Science of the Total Environment 663 (2019) 338–350

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Quantifying water and CO_2 fluxes and water use efficiencies across irrigated C_3 and C_4 crops in a humid climate

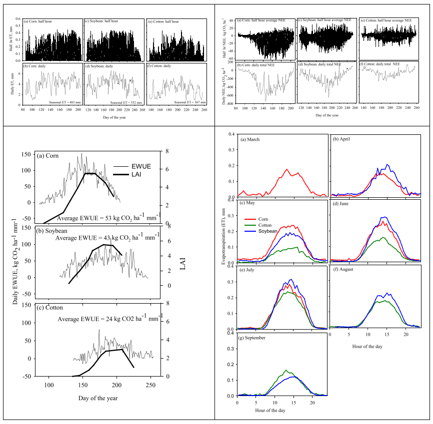
Saseendran S. Anapalli [a,*], Daniel K. Fisher [a], Krishna N. Reddy [a], Jason L. Krutz [b], Srinivasa R. Pinnamaneni [a], Ruixiu Sui [a]

[a] USDA-ARS, Crop Production Systems Research Unit, P.O. Box 350, Stoneville, MS 38776, United States of America
[b] Water Resources Research Institute, Mississippi State University, Starkville, MS, United States of America

HIGHLIGHTS

- Quantified EWUE across C_3 (soybean and cotton) and C_4 (corn) crops in a humid climate.
- The NEE of CO_2 and ET were measured using eddy covariance instrumentation.
- The three crops were a net sink for CO_2 during most of the growth period.
- Seasonal NEE of soybean and cotton were 25% and 75% less than that of corn.
- EWUE in C_4 corn was higher than in C_3 soybean and cotton.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 September 2018
Received in revised form 25 October 2018
Accepted 31 December 2018
Available online 02 January 2019

Editor: Ouyang Wei

Keywords:
Eddy covariance
Water use efficiency
Ecosystem
Ecosystem exchange

ABSTRACT

Underground aquifers that took millions of years to fill are being depleted due to unsustainable water withdrawals for crop irrigation. Concurrently, atmospheric warming due to anthropogenic greenhouse gases is enhancing demands for water inputs in agriculture. Accurate information on crop-ecosystem water use efficiencies [EWUE, amount of CO_2 removed from the soil-crop-air system per unit of water used in evapotranspiration (ET)] is essential for developing environmentally and economically sustainable water management practices that also help account for CO_2, the most abundant of the greenhouse gases, exchange rates from cropping systems. We quantified EWUE of corn (a C_4 crop) and soybean and cotton (C_3 crops) in a predominantly clay soil under humid climate in the Lower Mississippi (MS) Delta, USA. Crop-ecosystem level exchanges of CO_2 and water from these three cropping systems were measured in 2017 using the eddy covariance method. Ancillary micrometeorological data were also collected. On a seasonal basis, all three crops were net sinks for CO_2 in the atmosphere: corn, soybean, and cotton fixed −31,331, −23,563, and −8856 kg ha^{-1} of CO_2 in exchange for 483, 552, and 367 mm of ET, respectively (negative values show that CO_2 is fixed in the plant or removed from the air). The seasonal NEE estimated for cotton was 72% less than corn and 62% less than soybean. Half-hourly averaged maximum net ecosystem exchange (NEE) from these cropping systems were −33.6, −27.2, and −14.2 kg CO_2 ha^{-1}, respectively. Average daily NEE were −258, −169, and −65 kg CO_2 ha^{-1}, respectively.

---

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

https://doi.org/10.1016/j.scitotenv.2018.12.471

The EWUE in these three cropping systems were 53, 43, and 24 kg CO_2 ha^{-1} mm^{-1} of water. Results of this investigation can help in adopting crop mixtures that are environmentally and economically sustainable, conserving limited water resources in the region.

1. Introduction

The Lower Mississippi (MS) Delta is an important agricultural production region in the USA. >60% of the staple crops, soybean (*Glycine* max [L.]), corn (*Zea mays* L.,), cotton (*Gossypium hirsutum* L.), and rice (*Oryza sativa* L.), grown in this region are irrigated, with most of the irrigation water needs met from the limited groundwater available in the shallow MS River Valley Alluvial Aquifer underlying this region (Powers, 2007; Runkle et al., 2017). The increasing demands for irrigation water from global warming induced by anthropogenic greenhouse gases in the atmosphere is further compromising the sustainability of irrigated agriculture in this region (Anapalli et al., 2016). In the current scenario, for sustaining irrigated agriculture, there is a need for investigating, understanding, and developing management practices that potentially increase water use efficiency in crop production systems and thus reduce excessive withdrawals of groundwater from the depleting aquifers (Clark and Hart, 2009; Dalin et al., 2017). The need for conservation of irrigation-water resources for sustainable production in irrigated cropping systems is renewing interest in understanding and improving factors and processes that affect water use efficiencies in agriculture (Hatfield et al., 2001).

For plants that use the conventional C_3 Calvin–Benson cycle (C_3 plants), all the CO_2 involved in photosynthesis enters the plant through tiny pores in the epidermal leaf cells called stomata. These pores also allow water from the plant cells to diffuse out of the plant and to the air through the passive process known as transpiration, the evaporative loss of water from plants. Transpiration from plants combined with the evaporative loss of water from the soil-environment is termed evapotranspiration (ET). Under similar environmental conditions, C_4 plants typically assimilate more carbon with less water loss through ET due to their more-efficient photosynthetic pathway and leaf-cell anatomy, in contrast to C_3 plants, an added but spatially detached CO_2 metabolic cycle facilitated by phosphoenolpyruvate carboxylase (PEPCase). RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) is the CO_2 fixing enzyme complex in the Calvin-Benson photosynthetic cycle in plants (Hanifzadeh et al., 2018). The above extra process in the photosynthetic pathway outcomes in high CO_2 concentrations around RuBisCO (both a carboxylase and oxygenase) in the Calvin-Benson cycle, thus overturning the enzyme's oxygenase function and virtually removing photorespiration carbon and energy losses (Way et al., 2014). In this way, a C_4 plant can maintain high photosynthetic carbon assimilation rates with low stomatal opening or conductance, thereby losing less water to ET in exchange for CO_2, in contrast to their C_3 counterparts. Hence, C_4 plants in cropping systems exhibit higher EWUE compared to what is normally achieved in C_3 species (e.g. Sage et al., 2012; Way et al., 2014). Like many other processes at the plant level, photosynthesis and transpiration also are highly dependent upon plant-canopy microclimate and soil-plant-air conductance for water. Owing to the complex nature of the interconnection between plant transpiration (water loss) and photosynthesis (carbon gain) within the crop canopy-microclimate, water use efficiency (WUE, net carbon gain from photosynthesis to water lost through transpiration at the leaf level) is normally determined from leaf-level gas exchange measurements (Schulze and Hall, 1982; Way et al., 2014). However, measurements of CO_2, water, and energy fluxes at the plant ecosystem level (the land-atmosphere interface) are often needed to account for the influences of these fluxes on environment to analyze feedbacks at regional to global scales, for example, in climate-change research (Pielke et al., 1998). Also, information at the plant community/ecosystem level is a prerequisite for irrigation research and applications but seldom available. Integration and scaling of the leaf-level measurement to a crop-ecosystem level for irrigation-water management and climate-change detection and mitigation research is a challenge.

In this context, eddy covariance (EC), a sound micrometeorological theory-based method for measuring CO_2 and water fluxes between the atmosphere and land-surface, provides a unique method for quantifying EWUE at the crop-ecosystem level for research and applications in water management and climate change (Arneth et al., 2006; Way et al., 2014; Baldocchi et al., 2001). In the EC method, net ecosystem exchanges of CO_2 (NEE) and water vapor (ET) are estimated by tracking and measuring the turbulent transport of eddies in the plant canopy boundary layer of the atmosphere. Eddie fluxes are normally measured at 10 to 20 Hz and averaged at 30-min intervals. The NEE measured in the EC results from the net CO_2 uptake in photosynthesis (gross primary production, GPP) after accounting for the CO_2 efflux from the system due to ecosystem respiration, Reco (Reichstein et al., 2005). The GPP and ET at the ecosystem level on daily to annual timescales are derived (partitioned) from measurements of NEE and other micrometeorological data (Reichstein et al., 2005; Beer et al., 2009). In the literature, the GPP and Reco are mostly derived from simultaneous measurements of nighttime or daytime air or soil temperature data (Reichstein et al., 2005; Vickers et al., 2009; Lasslop et al., 2010). The EC theory and method have been used as a viable technique for quantifying and estimating CO_2 and ET in water management research (Baldocchi, 2003; Parent and Anctil, 2012; Shurpali et al., 2013; Tallec et al., 2013; Uddin et al., 2013; Anapalli et al., 2018). Beer et al. (2009) used the EC technique to study the temporal and among-location variability in EWUE at the ecosystem level in terrestrial ecosystems consisting of a mixture of photosynthetic functional types and climatic conditions.

