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Quantifying soybean evapotranspiration using an eddy covariance approach

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ABSTRACT

Quantification of evapotranspiration (ET_c) from crops is critical in irrigation scheduling in agriculture. In a pioneering study, in the Mississippi (MS) Delta region, we quantified ET_c from soybean (*Glycine max* L.) using the eddy covariance (EC) approach (ET_e). We also monitored ET_c using a residual energy balance (EB) approach (ET_b) and compared the fluxes. The unclosed energy fluxes in the EC were post-analysis closed using the Bowen ratio (BR) and latent heat (LH) methods. The measurements were conducted in a 35-ha clay soil planted to irrigated soybean in the lower MS Delta in 2016. The crop reached physiological maturity in 126 days after emergence (DAE). Maximum LAI was 5.7 and average grain yield was 4900 kg ha^{-1}. The EC showed an energy balance closure of about 88% on a 30 min and 90% on a daily flux accumulation. The ET_e was 18.2, 6.8, and 15.9% lower than ET_b, and ET_e corrected using BR (ET_{ebr}) and LH (ET_{ele}) approaches, respectively. Average soybean seasonal ET_e, ET_b, ET_{ebr}, and ET_{ele} were 422, 499, 451, and 490 mm, respectively. Seasonal reference-crop evapotranspiration for alfalfa (ET_o) and grass (ET_r) were 470 and 547 mm, respectively. Daily ET_e, ET_b, ET_{ebr}, ET_{ele}, ET_o, and ET_r averaged across the whole season were 4.4, 5.2, 4.7, 5.1, 4.9, and 5.7 mm, respectively. For scheduling irrigations, based on grass and alfalfa reference crop ET calculated from weather data, averages of the ET_e, ET_b, ET_{ebr}, and ET_{ele} daily estimates were used in deriving crop coefficients (K_c). The K_c for grass reference varied between 0.56 and 1.29 and for alfalfa reference varied between 0.56 and 1.02. The information developed will be useful for scheduling irrigations in the MS Delta region, and the methodology developed can be adapted for generating similar information elsewhere.

1. Introduction

Overexploitation of groundwater resources for irrigation is threatening the sustainability of irrigated crop production systems across the globe (Dalin et al., 2017). The MS Delta, one of the most important agricultural production regions in the USA, relies mostly on groundwater from the MS River Valley Alluvial Aquifer for meeting its irrigation water needs. Typically, over 60% of all the crops grown in this region are irrigated. Soybean represents about 53% of the irrigated area (366,163 ha), with the remaining 47% shared between rice, corn, cotton, and aquaculture (Heatherly, 2014; Powers, 2007). Pumping water from this shallow aquifer beyond its natural recharge levels has resulted in significant aquifer depletions, threatening the future water availability opportunities for irrigation in this region (Clark and Hart, 2009). Lack of scientific research integrating crop water demands (evapotranspiration, ET_c) with available water supplies in water management decision making, has been attributed as one of the major reasons for this trend. Traditionally, field experiments for quantifying ET_c were conducted for two or more years and crop variety-specific crop coefficients (K_c) were developed for scheduling irrigations. These K_c values were used by agronomists and crop consultants to schedule crop irrigations, across locations and seasons, based on weather data normally monitored by national weather agencies at those locations (Payero and Irmak, 2013). In the agricultural scenario in the MS region, the farmers depend upon local seed companies for their seedstock requirements. The same seed variety on average is available only for 3–4 years. The crop ET_c demands change with canopy characteristics, ground surface cover, maturity group, and pest and disease susceptibilities that are crop variety specific (Irmak, 2017). So, unlike in the past, an irrigation agronomist or consultant cannot wait for collecting 2–3 years of field data to develop robust ET_c and K_c information for irrigation scheduling, for by that time the same varieties are no longer available in the region for planting. Therefore, in the current agricultural scenario in this region and in similar situations elsewhere, agronomists are required to determine rapid but robust and scientifically sound solutions for developing irrigation scheduling information

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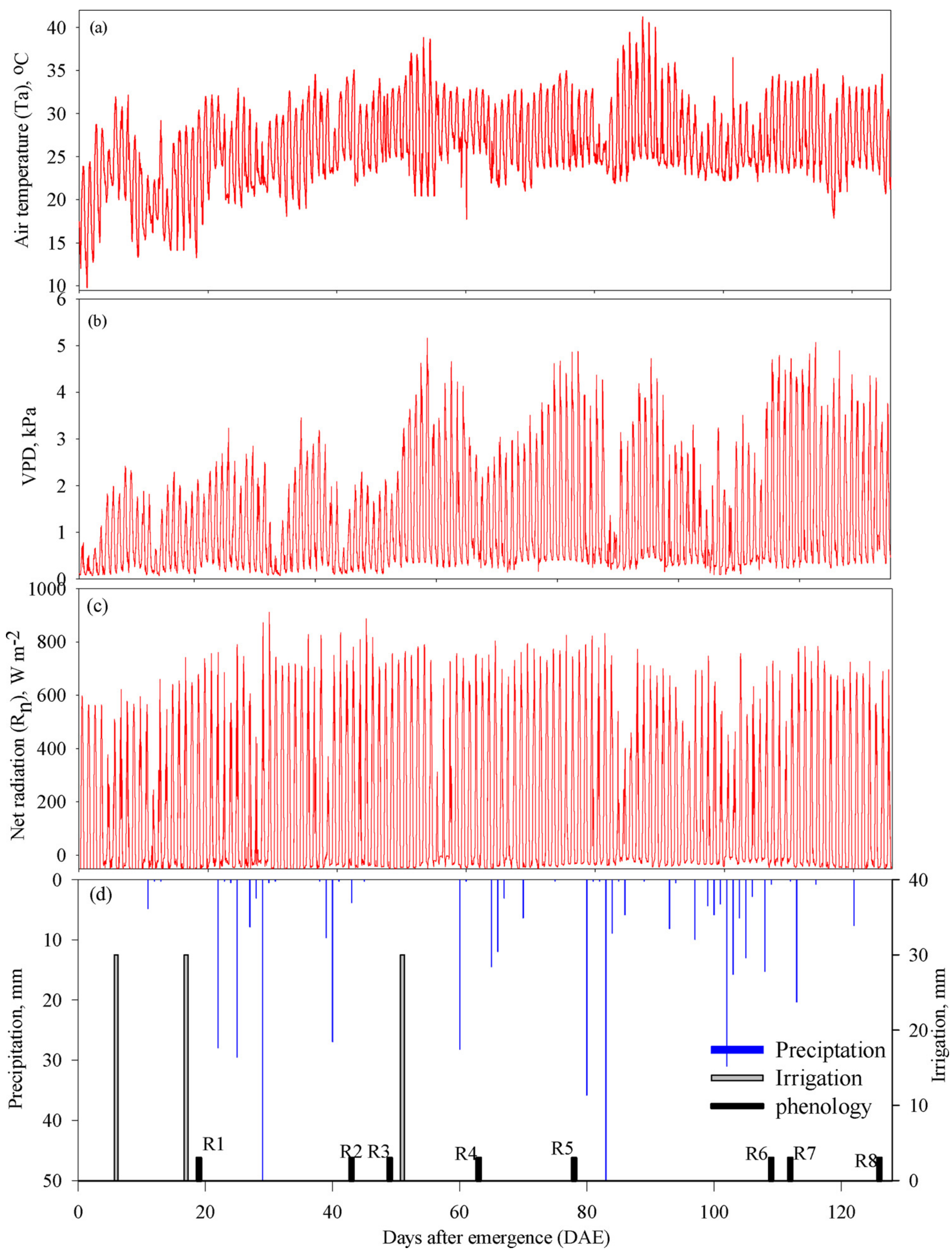

Fig. 1. Observed (a) air temperature, (b) vapor pressure deficit (VPD), (c) net radiation, and (d) precipitation, irrigation, and soybean crop phenology during the 2016 growing season (R1, R2… R8).

for conserving the limited water resources available for irrigation. The study presented here is an example in this direction.

