.5	5.4	4.7	4.2	4.5	605
Average ET_o	4.8	4.9	4.8	4.4	4.5	4.7	588
Average ET_r	5.8	5.5	5.8	5.3	5.5	5.7	716

ET is evapotranspiration

Table 3 Daily and seasonally averaged soybean evapotranspiration (ET_c) measured using the eddy covariance method in 2017, 2018, and 2019. ET_r is alfalfa, and ET_o is grass reference crop evapotranspiration. K_{cr} and K_{co} are crop coefficients for alfalfa and grass reference crops, respectively

Comparisons	May	June	July	Aug	Sept	Seasonal
	Relative differences, %					
2017						
$[(ET_r - ET_c)/ET_c]$	47	12	37	17	–	26
$[(ET_o - ET_c)/ET_c]$	17	− 8	14	− 5	–	2
$[(ET_r - ET_o)/ET_o]$	26	22	20	23	–	23
2018						
$[(ET_r - ET_c)/ET_c]$	62	− 3	− 3	4	83	12
$[(ET_o - ET_c)/ET_c]$	35	− 18	− 21	− 15	46	− 8
$[(ET_r - ET_o)/ET_o]$	20	18	22	22	26	21
2019						
$[(ET_r - ET_c)/ET_c]$	195	27	28	−2	10	30
$[(ET_o - ET_c)/ET_c]$	138	5	4	− 19	− 8	7
$[(ET_r - ET_o)/ET_o]$	24	22	22	20	20	22
Average 2017–2019						
$[(ET_r - ET_c)/ET_c]$	41	22	7	13	31	24
$[(ET_o - ET_c)/ET_c]$	17	9	− 11	− 6	7	− 2
$[(ET_r - ET_o)/ET_o]$	21	12	21	20	22	21

Anapalli et al. 2020). Since Doorenbos and Pruitt's (1977) first efforts in collating and publishing K_c values, efforts in current conventional crop breeding and advances in plant genetics and molecular biology also developed crop varieties with enhanced yield and water use efficiencies (Passioura 2002, 2004; Turner 2004a, b). The advent of such crop varieties and associated management technologies created novel crop water demand-supply scenarios in irrigated agriculture. In this evolving scenario, for sustainable irrigation water management, accurate knowledge of ET_c of modern crop varieties in climates and soils across locations is needed (Shiklomanov 2000; Irmak et al. 2013, 2014; Anapalli et al. 2018, 2019, 2020). In an eddy covariance study conducted in a semiarid climate in North Platte, Nebraska, USA, Payero and Irmak (2013) reported considerable deviations in measured K_c from the Allen et al. (1998) reported values. They recommended using locally quantified K_c values for irrigation scheduling to better conserve the limited water resources available for irrigations.

We observed considerable variations in the quantified daily K_{co} and K_{cr} from planting to physiological maturity, both within the season and across the crop seasons, in 2017, 2018, and 2019 (Fig. 9a–f). Monthly averaged K_{co} ranged between 0.88 and 1.16 in 2017, between 0.71 and 1.25 in 2018, and between 0.73 and 1.22 in 2019 (Table 4; Fig. 9 a, c, e). Monthly averaged K_{cr} ranged between 0.72 and 0.93 in 2017, 0.65 and 1.03 in 2018, and 0.62 and 0.9 in 2019 (Table 4; Fig. 9b, d, f).

Three-year average monthly K_{co} ranged between 0.79 in May and 1.18 in July and K_{cr} varied from 0.65 in May to 0.97 in July. The average seasonal value of K_{co} was 1.00, and K_{cr} was 0.80 (Table 4; Figs. 10, 11). On a seasonal scale, averaged from 2017 through 2019, ET_r values were 21% higher than ET_o, and the computed K_{cr} values were also 20 % higher than K_{co} (Table 4; Figs. 10, 11). The K_{co} provided in Allen