Our objectives of this study were to quantify: (1) NEE and ET from C_4 (corn) and C_3 (soybean and cotton) cropping systems in the Lower MS Delta, and (2) EWUE across these three cropping systems for irrigation water management applications.

2. Materials and methods

2.1. Experiment

Experiments were conducted at the USDA-ARS Crop Production Systems Research Unit's (CPSRU) farm, and two farmer's fields within about a 3-km radius, at Stoneville, MS, USA (33° 42′ N, 90° 55′ W, ~32 m elevation above sea level). Corn was grown in a 25-ha field on the CPSRU farm, and soybean and cotton crops were grown in farmer's fields with sizes over 500 ha each. The fields were land-formed to about a 1% slope. Height adjustable mast/towers each carrying EC instrumentation were centrally located in these fields (Fig. 1). Fetch for the EC sensors in each of the three fields was at least 250 m in all directions. The EC towers in the three fields were instrumented identically in terms of sensors, data logging systems, in-field flux computation systems, and solar panel-based power supply systems. In all three EC systems, the sensors were maintained constantly at twice the crop height above the canopy throughout the study using the height-adjustable towers.

The location of the experiment has a sub-tropical humid climate with mild winters and warm summers. Average annual precipitation at the location is about 1300 mm, with 30% received during May to August, the crop growing seasons of the three crops (Kebede et al., 2014;

Fig. 1. The eddy covariance system installed in corn (top panel), soybean (middle panel), and cotton (bottom panel) fields for measuring net ecosystem exchange of CO_2 and water.

Anapalli et al., 2016). Dominant soil type in all the three crop fields is a poorly-drained Tunica clay (clayey over loamy, montmorillonitic, nonacid, thermic Vertic Halaquepet) to a depth of about 1.2 m as measured. All the three fields historically have been planted to corn, soybean, or cotton under conventional tillage practices: deep tillage to break clay pans and overturn soils, burying of crop residue and killing of weeds, in three passes followed by another tillage to generate furrows and ridges for planting crops and to facilitate furrow irrigations.

For this study, corn (cv. DKC 66-97) was planted on ridges with 97-cm row-spacing at a seeding rate of 77,311 per ha on March 21, 2017, emergence was complete on March 28, 2017, and fertilizer was applied a week after emergence at 215 kg N ha^{-1}. The crop reached physiological maturity on July 17, 2018 (120 days after emergence). Soybean (cv. Progeny 4516) was planted on April 21, 2017 on north-south rows, with a 77-cm row spacing and a 407,550 seeding rate. Soybean seedlings fully emerged on April 28, 2017, and the crop attained physiological maturity on September 10, 2017 (135 days after emergence). No fertilizers were applied to soybean. Cotton (cv. Delta Pine Land 1522) was planted at 103740 seeds per ha on ridges with 77-cm row spacing on April 22, 2017, was fully emerged on May 1, 2017, and attained physiological maturity on September 10, 2017. Fertilizer was applied at a rate of 140 kg N ha^{-1}. As practiced in the region, the plant growth regulator Mepiquat chloride was applied to control plant height and excessive vegetative growth.

The three fields were equipped for furrow irrigation, in which water was applied through polyethylene pipes at the elevated end of crop rows to maintain water content in a 30-cm soil layer above 65% of maximum plant available water. During the copping season, the three crops were irrigated at 30 mm each, twice in the last week of July (200 and 204 Day of the year, Fig. 2). Water content and temperature at 8 and 30 cm soil layers were monitored using Stevens HydraProbe sensors (Stevens Water Monitoring Systems, Inc., Portland, OR USA). The sensors were installed three each in the north and south facing sides of the ridges on soybean rows and two in the furrow (between the rows).

Leaf area index (LAI) was measured at two-week intervals using an AccuPAR LP-80 Ceptometer (Decagon Devices, Inc., Pullman, WA USA). Plant heights (h) were monitored manually every week for adjusting the sensor heights above the canopy. All plant measurements were replicated at four random locations in the field and used in the calculation of standard error (SD) of measurements. On the seventh day after the physiological maturity of the crops, corn and soybean grains from the whole farm area were harvested and weighed using combines. Grain weights of soybean and corn were adjusted to, respectively, 13 and 15% moisture content. Harvested cotton was baled and transported to a ginning facility to separate lint and seeds, and average lint yield was recorded.

2.2. Water vapor and CO_2 flux measurements

For estimating the CO_2 and water vapor using the EC method, their flux densities in the upward transported eddies from the cropping system were measured using LI-7500-RS open-path infrared gas analyzers, IRGA (LI-COR, Inc., Lincoln, NE USA), and vertical velocities of transport of these eddies were measured using a Gill New Wind Master 3D sonic anemometer, GILL-WM (Gill Instruments, Lymington, UK). To ensure high level of accuracy, reliability, and repeatability in all measurements in the experiment, all the sensors and data loggers used were calibrated and maintained annually for quality before moving them 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 above the ground (Fig. 1). Lowest above-ground height of towers were 2 m. The maximum plant height measured during the season was 2.15 m for corn, 1.2 m for soybean, and 1.0 m for cotton. Whenever there was an increase in crop height that exceeded 5 cm, the sensor heights were adjusted to maintain a constant sensor height above the canopy. The LI-7500 and sonic anemometer data were collected at 10 Hz frequency.

2.3. Micrometeorological measurements

The sensors for measuring net radiation (NR-LITE2, Kipp & Zonen B.V., Delft, The Netherlands), air temperature (T_a) and relative humidity (HMP 155, Vaisala, Helsinki, Finland), and wind direction and speed (Gill 2D-Sonic, Gill Instruments) were maintained at 2 m above the crop canopy (within the cropped field) along with the EC sensors. Three self-calibrating soil heat flux sensors (HP01SC, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) were installed at an 8-cm depth below the soil surface. Water content and temperature in the 8-cm soil layer above the heat flux plates were monitored using a Stevens HydraProbe (Stevens Water Monitoring Systems, Inc.). Changes in heat energy storage above the flux plates were computed using