In the search for an ideal method for quantifying ET from cropping systems, many methods of varying complexity have been reported in the literature, including soil water balance, residual energy balance (EB), and Bowen ratio (BR) modeling; field lysimeters; sap flow measurements; and eddy covariance (EC) (Shi et al., 2008; Wilson et al., 2001). Among these methods, EC and EB have emerged as two scientifically sound and easy to install and operate methods for collection of accurate ET_c data in the crop field for irrigation water management applications (Baldocchi, 2003; Foken and Wichura, 1996; Parent and Anctil, 2012; Shurpali et al., 2013; Tallec et al., 2013; Uddin et al., 2013; Zhao et al., 2007).

The inability of EC measurements in balancing the energy inputs with the energy outputs from cropping systems, known as energy balance non-closure problem (EBC), continue to haunt this method, hindering its applications in irrigation water management (Foken et al., 2011; Foken, 2006; Gao et al., 2017; Leuning et al., 2012; Liu et al., 2017; Mauder et al., 2007; Oncley et al., 2007). As no universal solution has emerged to resolve the EBC, a few methods have been proposed for post-analysis forcing of a closure in the computed fluxes by making some assumptions about energy dynamics in cropping systems. One of the methods is based on the Bowen ratio (BR), which assumes that the BR of the unclosed energy fluxes has the same BR as the measured fluxes (Blanken et al., 1997; Ingwersen et al., 2011; Twine et al., 2000). Another method is to fully assign the unclosed energies to the latent energy (LE) flux (LH method; Twine et al., 2000). In another method, the whole unclosed energies were added the sensible heat fluxes (H) (Ingwersen et al., 2011). Payero and Irmak (2013) used the LH method to account for the unclosed energies in their EC measurements of soybean ET_c in Nebraska, USA.

Ground-based continuous, intensive, quantitative monitoring of energy balance components in cropping fields provides an alternative method for quantifying ET_c based on a residual energy balance (EB)

Table 1
Observed phenological growth stages, leaf area index (LAI), plant height, and sensor placement height above the soybean crop in 2016. Values in parenthesis are one standard deviation (SD) about the mean. DAE is days after emergence.

Phenological growth stages	Date observed, DAE	LAI	Plant height (m)	Sensor height above ground (m)	Biomass (kg ha^{-1})
Planting	–	–	–	2.0	–
Emergence (VE)	7[a]	–	–	2.0	–
Beginning Bloom (R1)	19	1.0	0.3	2.3	–
Full flowering (R2)	43	2.9	0.4	2.4	–
Beginning pod development (R3)	49	3.0	0.6	2.6	1667 (231)
Full pod (R4)	63	5.7	0.9	2.9	–
Full seed (R5)	78	5.5	1.1	3.1	5066 (412)
Full seed (R6)	109	2.6	1.1	3.1	–
Beginning maturity (R7)	112	2.5	1.1	3.1	–
Full maturity (R8)	126	0.4	1.1	3.1	–

[a] Emergence of seedling occurred seven days after planting, so this is not in DAE.

approach (Brown and Rosenberg, 1973; Heilman and Kanemasu, 1976; Su, 2002; Allen et al., 2007; Cammalleri et al., 2012). The LE and H fluxes computed from the EB approach can provide upper bounds for comparing and evaluating unclosed energy fluxes computed from the EC method, as well as increase confidence in the EC measurements for their applications in water management research (Wohlfahrt and Widmoser, 2013). Verma et al. (1976) developed and used an EB approach for monitoring ET_c from sorghum (*Sorghum bicolor* L.) and millet (*Panicum melimeurn* L.) that compared well with lysimetric measurements. Heilman and Kanemasu (1976) developed and applied an EB method and obtained ET_c estimates within 4% and 15% of lysimetric measurements for soybean and sorghum, respectively.

The ET_c information, in general, is developed for the climate of the location and applied across climates and seasons where such information is seldom available. In such situations, for estimating ET_c, Doorenbos and Pruit (1977) recommended a simple two-step approach in which ET_c is calculated from weather data monitored by national weather agencies, by defining ET_c for a reference crop surface, such as fully irrigated short grass or alfalfa and multiplying it with a crop coefficient (K_c) for the crop of interest to get ET_c (Allen et al., 1998). Our objectives of this study were to (1) quantify soybean ET_c using both EC and EB methods, (2) close the EC data for unclosed flux energies using BR and LH closure methods, and (3) develop K_c for predicting soybean ET from grass and alfalfa reference ET computed from climatological data.

2. Materials and methods

2.1. Experiment

An experiment was conducted at the USDA-ARS Crop Production Systems Research Unit farm, Stoneville, MS, USA (33° 42′ N, 90° 55′ W, ~32 m elevation above sea level). Soybean (soybean phase of a soybean-corn rotation experiment) was grown in a ~35 ha field, with less than 1% slope that was artificially maintained for draining out the rain and irrigation water in excess of the soil infiltration rates. An EC tower, carrying both EC and EB instrumentation, was installed in the middle of the field with fetch over 250 m in all directions. The sensors were maintained constantly at 2 m above the canopy throughout the study using height-adjustable towers. The climate of the region is sub-tropical humid with mild winter and warm summers. The location receives an average annual precipitation of about 1300 mm, with 30% received

Fig. 2. The eddy covariance system installed in the soybean field for measuring evapotranspiration. The tower on the left carries the eddy covariance and energy balance monitoring systems on the same tower, and the tower on the right is for measuring spectral characteristics of soybean canopy but not used in this study.

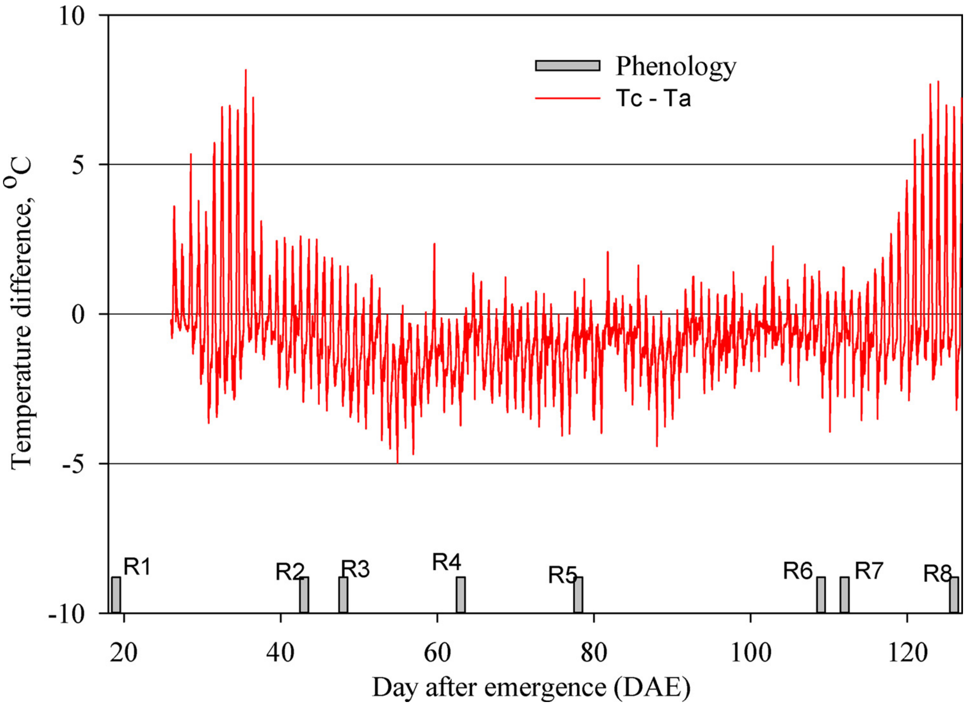

Fig. 3. Difference between measured canopy surface temperature (T_c) and air temperature (T_a) at 2 m above the canopy. R1 to R8 are the observed soybean crop phenology (Table 1) during the growing season.

during the soybean growing season from May to August (Kebede et al., 2014; Anapalli et al., 2016). Dominant soil type is a poorly-drained Tunica clay (clayey over loamy, montmorillonitic, non-acid, thermic Vertic Halaquepet) to a depth of about 1.2 m as measured. The field had been planted to soybean since 2010 under conventional tillage practices; deep tillage to break clay pans and overturn soils, bury crop residue and kill weeds, in three passes followed by tillage to generate furrows and ridges for soybean planting and to facilitate furrow irrigations. Soybean (cv. Dyna Grow 31RY45, a mid-maturity group IV cultivar) was planted (97-cm row spacing) on April 28, 2016 on north-south rows. The soybean plants fully emerged on May 10 and established a uniform crop stand and attained physiological maturity on September 9, 2016 (126 days after emergence). No fertilizers were applied.