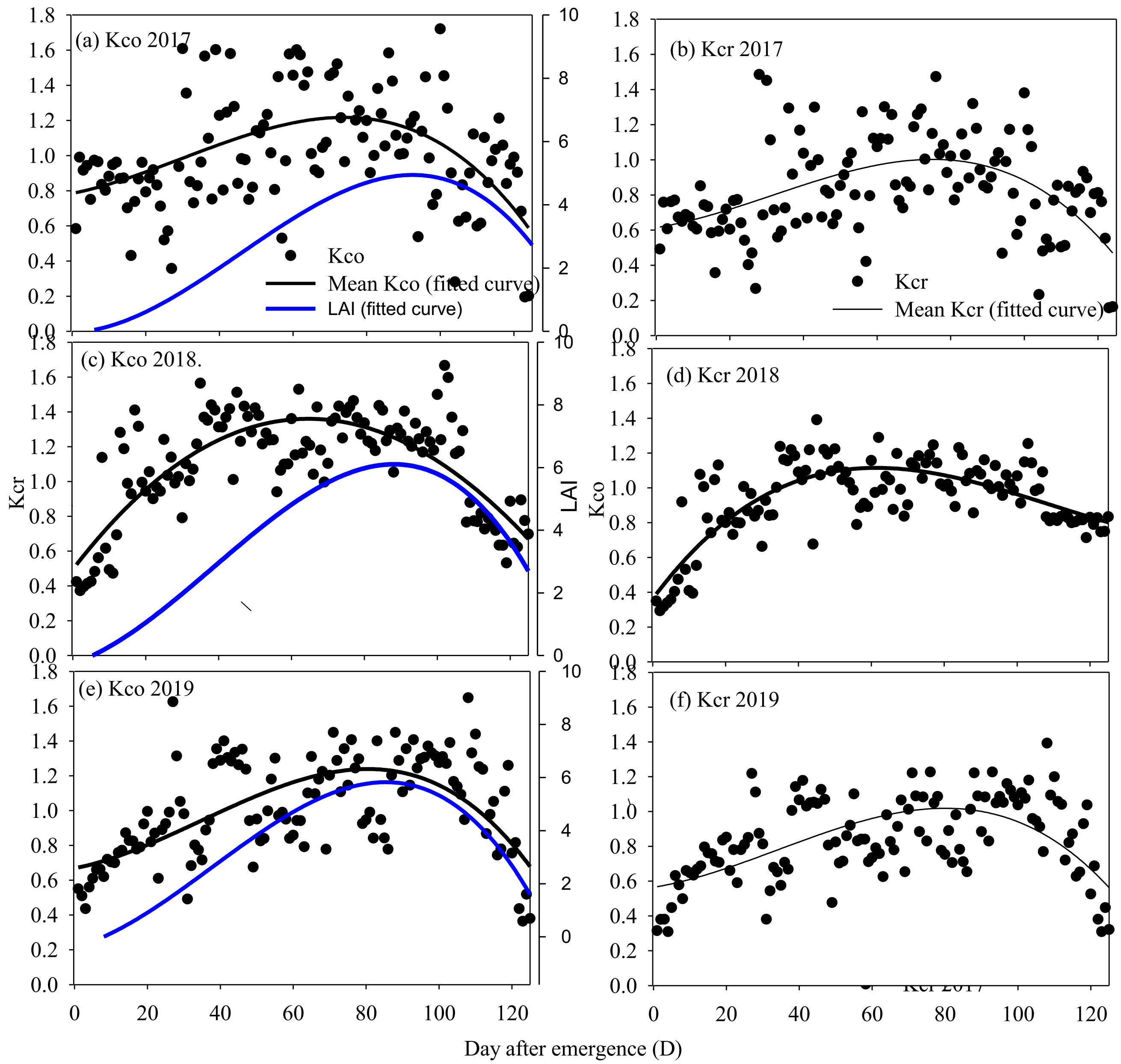


Fig. 9 Quantified daily crop coefficient computed for grass (K_{co}, panels **a**, **c**, **e**) and alfalfa (K_{cr}, panels **b**, **d**, **f**) reference crops in 2017, 2018, and 2019 (black dots). Cubic polynomial curves fitted to the K_{co} and K_{cr} values are also presented (continuous black lines). Cubic polynomials fitted to the measured soybean leaf area index (LAI) during the three crop seasons are also shown in panels **a**, **c**, and **e** (continuous blue lines)