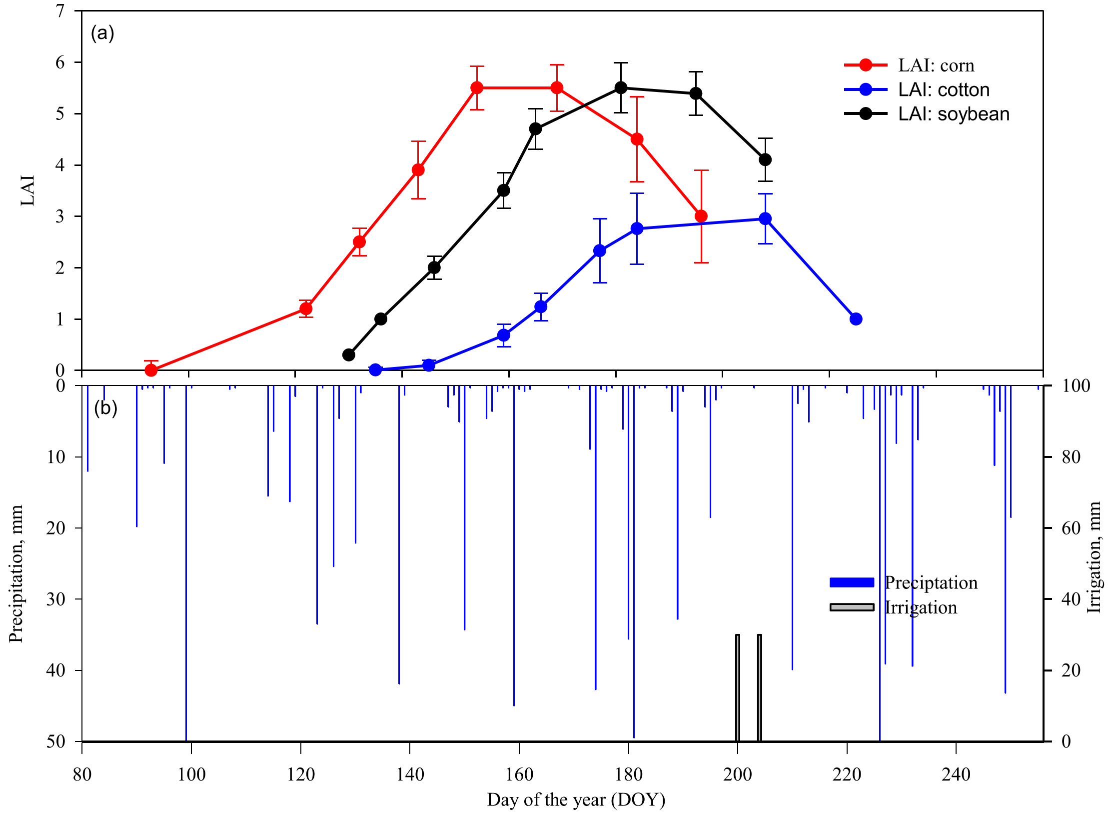


Fig. 2. (a) Leaf Area Indices (LAI) of corn, soybean, and cotton in the experiment, and (b) rainfall and irrigation recorded at the site of the experiment during the crop season in 2017.

Eqs. (1) and (2) (discussed below). Micrometeorological data were collected at 1-min intervals and averaged every thirty minutes and used in the analysis. All measurements started at planting and continued until harvest.

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

The raw eddy flux data were recorded and processed in the field on a SmartFlux microprocessor (LI-COR Inc.) 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., 1997, 2004); anemometer temperature correction for humidity (Van Dijk et al., 2004); and compensation for air density fluctuations (Webb et al., 1980).

The processed EddyPro data carries quality flags ranging in value from 0 (highest quality) to 2 (lowest quality) (Mauder and Foken, 2011). We discarded the fluxes with a quality flag of 2 and statistical outliers beyond ±3.5 standard deviations based on a 14-day running window (Wagle and Kakani, 2014). Turbulent fluxes were further filtered to keep within the realistic range from -200 to $500\ \mathrm{W\ m^{-2}}$ for sensible heat (H) and -200 to $800\ \mathrm{W\ m^{-2}}$ for latent heat (LE) (Sun et al., 2010; Wagle et al., 2015). Gaps in flux data were filled and GPP and Reco were estimated (flux partitioning) 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). 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). Reco and GPP were derived from night-time air temperature data using the Reichstein et al. (2005) method.

As stated above, the NEE reported in this study were the net CO_2 flux - this also include the CO_2 efflux due to Reco - from the cropping system that were measured with the EC method in units of $\mu\mathrm{mol\ m^{-2}\ s^{-1}}$. Further, the EWUE (kg CO_2 $\mathrm{ha^{-1}\ mm^{-1}}$ of water) is computed by dividing the half hourly NEE estimates by the ET (mm) estimates during the same period.

2.5. Energy balance closure

We computed the energy balance closure (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 R_n is net solar radiation, G_o is soil heat flux, and S_{bm} and S_{ph} are energy stored in the biomass and energy used in the photosynthesis process, respectively. Only high-quality (0 flags) and non-gap filled fluxes of H and LE were used to calculate EBC and only when all four components, H, LE, R_n, and G_o into or out of the soil, were available.

The S_{ph} was computed using the Meyers and Hollinger (2004) procedure in which a fixed canopy assimilation rate of 2.5 mg CO_2 $\mathrm{m^{-2}\ s^{-1}}$ per 28 $\mathrm{W\ m^{-2}}$ was used. Computing EBC on a daily basis, 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, within this time-scale, energy stored in the biomass in the morning is returned to the air in the afternoon and evening hours. So, instead of computing S_{bm} in this study, we also analyzed EBC on a daily scale to see if it helped in closure improvement.

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

$$G0 = G8 + Cs\Delta z\left(\frac{\Delta T}{\Delta t}\right) \tag{1}$$

where G_8 is the soil heat flux at 8-cm depth, Δz is the soil depth above the heat flux plate (8 cm), 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) as

$$C_s = \%M * C_m + \%OM * C_{om} + \%SWC * C_w \tag{2}$$

where, M is the mineral, OM is the organic matter, and SWC is the volumetric water content in the Δz soil depth, and $C_m = 1.9$, $C_{om} = 2.5$, and $C_w = 4.2$ MJ m^{-3} °C^{-1} are volumetric heat capacities of minerals, organic matter, and soil water in Δz, respectively.

3. Results and discussion

3.1. Canopy microclimate during the crop growth seasons

Water availability for plant uptake, from rainfall or irrigations, is the most limiting factor in crop production across climates and soils. In our experiments, the corn, soybean, and cotton crops, respectively, received 31, 44, and 42 rainfall events in 120, 135, and 137 days (crop duration from planting to physiological maturity) (Fig. 2b). Rainfall received during these periods was 593, 796, and 817 mm, respectively, and these rainfalls were fairly uniformly distributed throughout the crop seasons to maintain about 60–65% of field capacity of plant available water in the soil for plant root uptake throughout the crop seasons, excepting the third week of July (DOY 200 and 204) when two irrigations of 30 mm each were provided (Fig. 2b). Highest daily rainfall amounts were 69, 107, and 107 mm, respectively, during the three crop growth seasons.

Half-hour averaged global solar radiation (Rg) recorded over the crop canopies varied appreciably with time, indicating many days with significant clouding and or rain (Fig. 3a). The maximum amount of half-hour averaged Rg was 1104 μmol m^{-2} s^{-1}, which was close to clear day maximum Rg for this location (Meek, 1997). As such, solar radiation receipts at this location can be a significant limiting factor in photosynthesis and dry-matter assimilation in cropping systems. Further investigation would be required to estimate crop yield losses due to clouding in the MS Delta region.

When soil water is abundant, air temperature is an important factor that controls growth and development of crop plants. In corn, seasonally averaged daily air temperature 2 m above the plant canopy was 23 °C, with a peak of 31 °C and low of 13 °C. The average daily temperature at 2 m above the soybean canopy was 25 °C, with a peak at 38 °C and low at 13 °C. Highest average daily temperature over the cotton canopy was 33 °C, while the lowest was 17 °C, and the seasonal average was 25 °C. In general, there were only minor differences in the temperatures over the three canopies during their respective crop seasons (Fig. 3b). Vapor pressure deficit (VPD) is another atmospheric variable affecting evapotranspiration losses of water from landscapes and, thereby, impacting EWUE in cropping systems. On a seasonal average basis, VPD of air over cotton was highest (11.5 h Pa), and lowest over soybean (9.8 h Pa) (Fig. 3c). Average VPD over corn was 10.2 h Pa. Lower VPD over soybean can positively impact the EWUE of this crop by reducing ET loss of water from the system, compared to the other two crops. Soil temperature is an important environmental variable controlling many soils, water, and plant related processes in the soil environment; as such, it impacts crop performance and water use in cropping systems significantly. Compared to soybean and cotton, soil temperature under corn remained rather cooler throughout the season (Fig. 3d). Soil under cotton remained hottest and temperatures under soybean were intermediate of the other two crops. Daily average soil temperatures under corn, soybean, and cotton during their growing seasons were 23, 25, and 28 °C, respectively.

Corn had the higher leaf area index (LAI) and thicker canopy, blocking the solar radiation reaching the soil directly and heating it, starting earlier in the season compared to the other two crops, thereby helped the soil to remain cooler than that under the other two crops. The LAI of cotton was lowest, thereby allowing more sunlight to directly reach the soil and heat it, which explains the higher soil temperatures under this crop (Fig. 2a). The soybean crop, with LAI intermediate of the other two, was with soil temperatures also intermediate of those under corn and cotton (Fig. 2a and Fig. 3d).