The field was furrow irrigated by supplying water through polyethylene pipe at the head end of crop rows to maintain water content in a 30-cm soil layer above 65% of maximum plant available water. About 30 mm of water was applied at each irrigation event; a seasonal total of 90 mm water was supplied in three irrigation events from May 24 to July 18, 2016 (Fig. 1). The leaf area index (LAI) was measured every other week using an AccuPAR LP-80 Ceptometer (Decagon Devices Inc., Pullman, WA USA). Plant heights (h) were monitored manually every week (Table 1). All the plant measurements were replicated at four random locations in the field and used in the calculation of standard error (SD) of measurements. Soybean growth stages were recorded based on Fehr et al. (1971) recommendations (Table 1). On the seventh day after the R8 stage, grains from the whole farm area were harvested and weighed using combines. Grain weight was adjusted to 13.5% moisture content. Water content and temperature at 8 and 30 cm soil layers were monitored using Stevens HydraProbe (Steven Water Monitoring Systems Inc., Portland, OR USA). These sensors were installed three each on the north and south facing sides of the ridges on which soybean plants were grown and two on the furrow in between them.

A fourth-order polynomial equation,

$$LAI = 0.0142\, d^4 - 0.3063\, d^3 + 1.9345\, d^2 - 3.1116\, d + 1.5556 \quad (1)$$

was fitted ($R^2 = 0.96$) between the measured LAI and days after soybean seedling emergence (*d*, days) to obtain continuous, daily values of LAI. A second polynomial equation,

$$h = -0.0215\, d^2 + 0.3237\, d - 0.081 \quad (2)$$

was fitted ($R^2 = 0.98$) to measured plant height, h, and, d, to obtain continuous daily estimates of h (m).

2.2. Eddy covariance-based ET measurement

2.2.1. Water vapor flux measurements using eddy covariance systems

In the EC system, vertical velocity of eddy transport and sonic temperature were measured using a Gill New Wind Master 3D sonic anemometer (GILL-WM, Gill Instruments, Lymington, UK), and water vapor density in the eddies was measured using the LI-7500-RS open-path infrared gas analyzer (IRGA; LI-COR Inc., Nebraska, USA). All instruments were calibrated annually before moving to the field for measurements. The sensors were mounted on a telescopic, height-adjustable tower, and the sensor height was maintained above the canopy constantly at twice the crop canopy height from the ground (Fig. 2; Table 1). The maximum plant height measured during the season was 1.1 m. Whenever there was an increase in crop height that exceeded 5 cm, the sensor heights were adjusted to maintain constant sensor height above the canopy. The LI -7500 and sonic anemometer data were collected at 10 Hz frequency.

2.2.2. Data processing, screening, and gap filling of fluxes

The raw eddy flux data recorded at 10 Hz frequency were processed in-the-field on a SmartFlux™ (LI-COR Inc.) microprocessor at 30-min intervals (30-min block averaged) using the EddyPro software version 6.1.0 (LI-COR Inc.) in express mode. In EddyPro, standardized correction procedures were applied to the high frequency (10 Hz) data: anemometer tilt correction using double coordinate rotation, time-lag compensation, 30-min block averaging, and statistical tests(Vickers and Mahrt, 1997); spike filtering and spectral correction (Moncrieff et al., 2004, 1997); anemometer temperature correction for humidity (Van Dijk et al., 2004); and, compensation for air density fluctuations (Webb et al., 1980).

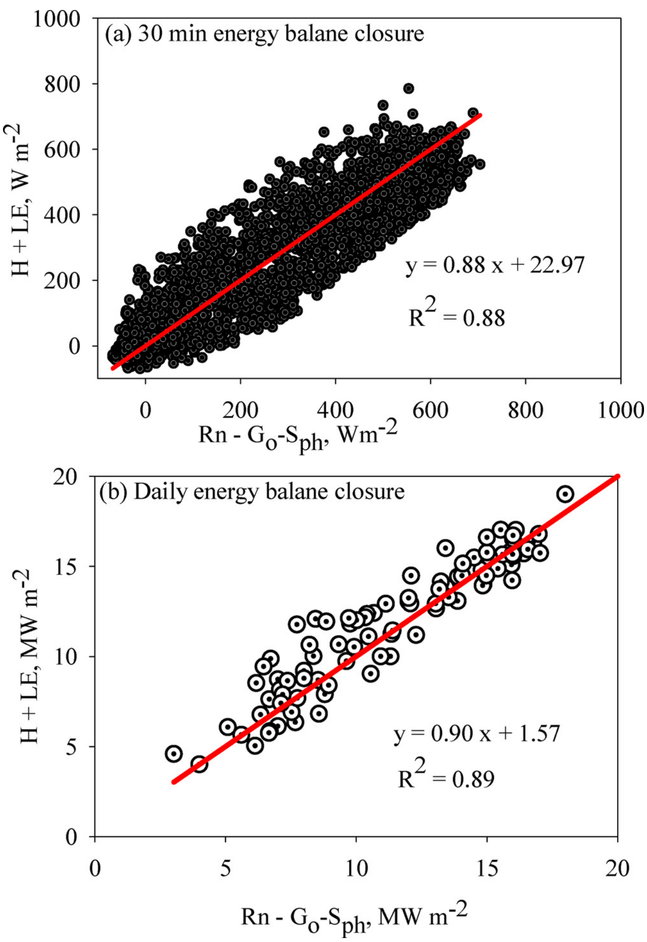

Fig. 4. Regression between measured or estimated energy input ($R_n - G_0 - S_{ph}$) and energy use/output (H + LE) using the eddy covariance system (energy balance closure) in soybean in 2016. (a) represents the energy balance closure with fluxes computed at 30 min. intervals and (b) the 30 min. fluxes accumulated to daily intervals. R^2 is the coefficient of determination.

The processed EddyPro data carries quality flags ranging in value from 0 (highest quality) to 2 (lowest quality) (Mauder and Foken, 2011). The computed fluxes with a quality flag of 2 and statistical outliers beyond ± 3.5 standard deviation based on a 14-day running window were discarded (Wagle and Kakani, 2014). Turbulent fluxes were filtered to keep within the realistic range from −200 to 500 W m^{-2} for H and −200 to 800 W m^{-2} for LE (Sun et al., 2010; Wagle et al., 2015). Gaps in flux data were filled using the REddyProc package on R-Forge, available online from the Max Planck Institute for Biogeochemistry (https://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWebRPackage). More details on gap filling procedures are available on their website. Briefly, the gap filling of the eddy fluxes and meteorological data was performed with methods similar to those of 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).

2.2.3. Energy balance closure (EBC)

Only high quality (0 flags) and non-gap filled fluxes of H and LE were used to calculate EBC only when all four components, H, LE, net radiation (R_n), and soil heat flux (G_o) into or out of the soil, were available. We computed the EBC from a linear regression between available energy ($R_n - G_o - S_{bm} - S_{ph}$) and sums of turbulent fluxes (H + LE) using half-hourly values for the crop growing season, where S_{bm} and S_{ph} are energy stored in the biomass and energy used in the photosynthesis process, respectively.