Table 4 Monthly and seasonally averaged daily crop coefficients for soybean computed for alfalfa (K_{cr}) and grass (K_{co}) reference crops in 2017, 2018, and 2019

Month	Monthly averaged daily crop coefficients (K_c)					
	May	June	July	August	September	Seasonal average
2017						
Average K_{co}	0.91	1.16	0.88	1.08	–	1.00
Average K_{cr}	0.72	0.93	0.70	0.87	–	0.80
2018						
Average K_{co}	0.80	1.23	1.25	1.20	0.71	1.00
Average K_{cr}	0.65	1.03	1.03	1.02	0.80	0.90
2019						
Average K_{co}	0.73	1.03	1.10	1.22	0.75	1.00
Average K_{cr}	0.62	0.85	0.90	1.02	0.62	0.80
Average for 2017–2019						
Average K_{co}	0.79	1.07	1.18	1.09	0.92	1.00
Average K_{cr}	0.65	0.88	0.97	0.90	0.79	0.80

et al. (1998) representing the initial-, mid-, and end-season growth stages of soybean were 0.5, 1.15, and 0.5, whereas the measured values were about 0.79, 1.18, and 0.92, respectively (Table 4). Using a single season combination of a residual energy balance and eddy covariance da T_a collected in experimental fields using a different soybean cultivar in clay soil, as stated above, Anapalli et al. (2018) reported weekly averaged K_c values between 0.56 and 1.29 for grass and between 0.46 and 1.02 for alfalfa reference crops. This study used da T_a collected over three crop seasons to derive daily K_c values, which can be more dependable for long-term use in water management applications daily.

In general, K_{cr} and K_{co} increased with increasing leaf expansion growth (increase in LAI) (Fig. 9a, c, e). A cubic polynomial curve explained well the K_{co} and K_{cr} across the three crop seasons, and they followed a similar pattern and overlapped substantially (Fig. 9a–f). Therefore, to get a general K_c curve, the 3-year da T_a were pooled, and an average K_c curve, again cubic polynomials, was constructed separately for K_{cr} and K_{co} (Fig. 10 a, b). The predictive equation relating DAE with K_{cr} and K_{co} is given in Fig 11. These cubic polynomial relationships can be directly used along with DAE for deriving K_{cr} and K_{co} values in Eq. 3 or 4 for computing ET_c for irrigation scheduling based on ETo or ETr computed from location-specific weather data.

Some researchers noted the advantages of developing K_c curves as a function of GDD (Ayars et al. 2008; Lopez-Urrea 2009b; Sammis et al. 1985). This would imply that irrigation scheduling for crops can be more effective if based on parameters such as Growing Degree Days (GDD), rather than merely on DAE (McMaster and Wilhelm 1997; Scholberg et al. 2000). Therefore, computed K_{co} and K_{cr} as a function of average GDD required by the crop from seedling emergence to physiological maturity also were presented (Fig. 11).