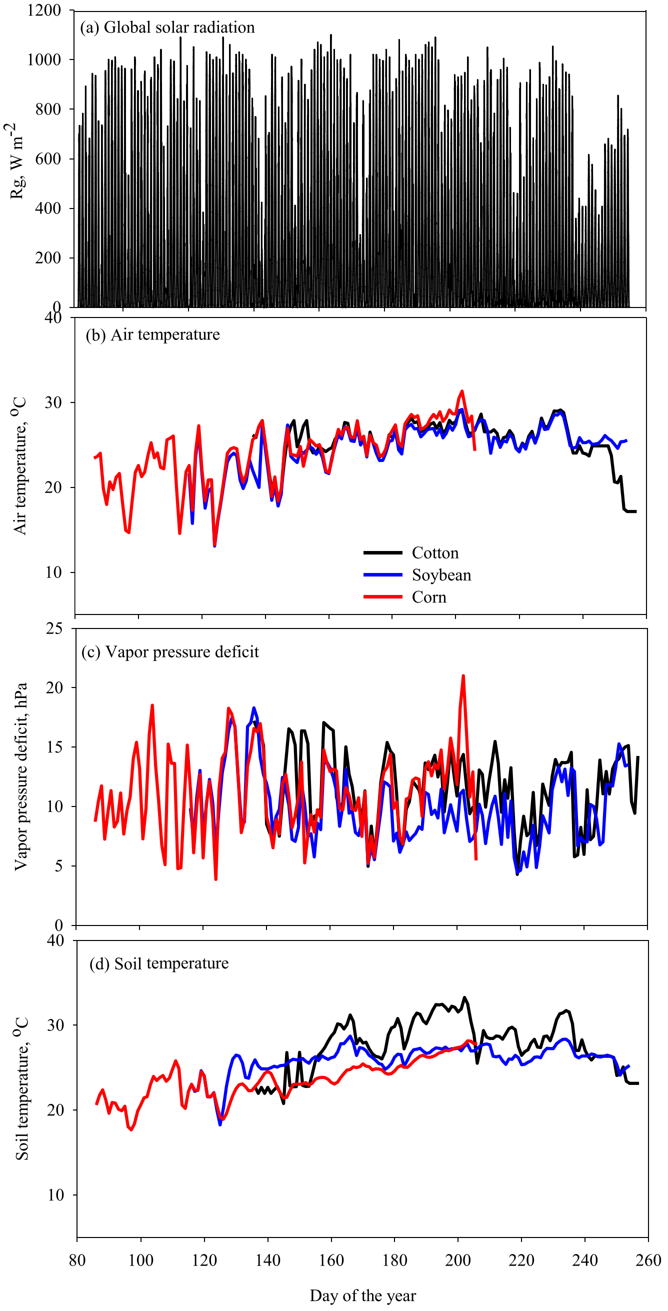


Fig. 3. (a) Global solar radiation (Rg), (b) air temperature, (c) air vapor pressure deficit (VPD), and (d) soil temperature in corn, soybean, and cotton during the crop growth season in 2017.

3.2. Crop growth and development

The emergence of corn seedlings was complete in seven days after planting (DAP) and reached physiological maturity in 120 days after emergence (DAE). The Leaf Area Index (LAI) of crop-plants in cropping systems has the most influence on NEE in those systems (Norman and Campbell, 1989). LAI also controls both the radiation balance and ET from the system. Corn plants reached maximum leaf growth (LAI = 5.5) in about 61 days after emergence (Fig. 2a). Harvested average corn yield was 12,772 kg ha^{-1} with a standard deviation (SD) of 203 kg ha^{-1}.

Soybean plants fully emerged, and crop stand was established in 6 DAP and reached physiological maturity in 135 DAE. Crop stand attained its maximum LAI of 5.8 in 64 DAE and harvested grain yield averaged 4777 kg ha^{-1} with SD = 396 kg ha^{-1}.

The cotton seedlings emerged in 6 DAP and reached physiological maturity in 137 DAE. Plant growth hormones were used to suppress the vegetative growth of the cotton plants four times during two weeks before blooming and three weeks after blooming. Cotton crop attained maximum LAI growth of 3.0 in 63 DAE on September 10, 2017. Cotton lint yield averaged 1260 kg ha^{-1}.

3.3. Energy balance closure

As above, quantification of CO_2 and water fluxes from cropping systems using the EC method was achieved by measuring the covariances of the vertical wind speed for eddy transport and the concentrations of CO_2 and water vapor in the eddies (Foken et al., 2011; Mauder et al., 2007; Anapalli et al., 2018). Water vapor flow out of the system represents the LE energy that is a prime component of the radiation-energy balance in the system. Following the first law of thermodynamics, the energy input to the system (R_n-G_o-S_{bm}-S_{ph}) and energy output from the system (H + LE) must balance. Hence, the extent to which the inputs and outputs of energies from the system are balanced reflects on the accuracy in measurements of water vapor flux from the system. As both CO_2 and water vapor concentrations in the air are measured with the same infrared gas analyzer and a single measurement of vertical wind speed of the eddies to calculate both the fluxes, the EBC also should reflect on the accuracy of CO_2 flux measured. Owing to reasons related to inadequate theory to measurement problems, energy measure imbalances of the order of 0 to 30% have been reported in the literature (Foken et al., 2011; Leuning et al., 2012; Anderson and Wang, 2014; Liu et al., 2017). We analyzed the fluxes measured in the EC systems and analyzed EBCs in the systems at a half-hourly time interval (Fig. 4a, c, e). At this interval, EBCs computed for flux measurements in corn, soybean, and cotton systems were 88, 84, and 84%, respectively (slope of the linear regression relationship between $R_n - G_0 - S_{bm} - S_{ph}$ the energy input and H + LE, the energy output from the system). Anderson and Wang (2014) reported improvements in energy balance closures by 8 to 10% in sugarcane fields in Hawaii, USA when EBC was computed at daily intervals. When computed on a daily basis, we achieved EBC closures of 96, 92, and 94%, that is, 8, 8, and 10% improvements in closures in corn, soybean, and cotton systems, respectively (Fig. 4b, d, and f). So, the results of flux measurements and NEE reported in this study is expected to have errors between 4 and 8%. Anapalli et al. (2018) measured similar fluxes in soybean using similar instrumentation used in this study but at a different location (about 3 km apart) in the MS Delta in 2016 and reported EBC improvement to the daily analysis of only 2%. This shows the possibility of the EBC improvement achieved in this way to depend heavily on the climate during the growing season and other varying crop-environmental conditions but needs further investigations before making recommendations.

3.4. NEE from the cropping systems

The net vertically transferred fluxes of CO_2 as measured in the EC method, NEE, represent the balance from the gross primary production (GPP, the amount of CO_2 fixed in photosynthesis) minus the CO_2 released in plant respiration and as a byproduct of organic matter decomposition in the soil environment. Following the micrometeorological sign-conventions, if the net flux of CO_2 is coming down towards the crop (sink or uptake of CO_2), it is expressed as a negative in value (Fig. 5).

As the crop advanced through different stages of growth from planting to harvest, the amounts of NEE exchanged also elevate and cease with the crop. This waxing and waning pattern in NEE is reflected in its diurnal patterns, averaged monthly, from March to September, of all the three crops. Between corn, soybean, and cotton, appreciable differences in the amounts of NEE are reflected (Fig. 5a–g). Daily biomass assimilation was highest in corn, followed by soybean, and least in cotton. Corn was planted on March 21 and seedlings emerged on March 28, as such, the flux pattern in March reflected only the soil respiration during the fallow season (Fig. 5a - negative values represent CO_2 intake into the system and positive values represent CO_2 given out of the system). From April, corn growth increased tremendously in May, further increased in June, and decayed with maturity in July: monthly peak diurnal NEE averaged −3.8, −30.4, −33.6, and −26.7 kg CO_2 ha^{-1} in April, May, June, and July, respectively (Fig. 5c, d, and e). Corn remained a net sink for CO_2 across these four months.

Both soybean and cotton were planted in April and harvested in September. While soybean was a net sink for CO_2 from April through August (Fig. 5b, c, d, e, f), cotton was a net sink for CO_2 only in the months of June, July, and August (Fig. 5c, d, e, f). Though cotton was planted on April 22, it fully emerged, and crop stands were completely established only by April 31, so the crop did not have any biomass growth in March. Monthly diurnal peak NEE for soybean averaged −11.1, −15.4, −23.3, −27.2, and −15.7 kg CO_2 ha^{-1} in April, May, June, July, and August, respectively. Similar diurnal peaks of NEE for cotton averaged −3.2, −6.0, −14.2, and −10.4 kg CO_2 ha^{-1} in May, June, July, and August (Fig. 5a–g).