The G_o was estimated using the following equation (Kimball et al., 1999):

$$G_0 = G_8 + Cs\Delta z\left(\frac{\Delta T}{\Delta t}\right) \tag{3}$$

where G_8 is the soil heat flux at 8 cm depth, Δz is the soil depth above the heat flux plate (8 m), Δt is the time between two consecutive soil temperature measurements, ΔT is the change in temperature in Δz during Δt, and C_S (the volumetric heat capacity of soil in the Δz) is calculated following de Vries (1963)

$$C_s = \%M * C_m + \%OM * C_{om} + \%SWC * C_w \tag{4}$$

where, M is the mineral, OM is the organic matter, and SWC is the volumetric water content in Δz soil depth; $C_m = 1.9$, $C_{om} = 2.5$, and $C_w = 4.2$ MJ m^{-3} °C^{-1} are volumetric heat capacities of minerals, organic matter, and soil water in Δz, respectively. We computed S_{bm} and S_{ph}, based on the procedure given by Meyers and Hollinger (2004): for computation of S_{ph}, a fixed canopy assimilation rate of 2.5 mg CO_2 m^{-1} s^{-1} per 28 W m^{-2} was assumed. However, we did not compute S_{bm} following the recommendations from past studies: Leuning et al. (2012) and Anderson and Wang (2014) reported negligible net energy gain or loss due to S_{bm} changes in the plant biomass, because, on a daily timescale, energy stored in the biomass in the morning is returned to the air in the afternoon and evening hours. Therefore, in this study, we initially computed energy fluxes at half-hour intervals, then accumulated those fluxes for the whole day and analyzed energy balance closure on a daily scale. This procedure eliminated the need for accounting for this storage in the energy balance equation.

2.2.4. Post-analysis correction of energy balance non-closure

We used two methods for closing the unaccounted energies in the measured EC fluxes of LE and H:

(1) The LE post-analysis closure method (LH, Twine et al., 2000) assumes that the H flux is accurately measured by the EC system, therefore, the whole unaccounted energy is added to the LE; and
(2) The BR post-analysis closure method assumes that the measured BR in the EC system was correct and the missing turbulent fluxes will also have the same BR (Blanken et al., 1997; Chávez et al., 2009; Twine et al., 2000). Under this assumption, the measured BR was used to partition the unclosed energy into its LE and H components and added to their base values. The method is described in detail by Chávez et al. (2009). In this study, we computed 30-min fluxes, and the BR value used for correction of the fluxes were based on the average BR values from 10.00 a.m. to 2.00 pm, as described by Kustas et al. (2005).

2.3. Energy balance quantification of ET

2.3.1. Micrometeorological measurements

The sensors for measuring energy balance components were also co-located on the EC tower and its sensors. The sensors for measuring T_a and relative humidity (Vaisala, HMP 155), net radiation (NR-LITE2, Kipp & Zonen Inc.), infrared canopy surface temperature (SI-111 Standard View Infrared Sensor, Apogee) from a view of the ground at a 60^{O} zenith angle, and wind direction and speed (Gill 2D-Sonic) were maintained at 2 m above the crop canopy along with the EC sensors. Three self-calibrating soil heat flux sensors (HP01SC, Hukseflux) were installed at an 8-cm depth in the soil. Water content and temperature in the 8-cm soil layer above the heat flux plates were monitored using a Stevens HydraProbe (Steven Water Monitoring Systems Inc.). Changes in heat energy storage above the flux plates were computed using Eqs. (3) and (4). All measurements started at planting and continued until harvest.

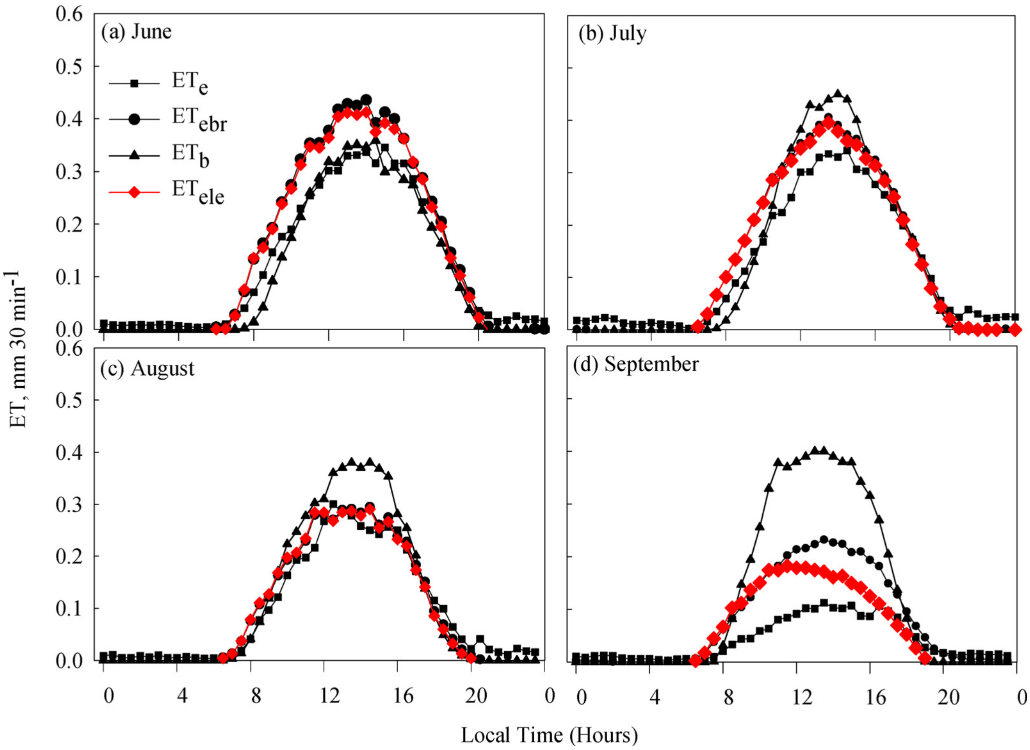

Fig. 5. Monthly averaged diurnal variations in evapotranspiration (ET) estimated from eddy covariance (ET_e), residual energy balance (ET_b), and ET_e post-closure corrected using Bowen ratio (ET_{ebr}) and latent heat (ET_{ele}) methods in June, July, August, and September.

2.3.2. Residual energy balance approach for ET

An energy balance equation for a cropped soil surface can be written as

$$R_n = LE + G_0 + H + S_{bm} + S_{ph} \tag{5}$$

All the energy balance components are considered positive when the flux is toward the crop surface and negative when the flux is away from the surface. The ET is calculated from Eq. (5) by dividing LE by the latent heat of vaporization of water:

$$ET_c = (R_n - G_0 - H - S_{bm} - S_{ph})/\lambda \tag{6}$$

The G_o, S_{bm}, and S_{ph} were estimated using the same procedure as used in the EC method as discussed above. We employed a resistance approach to compute H, analogous to Ohm's law, for electric current in conductors, following Triggs et al. (2004):

$$H = \rho_a C_p (T_o - T_a)/r_a \tag{7}$$

where ρ_a is the density of air (kg m^{-3}) calculated from the ideal gas equation, C_p is the specific heat of air assumed constant at 1020 J $kg^{-1} K^{-1}$, T_o is canopy aerodynamic temperature (K), T_a is the air temperature at sensor height above the crop canopy (K), and r_a the bulk aerodynamic resistance to sensible heat transfer (s m^{-1}). T_o for soybean was calculated based on Chávez et al. (2005):

$$T_0 = 0.534\,T_c + 0.39T_a + 0.224\,LAI - 0.192\,u + 1.67 \tag{8}$$

where T_c is surface radiometric temperature, u is the wind speed at temperature sensor height (m s^{-1}), and LAI is leaf area index. Chávez et al. (2005) reported coefficient of determination (R^2) of 0.9 for regression between H computed using T_0 estimated with the above method and T_0obtained by inverting the energy balance equation. The procedure laid out in Anapalli et al. (2018) was employed for estimating r_a.