Conclusions

Basing irrigation schedules on accurate water requirements in response to current weather in crop fields can help optimize irrigation water productivity. In weather-based irrigation scheduling, the location-specific crop water requirement is computed as a product of a reference crop ET calculated from weather da T_a and crop-specific K_c value. In this 3-year study, water requirements (ETc) of soybean (cv. 46X6) in silty clay soil in a humid climate were quantified. This ET_c was used for generating K_c that links dynamic, location-specific ET_c with a grass reference ET (ETco) and alfalfa reference ET (ET_{cr}) computed from location-specific weather data. Calculated daily K_{co} ranged from 0.79 to 1.18, and K_{cr} ranged from 0.65 to 0.97. Over the three crop seasons, the soybean ET_c for the 130-day soybean crop varied between 584 and 640 mm, producing, respectively, 4771 and 5783 kg ha^{-1} soybean grains. Average seasonal ET_c, ET_o, and ET_r were 605, 588, and 716 mm, respectively. On average, the calculated ETr was 21% more than ET_o. The K_{co} and K_{cr} quantified in this study can help develop soybean irrigation schedules, across climates and soils, based on ET_o, and ET_r computed from real-time weather da T_a collected at specific locations of interest. This study is being continued for quantifying ET_c and K_c in response to long-term climate at multiple locations, which can be used with better confidence in irrigation scheduling across different climates, soils, and locations.