Half-hour averaged NEE values for corn, soybean, and cotton showed distinctive patterns, with different amounts of CO_2 exchanged with time during their crop seasons (Fig. 6a, c, e). Highest NEE was in corn, followed by soybean and cotton. All the crops were grown with ample N (soybean being an N fixer, no fertilizer was applied to this crop) and water so that they did not suffer from N or water stress and exhibited optimum growth. However, they fixed distinctly different amounts of carbon: corn is a C_4 crop, so, as explained earlier, for a given amount of resources, it fixes more CO_2 than the C_3 soybean and cotton crops could fix. Half-hour values of NEE realized in cotton averaged −5.4 kg CO_2 ha^{-1} for the whole season, the highest among the three crops. Maximum and minimum half-hour average NEEs in corn during the season were −64.7 and 22.7 kg CO_2 ha^{-1}, respectively. Maximum half-hour averaged value of NEE measured in soybean was −46.8 kg CO_2 ha^{-1} and minimum was 31.2 kg CO_2 ha^{-1}, with an average value of −3.5 kg CO_2 ha^{-1}. Half-hour averaged NEE values in cotton ranged between 33.5 (minimum) to −39.6 (maximum) kg CO_2 ha^{-1}, with an average of −1.7 kg CO_2 ha^{-1}.

Daily total NEE fluxes from the three cropping systems also clearly demonstrated the advantage of corn, a C_4 crop, in fixing more biomass compared to the soybean and cotton crops with C_3 photosynthetic pathways (Fig. 6b, d, f). Average daily NEE from corn was −258 kg CO_2 ha^{-1}, with a maximum of −739 kg CO_2 ha^{-1} and minimum of 70 kg CO_2 ha^{-1}. Total NEE for the whole season was −31,331 kg CO_2 ha^{-1}. In the case of soybean, average daily NEE was −169 kg CO_2 ha^{-1}, with a maximum of −659 kg CO_2 ha^{-1} and minimum of 124 kg CO_2 ha^{-1}. Total NEE during the whole season of soybean was −23,563 kg CO_2 ha^{-1}, which was 25% less than that of the corn. The whole season NEE estimated for cotton was −8856 kg CO_2 ha^{-1}, which was 72% less than corn and 62% less than soybean and was the least among the three crops. Daily maximum NEE estimated for cotton was −274 kg CO_2 ha^{-1} and the minimum was 121 kg CO_2 ha^{-1} with an average of −65 kg CO_2 ha^{-1}.

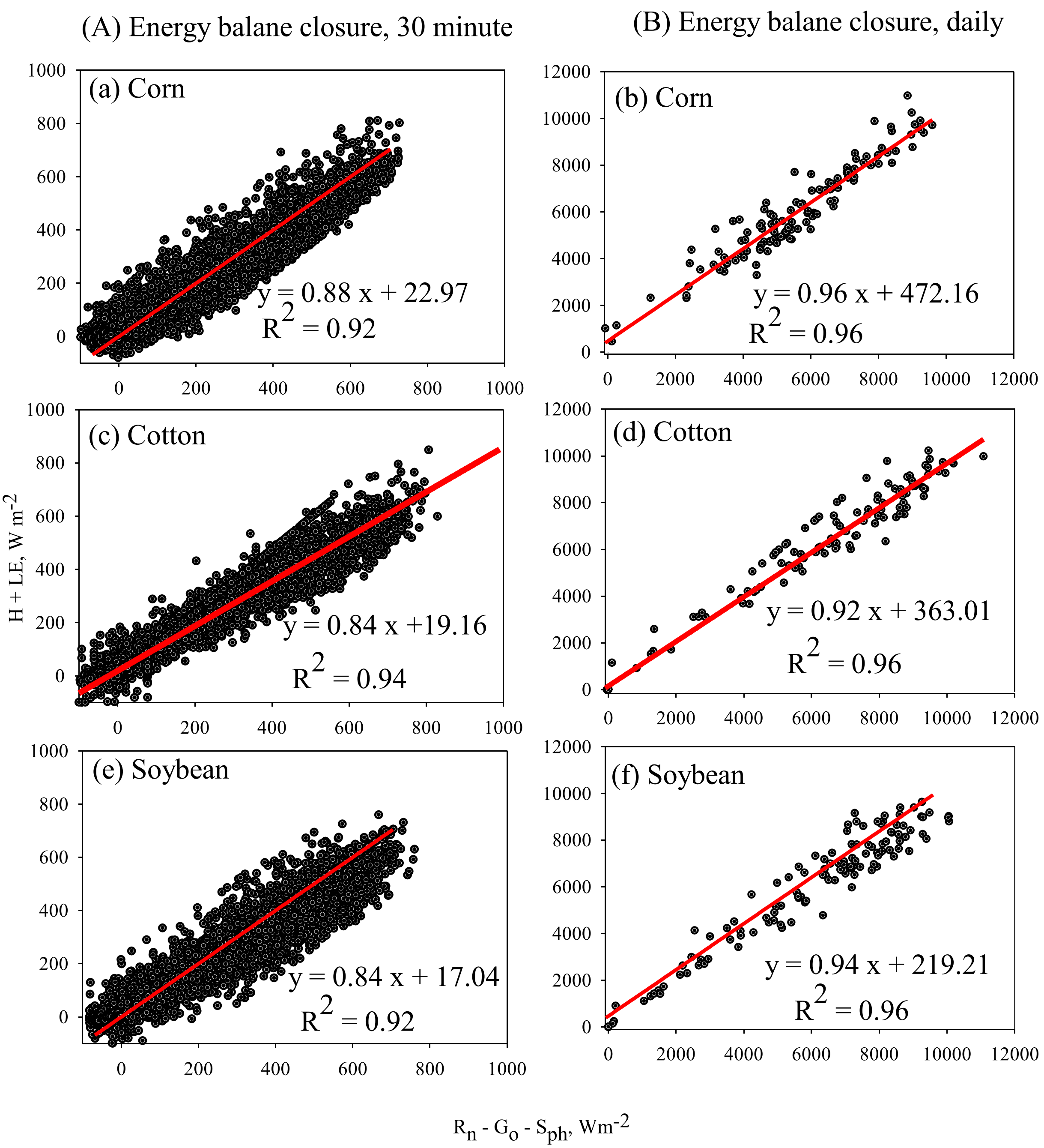


Fig. 4. Regressions between measured or estimated energy inputs ($R_n - G_0 - S_{ph}$) and energy use/outputs ($H + LE$) measured using the eddy covariance systems in corn, soybean, and cotton systems in 2017: Panel (A) represents fluxes averaged at half-hourly intervals and panel (B) of gives total fluxes in daily intervals. Slopes of the linear relationships between input and output fluxes represent energy balance closures in the flux measurements. R^2 is the coefficient of determination.

3.5. Relationships between NEE and environmental variables

Given the genetic potential of plant species in fixing carbon, the NEE in an agricultural ecosystem depends on the state of the soil-water-air environment in which the crop-plants are growing (Carrara et al., 2004; Lei and Yang, 2010). In systems ecology, mathematical relationships between carbon assimilation rates and environmental variables are often built and used for predicting carbon gains in the system under conditions that are different from the conditions under which the measurements were made (Hall, 1979; Hesketh, 2017). In that direction, in order to quantify the individual contributions of measured environmental parameters on carbon dynamics in our experiments, we examined the dependence of half-hour average estimates of NEE of corn, soybean, and cotton crops on soil temperature and moisture, air temperature, relative humidity, VPD, and Rg. Of these six environmental variables, only Rg and VPD showed appreciable relationships with NEE, with R^2 (fraction of variations in NEE explained by its quadratic regressions with Rg or VPD) between 0.32 (NEE vs. VPD for cotton) and 0.66 (NEE vs. Rg for soybean) (Fig. 7h, d). Quadratic relationships with Rg explained variations in the measured half-hourly NEE in corn, soybean, and cotton by 64% ($R^2 = 0.64$ in Fig. 7a), 66% ($R^2 = 0.66$ in Fig. 7d), and 51% ($R^2 = 0.51$ in Fig. 7g), respectively. Similar quadratic relations with VPD explained variations in half-hourly averaged NEE in the three crops by 64% ($R^2 = 0.64$ in Fig. 7b), 63% ($R^2 = 0.63$ in Fig. 7e), and 32% ($R^2 = 0.32$ in Fig. 7d), respectively. Negligible differences in the above relationships were found when GPP