2.4. Computation of alfalfa and grass reference crop ET and K_c

We computed the K_c for soybean as:

$$K_c = \frac{ET_c}{ET_{ref}} \tag{9}$$

where, ET_{ref} is the reference crop ET. The ET_{ref} is computed from weather data for short grass (ET_o) and alfalfa (ET_r) reference crops using the Allen et al. (1998) and ASCE-EWRI (2005) computation procedures, respectively. Weather data collected at 2 m height from a weather station located within 1 km from the experiment location were used. The ET_c in Eq. (9) was represented by an average of ET_e, ET_b, ET_{ebr}, and ET_{ele}.

For computing an average K_c curve, that is transferable across locations for irrigation scheduling applications, weekly averages of the ET_c, ET_r,and ET_o were computed, and then we took five-day moving averages of these values to derive a smooth curve as presented in Eq. (9).

3. Results and discussion

3.1. Soybean crop canopy microclimate

Air temperature is one of the main driving factors controlling the consumptive water requirements, ET, of a cropping system, and also controls plant growth, development, and grain and biomass yield. As the season progressed from planting to harvest, T_a gradually increased: average daily T_a on planting day was 21.6 °C and maximum at 31.2 °C on DAE (Days After Emergence) 90 (July 31) (Fig. 1a). The maximum T_a recorded during the crop season was 41.2 °C on DAE 92 (August 2) and the minimum was 10.2 °C on the day of plant emergence (May 7). The VPD, another critical weather variable that controls ET via stomatal regulation, also increased with the observed increase in T_a with the season (Fig. 1b) since VPD increases with increasing T_a. Daily maximum VPD varied from 0.1 to 2.4 kPa at the beginning of the crop season and varied from 0.1 to 5.1 kPa on DAE 57 (July 8). Net radiation (R_n) provides latent heat energy directly from the sun for conversion of water from liquid to vapor state. As the season progressed from spring at planting to summer, the maximum daily R_n received on the crop

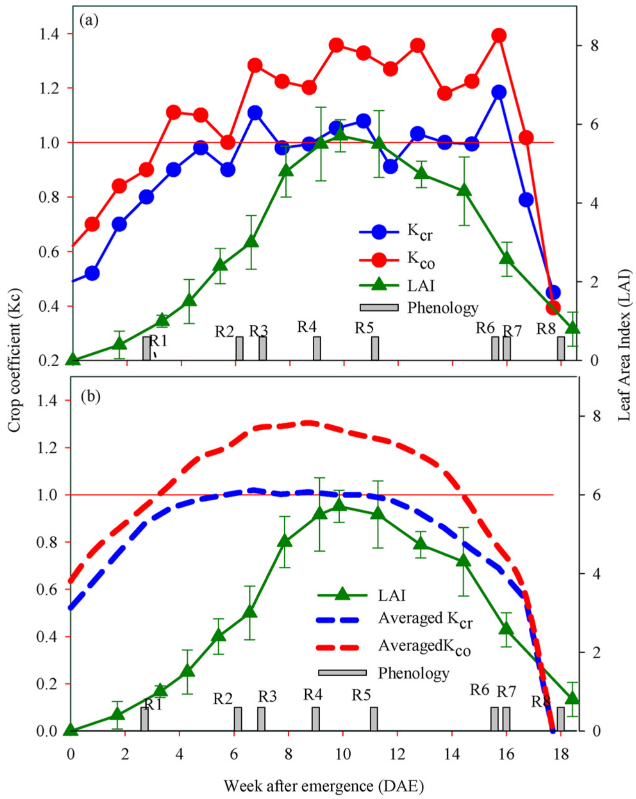

Fig. 6. (a) Soybean crop coefficients for estimating soybean evapotranspiration (ET) from alfalfa (K_{cr}) and grass (K_{co}) reference ET computed from climate data. The soybean ET_c used were weekly averages of estimates from eddy covariance (ET_e), residual energy balance (ET_b), and ET_e post-closure corrected using Bowen ratio (ET_{ebr}) and latent heat (ET_{ele}) methods; (b) Five-point moving-average of K_{cr} and K_{co}. R1 to R8 are the observed soybean crop phenology during the crop season. LAI is the Leaf Area Index. The error bars show one standard deviation in measurements across treatment replications.

increased from about 700 W m^{-2} on the day of planting to 850 W m^{-2} on DAE 83 (July 24), after which it decreased gradually to 670 W m^{-2} on DAE 126 (Fig. 1c). Most of the sudden drops in T_a coincided with decreases in R_n were associated with rain and cloudy weather (Fig. 1c, 1d). Rainfalls received during the crop season (133 days from planting to physiological maturity) were uniform with a seasonal total of 525 mm. There were 51 rainfall events, most of which were less than 30 mm day^{-1} (Fig. 1d). A total of about 90 mm water was applied in three furrow-irrigation events.

Plant canopy temperature (T_c) can be an indicator of plant water status and water availability in the soil for uptake. Hence, T_c minus T_a is often used as an index of plant water stress (Jackson et al., 1981). T_c decreases after irrigation due to enhanced transpiration cooling of the canopy, and then increases when sufficient water is not available in the soil for uptake to meet ET demands of the crop. As the infrared thermometer for T_c measurements was installed to view the ground at a 60^O zenith angle, it mostly recorded the soybean canopy surface temperature. From planting to the R2 stage, $T_c - T_a$ values remained positive during the day, and on DAE 35 reached a maximum value of 8.2 °C when the T_a was 32.6 °C (Fig. 3). From planting to the R3 stage, local farmers do not normally irrigate the crop unless water stress is very severe. From about R3 to the R6 stage, T_c remained less than T_a for the most part. Moreover, from about R7 stage until R8, again T_c-T_a was highly positive. At the R7 stage, soybean seeds started maturing, and the canopy rapidly lost its moisture and turned color from green to brown. The crop is not normally irrigated once the R7 stage sets in, so we did not apply any irrigations during the R7-R8 stage. These changes in the canopy characteristics and lack of moisture for evaporative cooling helped T_c to remain well above T_a during this period.

3.2. Soybean growth and development

Soybean seeds were sown on April 28, 2016, under conventional tillage practices as followed in the Lower MS Delta region. The plants started emerging seven days later and about 100% emergence took place in ten days. Along with a flat terrain (the land area for the experiment had about a 1% slope), establishing a crop stand with uniform crop canopy over the fetch area for the EC and EB sensors is a prerequisite for EC flux measurements. Rainfall of about 16 mm occurred three days before planting that helped plant stands to establish uniformly without noticeable gaps across the field. Maximum crop height reached about 1.1 m at the R5 stage (Table 1). The measured LAI was 1.0 at R1 and reached a maximum value of 5.7 at R4, after which it gradually declined to 0.4 at the R8 stage (Table 1). Plant biomass measurements were sporadic, 1667 kg ha^{-1} at the R3 stage (DAE 46) and 5066 kg ha^{-1} at the R5 stage (Table 1).

3.3. EBC measurements

In the EC method, ET is quantified from the measured LE flux from the soil-canopy system by measuring the covariance of the vertical wind speed for eddy transport and the concentration of water vapor in the same air stream. This method is widely popular for measurement and research on mass, energy, and matter fluxes in the earth-atmosphere system (Foken et al., 2006; Mauder et al., 2007). Nevertheless, as this is a method of estimating ET by measuring energy fluxes, to have confidence in the measured values, according to the first law of thermodynamics, the total energy input to the system ($R_n - G_o - S_{bm} - S_{ph}$) and energy output from the system (H + LE) must balance. Various attempts in the past to understand and correct problems in measurements of different components of the energy fluxes, however, have not lead to any adequate solutions (Liu et al., 2017).