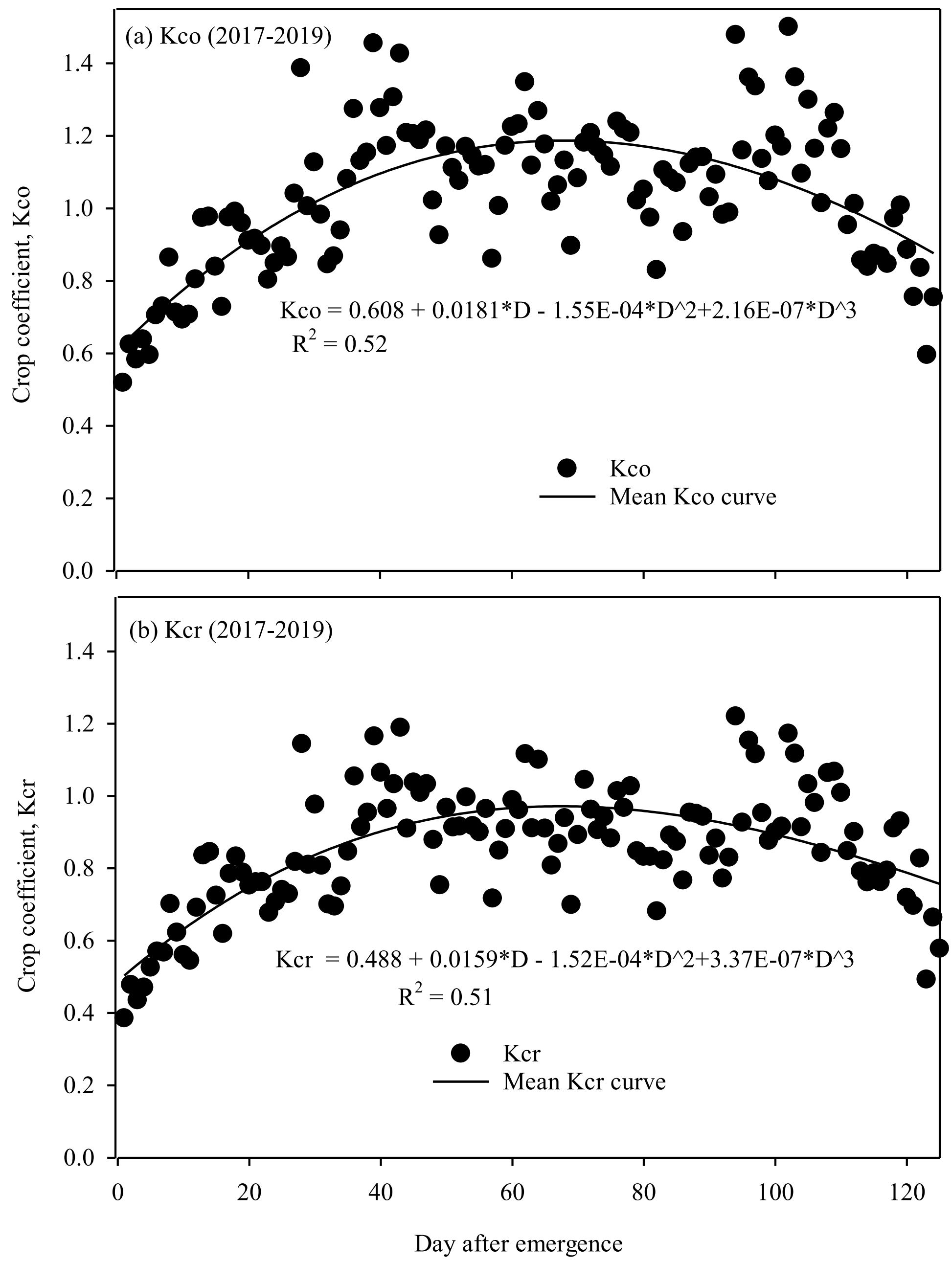


Fig. 10 **a** Three-year (2017–2019) average daily crop coefficient for grass (K_{co}) and **b** alfalfa (K_{cr}) reference crops for estimating soybean ET_c. The thin black lines in panels a and b show the cubic polynomials fitted to the data

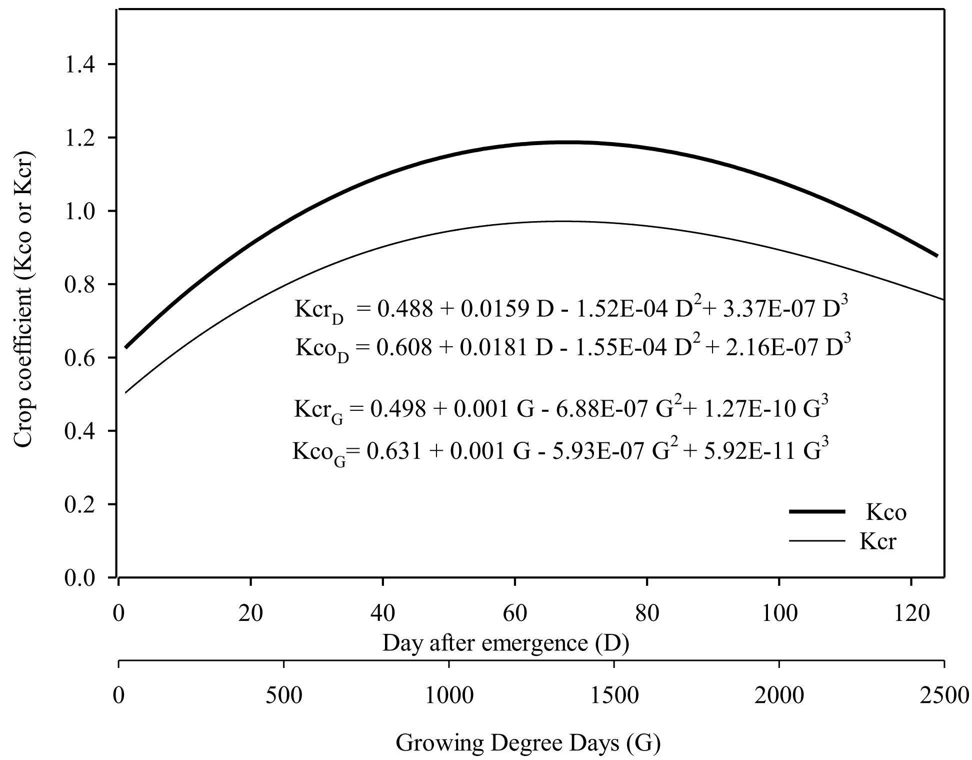


Fig. 11 Cubic polynomials representing the 3 years (2017–2019) average daily crop coefficient for grass (K_{co}) and (b) alfalfa (K_{cr}) reference crops presented as functions of (1) day after emergence (D) and (2) growing degree days (G, °C), for estimating soybean evapotranspiration (ET_c). $K_{co\,D}$ is K_{co} as a function of D, $K_{cr\,D}$ is K_{cr} as a function of D, $K_{co\,G}$ is K_{co} as a function of G. Kcr_G is K_{cr} as a function of G

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