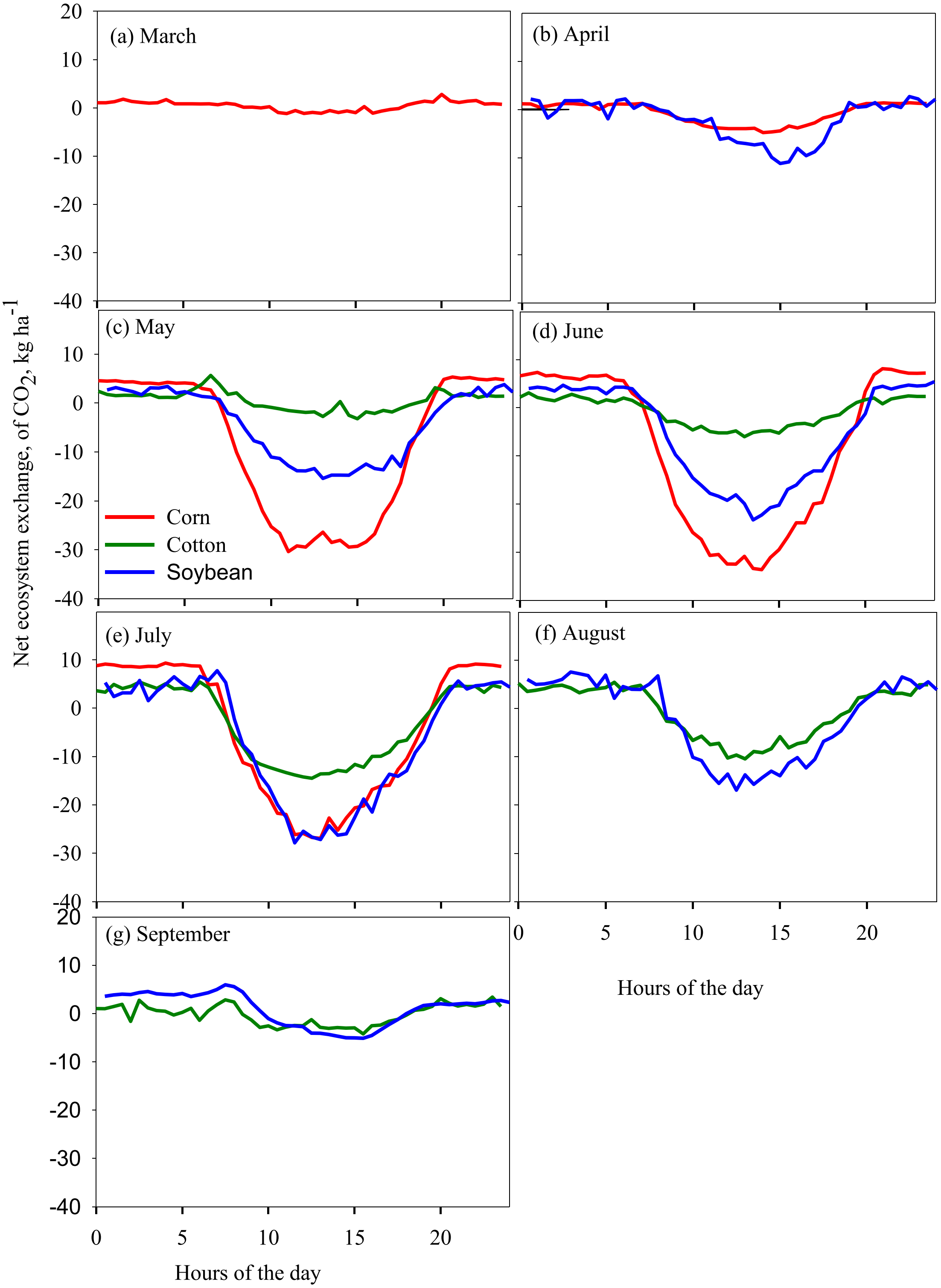


Fig. 5. Monthly (March to September) averaged diurnal variations in net ecosystem exchange of CO_2 (NEE) estimated from eddy flux measurements in corn, soybean, and cotton cropping systems.

derived from night-time air temperature data using the Reichstein et al. (2005) method was used in place of NEE in the relationships (Fig. 7c, f, i).

3.6. Water flux from the cropping systems

In general, peak values of monthly averaged diurnal ET (as estimated from half-hourly EC data) from corn, soybean, and cotton cropping systems increased with increase in crop growth and seasonal increase in air temperature from March/April until July, and then declined with crop maturity in August/September (Fig. 8a–g). These patterns in ET also matched well with the growth patterns of these crops as reflected in the measured LAI, with maximum crop growth and higher LAI values from DOY 182 to 212 (Fig. 2a). Overall, diurnal ET from soybean was higher than that from corn and cotton, excepting the month of May, in which corn ET values exceeded those of the other two crops. Diurnal

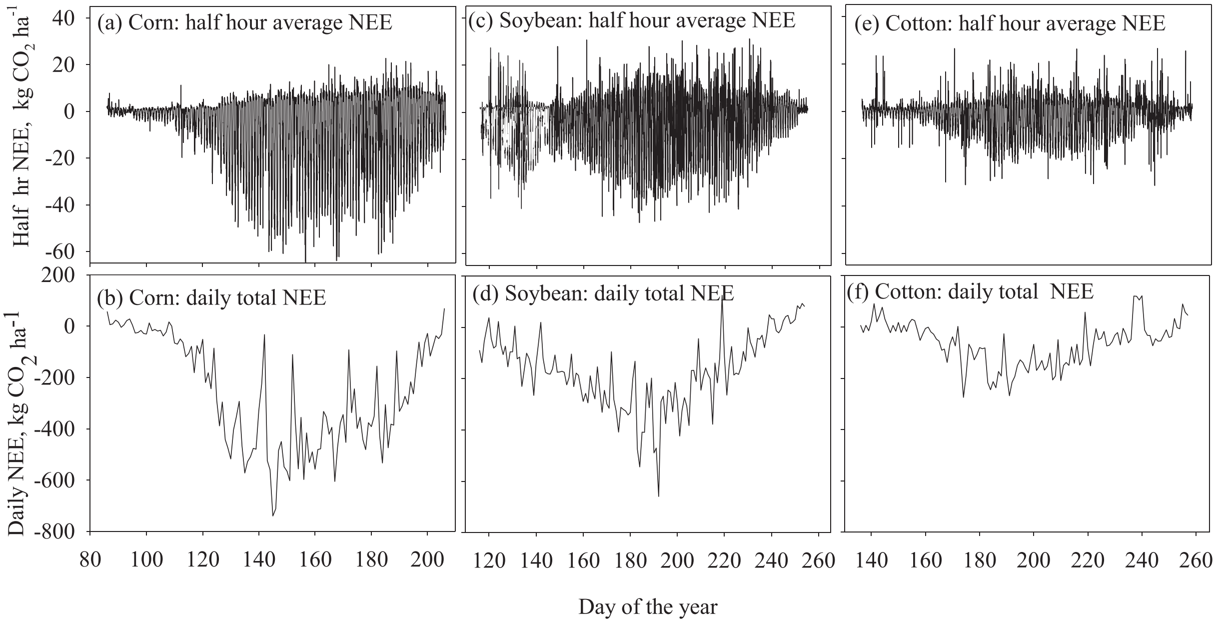


Fig. 6. Daily half-hour averaged and cumulative daily net ecosystem exchange of CO_2 (NEE) in corn, soybean, and cotton during their cropping seasons in 2017.

peak ET in corn increased from 0.15 mm in April to a maximum of 0.28 mm in July. In the case of soybean, the peak in diurnal ET increased from 0.19 mm in May to 0.32 mm in July. ET from cotton was considerably lower than ET from corn and soybean: peak ET from cotton varied from 0.10 mm in May to 0.23 mm in July. The LAI measured in cotton also was much lower than that measured in corn and soybean: maximum LAI in cotton was 2.9, while it was 5.5 and 5.6, respectively, in corn and soybean (Fig. 2a).