The energy balance closure obtained so far, in most of the literature, has varied between 70 and 90% (Gao et al., 2017; Leuning et al., 2012; Liu et al., 2017). In our study, when fluxes were accumulated at 30-min

Table 2
Average daily and seasonal (June to September) evapotranspiration (ET) of soybean computed by eddy covariance (ET_e), residual energy balance (ET_b,), ET_e corrected using Bowen ratio method (ET_{ebr}), and ET_e corrected using latent heat method (ET_{ele}). DAE = days after emergence. Mean = average of ET_e, ET_b, ET_{ebr}, and ET_{ele} estimates. ET_o and ET_r are potential ET computed for grass and alfalfa reference crops, respectively.

ET method	Jun. (mm d^{-1})	Jul. (mm d^{-1})	Aug. (mm d^{-1})	Sept. (mm d^{-1})	Seasonal total (mm)	Seasonal (mm d^{-1})	Difference from ETe (%)
ET_e	5.4	5.3	4.1	2.1	422	4.4	–
ET_b	6.4	6.0	4.8	3.1	499	5.2	18.2
ET_{ebr}	5.6	5.2	4.2	2.9	451	4.7	6.8
ET_{ele}	6.6	5.5	4.2	2.9	490	5.1	15.9
Mean:	5.9	5.6	4.4	2.9	466	4.8	11.4
ET_o	5.1	5.1	4.0	5.1	470	4.9	11.4
ET_r	6.1	6.1	4.8	6.1	547	5.7	29.5

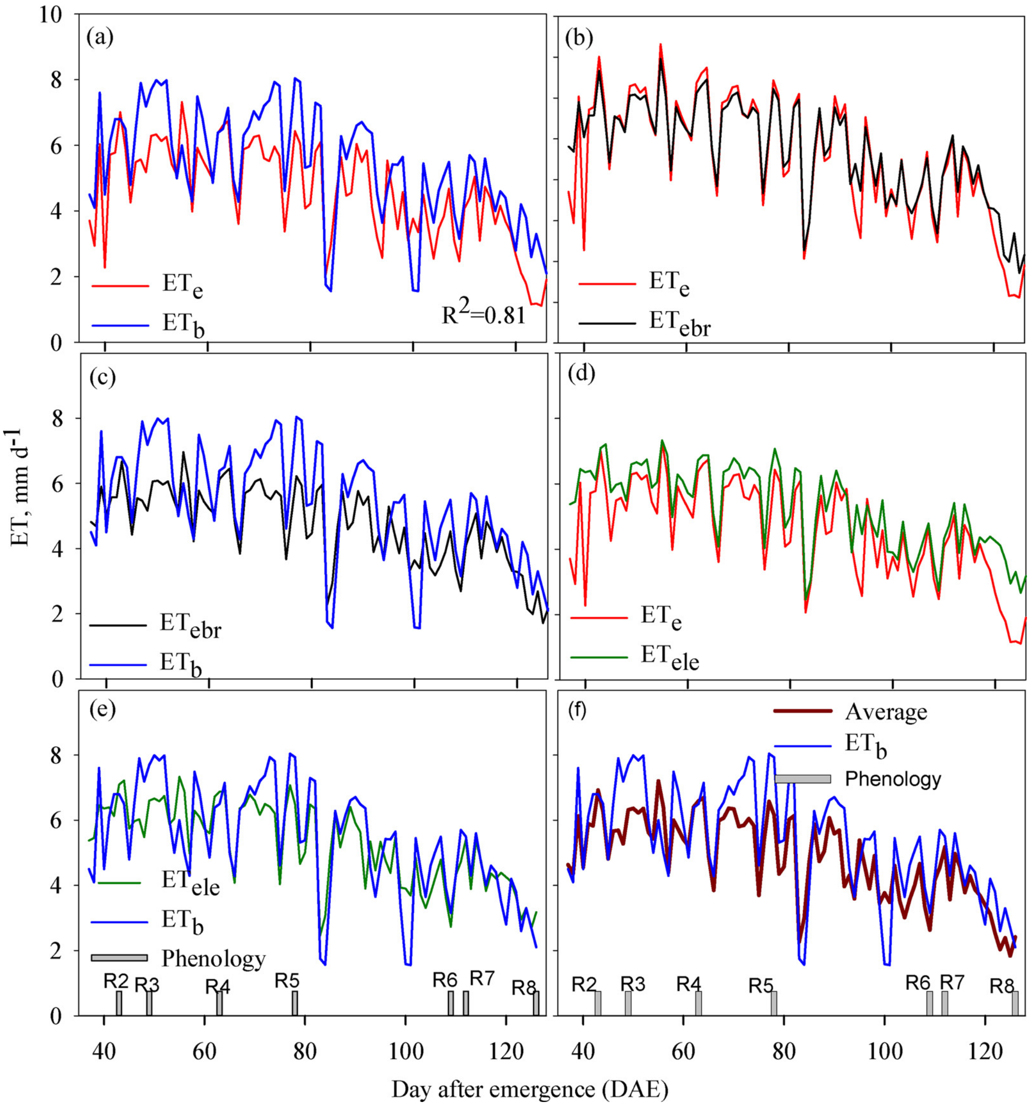

Fig. 7. Daily soybean evapotranspiration (ET_c) estimated from eddy covariance (ET_e), residual energy balance (ET_b), and ETe post-closure corrected using Bowen ratio (ET_{ebr}) and latent heat (ET_{ele}) methods. R1 to R8 are the observed soybean crop phenology during the crop season. R^2 is the coefficient of determination.

intervals, we obtained a closure of 88% (Fig. 4a; the slope of the regression line between $R_n - G_o - S_{ph}$ and H + LE). In these calculations, we could not consider the contributions of plant-biomass in storing or releasing heat energy as we could not collect relevant data to estimate those. Leuning et al. (2012) and Anderson and Wang (2014) found that when energy fluxes in a cropping system were accumulated over the whole day, in contrast to the 30-min intervals followed in our study, the energy gained due to plant-biomass absorption and storage during the earlier part of the day was compensated for by energy losses due to reemission of the absorbed energy during the latter part of the day. When energy fluxes were accounted for in this manner, Anderson and Wang (2014) reported improvements in energy balance closures by 8–10% in sugarcane fields in Hawaii, USA. Notwithstanding, in our study, when fluxes were computed daily, we could improve the closure by 2%, improving the total closure to 90% (Fig. 4b).

3.4. Diurnal variations in ET

The diurnal patterns, averaged monthly, of estimated ET_e, ET_b, ET_{ebr}, and ET_{ele} were similar to each other in June, roughly from the R2 to R3 stages (Fig. 5a). However, as the season progressed, in July, August, and September, the diurnal pattern of ET_b deviated from the others substantially (Fig. 5b–d). The diurnal maxima in ET (estimated at 30-min intervals), averaged across the above four methods, was 0.36 mm in both June and July, but decreased to 0.28 mm in August and further decreased to 0.22 mm in September. Across all four ET estimations, the daily maxima occurred at around 1:30 PM (local time). The observed decrease in ET estimates with time is a reflection of the decreasing water demand for crop growth as the crop progressed through its active vegetative and reproductive growth stages (R2 to R5 in June and July, Fig. 5a, b) to organ (leaf, petiole, and stem) senescence (decreased water uptake in August, Fig. 5c), followed by physiological maturity stage (least water demand in September, Fig. 5d). These patterns in crop water requirements (ET_c) with time followed the measured patterns in LAI development and decay well: LAI increased from 0.80 at the R1 stage to 5.7 at the R4 stage, then decreased to 3.0 at the R6 stage (Fig. 6a, b). The LAI further decreased to 0.8 at the R8 stage. Mace and Harris (2013) reported vigorous plant growth combined with a steady increase in water demand in soybean plants from the R1 to R5 stages, followed by a sharp decrease in water demand and soybean growth rates until the R7 stage. From the R7 to R8 growth stage, there were hardly any water demand or uptake by the crop.

In June, the peak water use estimated by both ET_e and ET_b were similar to each other: 0.35 and 0.36 mm, respectively (Fig. 5a). However, these two separate estimates (the EC and EB methods) of soybean ET started diverging as the season progressed through July, August, and

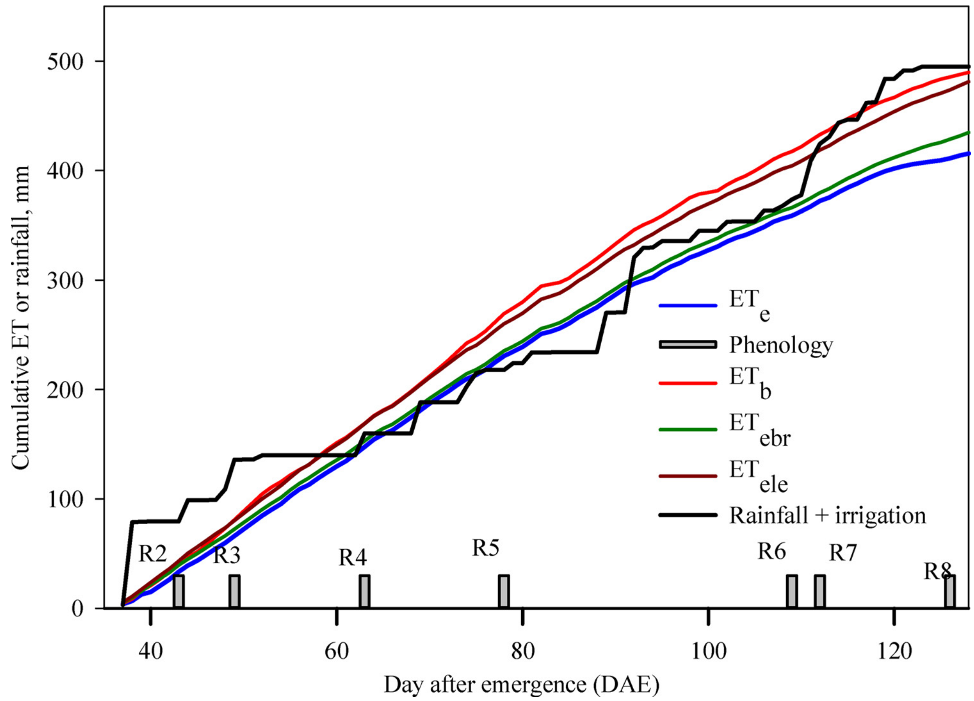

Fig. 8. Cumulative rainfall and irrigation, evapotranspiration estimated by eddy covariance (ET_e), energy balance (ET_b), and ET_e corrected using Bowen ratio (ET_{ebr}) and latent heat (ET_{ele}) methods during the soybean season. R1 to R8 are the observed soybean crop phenology during the crop season.

September (Fig. 5b–d). The ET_e and ET_b diurnal peak estimates, computed at 30-min intervals, were, respectively, 0.36 and 0.46 mm in July, 0.25 and 0.38 mm in August, and 0.11 and 0.39 mm in September. These differences in ET estimates followed the differences in the measured H estimates by the EC and EB methods as discussed below. The crop reached the R7 stage (beginning maturity) on August 26 and reached the R8 stage (full maturity) on September 9, so the month of September not only represented nine days of the month, but also coincided with the period of rapid decrease in water uptake associated with crop senescence. As such, the ET requirement estimated for soybean in September in our study does not represent the crop's consumptive use requirement during active growth in this region. The soybean crop does not need any irrigation during its senescing growth stage, from R7 to R8.

3.5. Daily variations in ET

Averaged across the whole crop season, the daily ET_e and ET_b (quantified from the EC and EB methods) were 4.4 and 5.2 mm, respectively (Table 2). Daily values of ET_e varied between 1.1 mm in September and 7.3 mm in June, and ET_b between 2.1 mm in September and 8.0 mm in June (Fig. 7a). High ET demand in June coincided with R3 to R5 stages of rapid reproductive growth of the crop. For the soybean variety used in this study, an indeterminate, these reproductive stages are accompanied by rapid vegetative growth and its consequent ability to take-up more water from the soil (Mace and Harris, 2013). However, for active uptake to occur, continuous supply of water from the soil is required, in response to other factors contributing to the high uptake, including higher temperature and water vapor deficits in the soil-air environment. For example, on June 30 (DAE 55), both T_a and VPD peaked at the highest observed amounts during the crop season, and this was also preceded by two irrigations we provided (Fig. 1a, b, and d), with all factors contributing to the highest ET measured on that day.

The computed daily ET_b correlated reasonably well with ET_e of with an $R^2 = 0.81$ (Pearson's correlation coefficient, $r = 0.9$) (Fig. 7a). This shows that the EB computation procedure that we adopted in this study worked reasonably well for estimation of ET_c when compared to the EC method. However, the two methods differed in capturing the actual variations in ET in response to realized weather with time (days). The daily ET_{ebr} and ET_{ele} estimates, that were the post-analysis corrected ET_e values, were 4.7 and 5.1 mm, respectively, when ET_e was 4.4 mm d^{-1} (Table 2). The computed daily ET_{ebr} and ET_{ele} were between 2.8 mm in September and 7.0 mm in June, and between 2.7 mm in September and 7.3 mm in June, respectively (Fig.7b–e).

The difference between daily ET_b and ET_{ele} averaged across the whole crop season was 0.1 mm: 5.2 and 5.1 mm d^{-1}, respectively (Table 2). In the EB method, all energy in excess (residual) of H, G_o, S_{ph}, and S_{bm} was attributed to crop evaporation demand (Eq. (6)). In computations of ET_{ele}, all the unclosed energy in the EC measurements were added to the measured LE. As such, ET_b and ET_e, ideally should coincide, however, the small difference occurred as the H in the EC method was measured in the EC system, but H in the EB method was computed from the measured micrometeorological parameters using Eq. (7).

3.6. Seasonal ET

The EC and EB measurements used in this study were from DAE 38 to physiological maturity. While we missed the first 37 days of the EC data, this period also coincided with the time of crop-stand establishment in the field, during which the farmers do not irrigate the crop in order to avoid seedling death from water-saturated soils (Mace and Harris, 2013). As such, the data collected in the experiment was adequate for estimating crop water requirements of the crop for irrigation planning applications.

As discussed above, the EBC achieved in our measurements during the season was 90%, which means 10% of the energy input into the system remained unaccounted for in the computed fluxes. Seasonal cumulative ET_e, ET_b, ET_{ebr}, and ET_{ele} were 422, 499, 451, and 490 mm, respectively, with an average of 466 mm (Table 2, Fig. 8). The ET_b was higher than ET_e by 18.2% (Table 2). When the ET_e was modified for the unaccounted 10% of energies, the ET values were 451 (ET_{ebr}) and 490 mm (ET_{ele}) for the BR, and LH based EC post-analysis closure methods, respectively. The value of ET_{ele} (490 mm) was the closest to