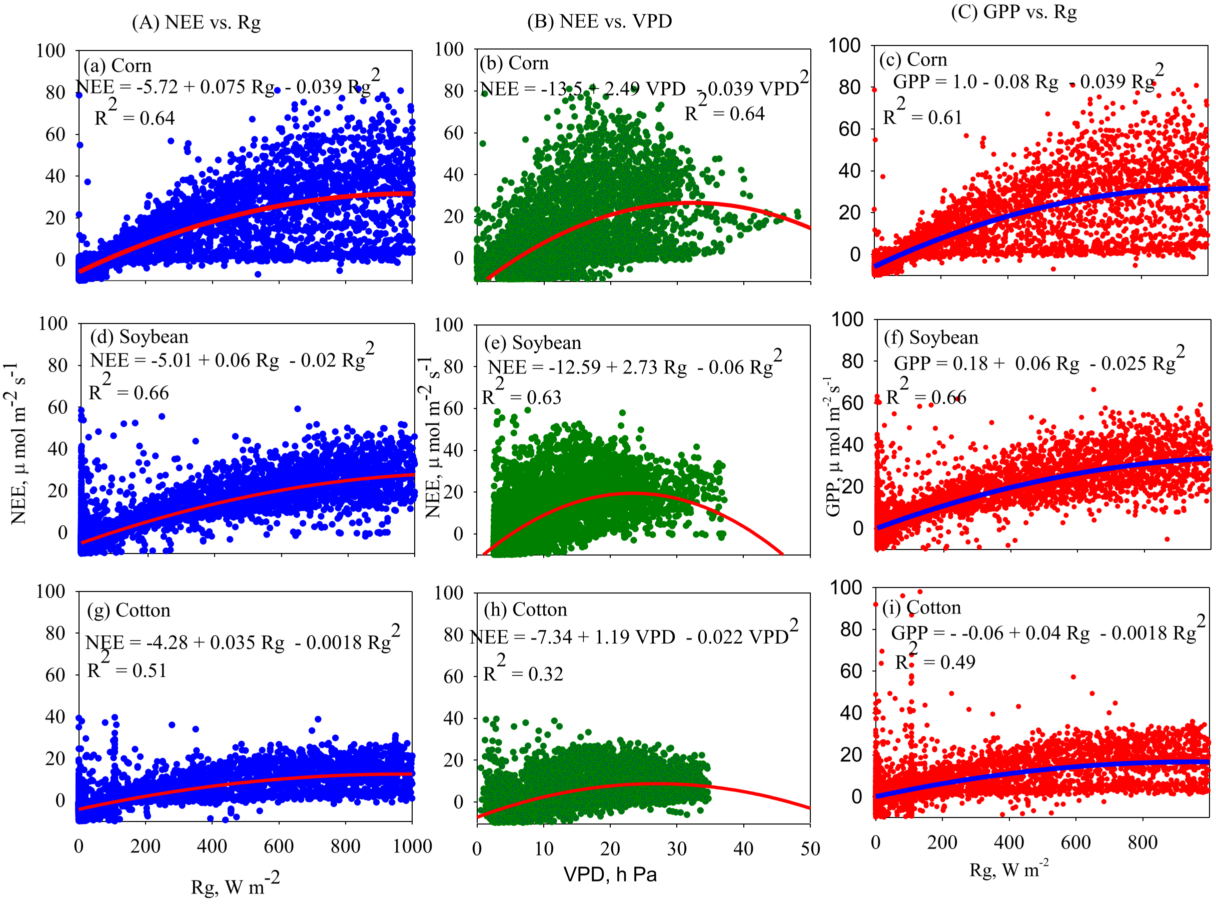


Fig. 7. Relationships between half-hour averaged gross primary production, expressed as amount of CO_2 fixed (GPP) and net ecosystem exchange of CO_2 (NEE), and environmental variables in corn, soybean, and cotton cropping systems: (a), (d), and (g) are between NEE and total global solar radiation (Rg); (b), (e), and (h) are between NEE and VPD; and (c), (f), and (i) are between GPP and Rg.

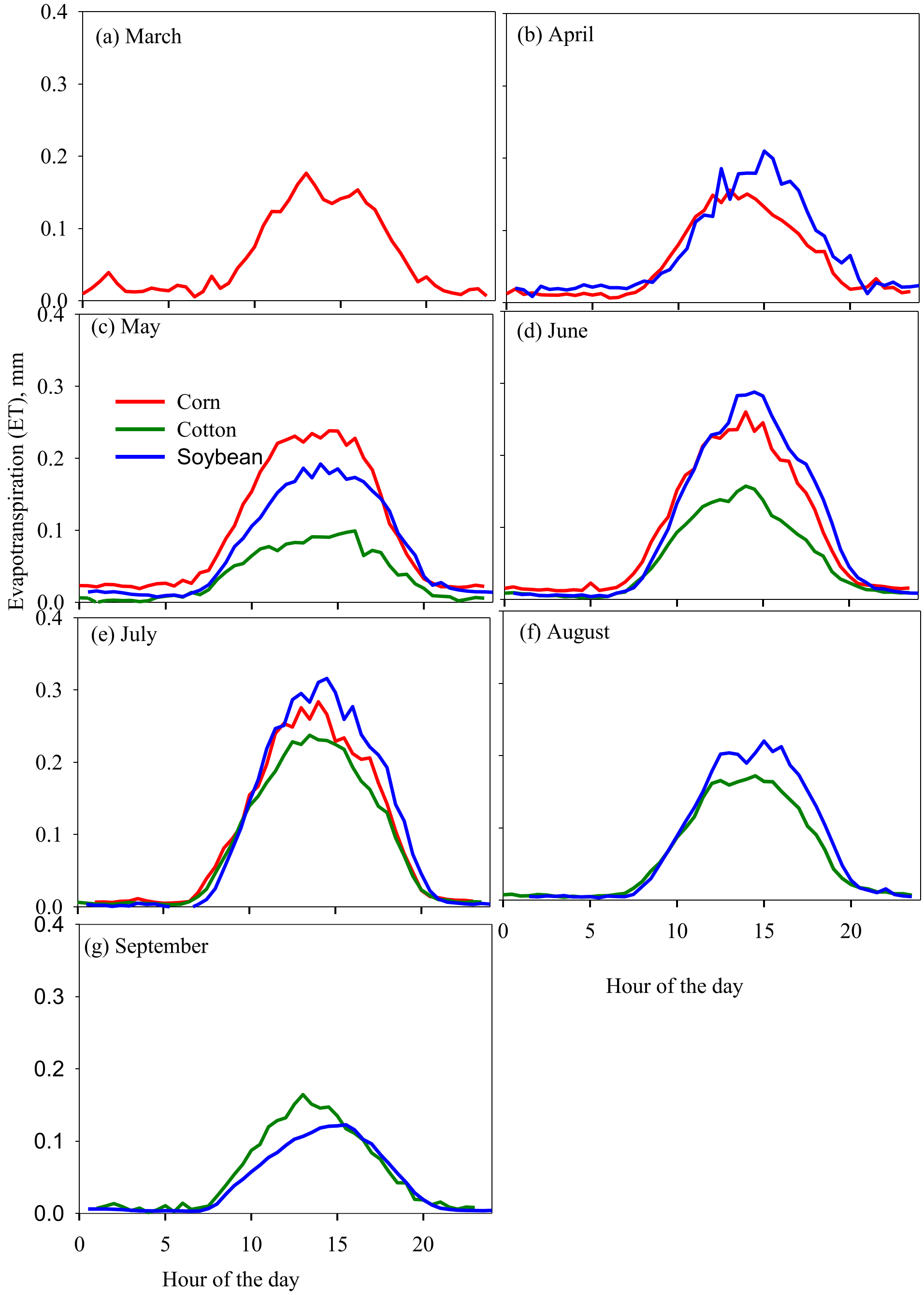


Fig. 8. Monthly averaged diurnal variations in evapotranspiration (ET) estimated from eddy flux measurements in corn, soybean, and cotton cropping systems.