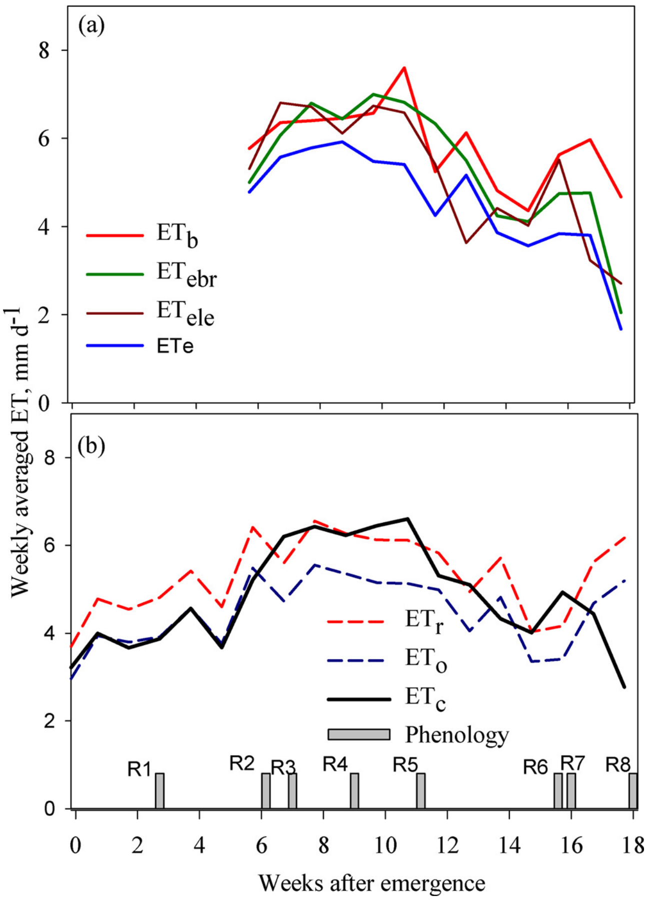

Fig. 9. (a) Daily evapotranspiration, averaged weekly, estimated from eddy covariance (ET_e), residual energy balance (ET_b), and ET_e post-analysis closed using Bowen ratio (ET_{ebr}) and latent heat (ET_{ele}) methods, (b) average weekly ET_c averaged across the above three methods (ET_c). ET_c is the average of ET_b, ET_{ebr}, and ET_{ele}. R1 to R8 are the observed soybean crop phenology during the crop season.

ET_b (499 mm), with a difference of 6 mm. Any of the computed ET_e, ET_b, ET_{ebr}, and ET_{ele} estimates could potentially represent the actual soybean ET_c during the season, however, we could not determine any of those to be the best estimate since there is no way to know the true value of ET_c in nature. Under the circumstances, we would recommend the average of all these estimates, that is, 466 mm, as the most appropriate estimate of soybean seasonal ET_c in 2016.

It is important to note that the amount of water that may be required to grow a crop in any specific crop season depends on the actual weather (T_a, amount of solar radiation received, wind speed, vapor pressure deficit in the air, rainfall, etc.), as well as irrigation water applied and amount of soil water available for plant-uptake during that season. As such, the observed absolute value of ET that we arrived at may not have a direct comparison with other years for the same location or in the same year elsewhere. A full season of soybean in the semi-arid climate of Australia, for example, depending on the local weather conditions could range from 900 to 1200 mm (Mace and Harris, 2013). In these circumstances, estimates of ET_c at other locations and seasons of interest can be obtained from Eq. (9) presented above. The K_c for use in this equation could be derived by computing grass and alfalfa reference crop ET (ET_o and ET_r) for the same duration of the experiment from weather data (Allen et al., 1998; ASCE-EWRI, 2005), and relating it to the average of the ET_e, ET_b, ET_{ebr}, and ET_{ele} computed above as a reasonable estimate of ET_c. Advantages of taking an average of the different estimates of ET to represent ET_c are, (1) it would absorb some of the uncertainty in the measurements and methods and (2) would overcome the inherent issue of under-prediction of LE (in EC system) - therefore an average value will push the water requirement towards the upper range (a safer limit or a more conservative approach).

3.7. K_c for soybean

As stated earlier, the EC and EB measurements were available only from DAE 38 onwards up to harvest (Week 6 in Fig. 9a). So, the weekly time series from this day were extended backward to DAE 1 (Week 0 in Fig. 9) by developing a regression equation between the simultaneous measurements of ET_r and averaged ET_c estimated during this period (Fig. 9b). Average weekly ET_e, ET_b, ET_{ebr}, and ET_{ele} values ranged between 1.6 and 5.9, 4.4 and 7.6, 2.1 and 7.0, 2.7 and 6.7 mm d^{-1}, respectively (Fig. 9a). The ranges of variations in each of these ET_c estimates, in general, represented the growth pattern of the crop as reflected in the LAI progression with crop growth during the season (Fig. 6). The maximum LAI (5.7) occurred at the peak growth stages of the crop, during the second week of July (Fig. 6). This period also coincided with high T_a and moderate VPD (Fig. 1a, b), and water from rain or irrigation was available in the soil for plant-root uptake. The decrease in the estimated ET values during the week following DAE 89 (around week 12 in Fig. 9) was due to lower T_a, VPD, and R_n due to cloud cover and rain, which lasted about ten days (Fig. 1a–c). A second peak in the computed ET_r (5.7 mm d^{-1}) and ET_o (4.8 mm $^{-1}$) values was found during the week around DAE 96 (between week 13 and 14 in Fig. 9a and b). This also resulted in a decrease in the computed K_c values for both ET_r (K_{cr}) and ET_o (K_{co}) during the week. These variations in the computed K_{cr} and K_{co} were smoothened by taking five-day moving averages of the weekly time series of the K_c values (Fig. 6b). Both K_{cr} and K_{co} curves up to the R1 stage of the crop were forced to follow the LAI growth curve to make the curve represent, for the most part, the transpiration losses of water from the crop and minor soil evaporation losses, thereby enabling an irrigator to avoid over-irrigation and reducing water supply for meeting the soil evaporation requirements during this period of un-closed canopy. The final K_{cr} curve that we developed ranged from 0.48 at the start of the season, peaked to 1.02 when the LAI was maximum (R3 to R5 stages), and decreased to 0.56 at the R7 stage. Using a BR energy balance system, Irmak et al. (2013) derived K_{co} values between 0.27 and 1.47 in the 2007–2008 seasons for soybean in south-central Nebraska, USA. Given the difference in climates between Nebraska (semi-arid) and the Delta region of MS (humid), the values we derived seemed reasonable. However, using the EC method, Payero and Irmak (2013) reported K_{co} values between 0.5 and 1.23 (weekly basis) for the 2002–2005 growing seasons over North Platte, Nebraska, USA.

Similarly, the K_{co} was 0.5 at the start of the crop season, peaked at 1.3 at the maximum LAI growth of the crop during the R3-R5 stages, and declined to 0.57 at the R7 stage. As there is no substantial water demand for growth after R7 (senescence phase), the crop is typically not irrigated in late season, and K_c was assigned a value of 0.0 during this period. The Irmak et al. (2013) study for soybean in the semi-arid climate of Nebraska, USA, reported K_{cr} values between 0.2 and 1.12. The slightly lower K_{cr} values we obtained in the Delta region of MS are as attributed to lower ET demands which normally characterize the humid climate of this location.

4. Conclusions

This study presented a new approch to quantify ET_c (consumptive water requirements) of soybean in the MS Delta using the eddy covariance technique. On average over the crop season of 2016, 90% of the measured net energy received from solar irradiance was accounted for in the measured latent and sensible heat energy fluxes using the EC method for quantifying ET_c, with the remaining 10% of the energy unaccounted for. To compensate for this unaccounted energy in the measured ET_e, we corrected the estimated latent heat energy fluxes using the Bowen ratio and latent heat EC post-analysis correction methods. We also calculated ET_c using a residual energy balance method that we developed by synthesizing information available on modeling the various components of the energy balance in cropping systems available in the literature. To facilitate this, we continuously monitored crop-canopy temperature along with the EC measurements. Average daily ET_c values estimated from the EC, EB, and EC corrected using BR and LH methods were 4.4, 5.2, 4.7 and 5.1 mm, respectively, with an average of 4.8 mm. Average daily alfalfa and grass reference crop ET calculated from weather data for the same period were 4.9 and 5.7 mm, respectively. On a seasonal scale, the ET_e, once corrected for non-closure of the EC method using the LH correction, ET_{ele}, was closer than other estimations to ET_b. Averaged across estimates of ET_e, ET_b, ET_{ebr}, and ET_{ele}, soybean irrigation water requirement for the 2016 growing season was 466 mm. The computed K_c for predicting the average ET_c for soybean from grass and alfalfa reference ET computed from weather data varied between 0.57 and 1.29, and 0.48 and 1.02, respectively.

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