In general, among all the three crops, maximum daily ET occurred in July (Fig. 9b, d, f). Average (over the whole crop season) daily ET from corn was 4.0 mm, with a maximum of 6.4 mm and a minimum of 1.0 mm (Fig. 9b). Seasonal average daily ET of soybean was 3.9 mm, with a maximum of 6.6 mm and a minimum of 1.3 mm. In the case of cotton, the daily ET maximum was 5.7 mm and minimum was 1.0 mm with an average of 3.0 mm for the whole season. The PEP photosynthetic pathway used by the C_4 crop, corn, explains why it had at least marginally less ET than the C_3 crop soybean (Way et al., 2014). Crop seasonal ET totals for corn, soybean, and cotton were 483, 552, and 367 mm, respectively. Though crop duration of soybean and cotton did not differ appreciably (crop durations were 120, 135, and 137 days for corn, soybean, and cotton, respectively), cotton ET was 33% lower than soybean due to its lower LAI growth compared to soybean (Fig. 2a). Across corn, soybean, and cotton, correlations of half-hourly estimates of ET with weather parameters showed that Rg is correlated with ET ($R^2 = 0.77$) better than Tair ($R^2 = 0.34$) and VPD ($R^2 = 0.53$) in the humid climate of the MS Delta.

3.7. Daily EWUE in cropping systems

Commonly, in agricultural science, water use efficiency (WUE) is used to denote the ratio of the amount of harvested yield, either grain or biomass, to the amount of water used in raising the crop. With the advent of eddy covariance flux measurements of biomass assimilation or NEE from the system, calculation of instantaneous WUE representing all the processes of CO_2 uptake and emissions from the ecosystem, known as EWUE, became possible (VanLoocke et al., 2012; Wagle et al., 2016).

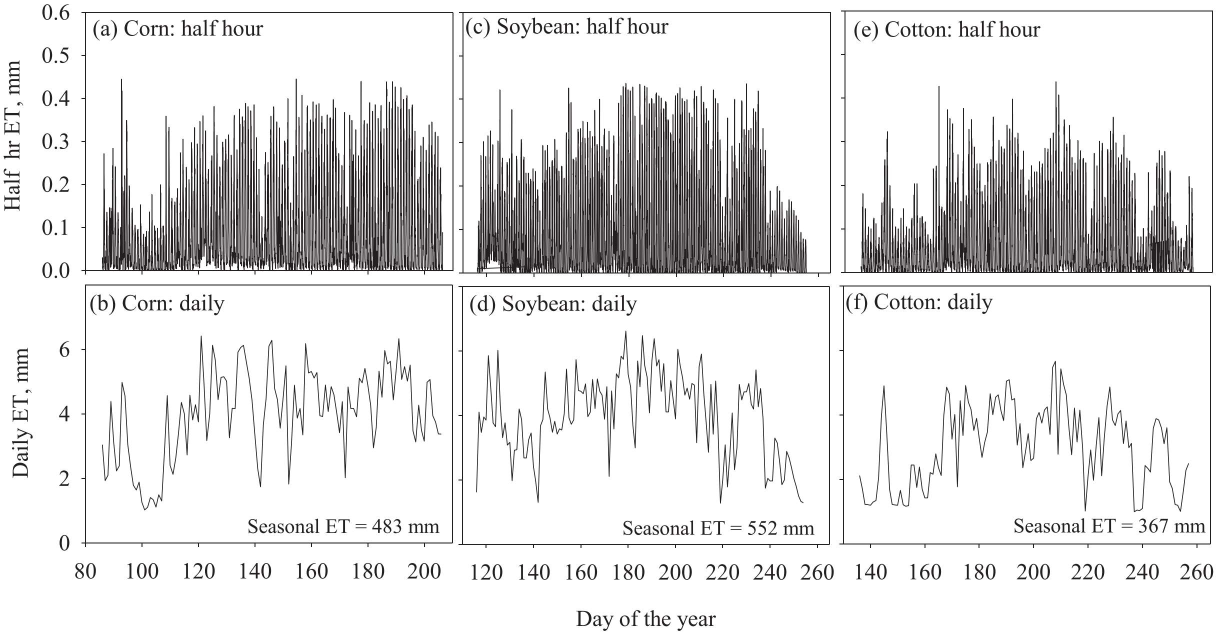


Fig. 9. Daily half-hour averaged and cumulative daily evapotranspiration (ET) from corn, soybean, and cotton during their cropping seasons in 2017.

However, as the EC method has become ubiquitous in measuring CO_2 fluxes in terrestrial ecosystems across disciplines, various definitions and units for representing EWUE evolved that lead to some confusion, making a comparison of results across studies a difficult task (Wagle et al., 2016). In this study, our main objective was to quantify the NEE and amount of water used in that process, as stated above: we used it as a ratio of NEE and ET from the crop-ecosystem as a whole at a daily or seasonal time scale and was expressed as kg CO_2 ha^{-1} mm^{-1} of water. For the EWUE computations, the conventional negative sign of the NEE values was reversed so that maximum values are positive and minimum values are negative.

In general, the computed daily EWUE in corn (C_4 crop) were higher than that estimated in soybean and cotton (C_3 crops) (Fig. 10a, b, c). Among the C_3 crops, soybean exhibited a higher EWUE than that of cotton. Overall, daily EWUE in all the three crops followed the LAI growth pattern of the crops: EWUE started increasing from a low value at the early growth stages of the plants and reached maximum values coinciding around the time the crop reached maximum LAI (Fig. 10a–c). Further, following the LAI declines with leaf senescence in the crop plants, EWUE gradually decreased to a minimum towards crop maturity. With lower LAI, lower photosynthetic carbon assimilations were achieved in the crop plants, but more soil surfaces were also exposed to the direct sunlight, causing more ET loss of water from the system. This way, more ET in exchange of less CO_2 intake leads to less EWUE at the beginning and end growth stages of the plants (Fig. 10a–c). However, with LAI increase, more solar radiation was intercepted by the leaves, leading to more photosynthesis and dry matter assimilation. At the same time, with more LAI, fewer soil surfaces were exposed to direct sunlight, leading to less evaporation from the soil contributing to ET. Hence, higher rates of EWUE was achieved during the peak LAI growth stages of the three crops (Fig. 10a–c). Wagle and Kakani (2014) reported maximum EWUE from switchgrass during its peak growth stages. Wagle et al. (2015) reported a reduction in NEE and ET during drought periods leading to lower EWUE in switchgrass. However, as the crops in our experiments were free of water stress, chances of drought-induced reductions in EWUE were less.

In the case of corn, lowest daily EWUE varied between −5 and 154 kg CO_2 ha^{-1} mm^{-1} (of water) with an average of 53 kg CO_2 ha^{-1} mm^{-1} (Fig. 10a). Average daily EWUE achieved in soybean was

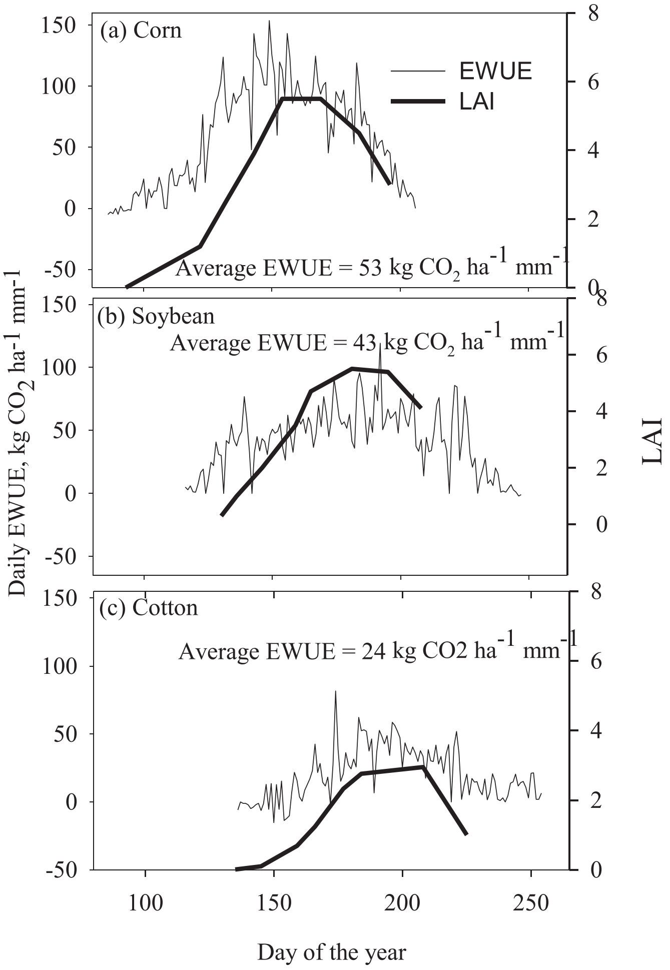


Fig. 10. Daily water use efficiencies (EWUE) of corn, soybean, and cotton cropping systems in 2017.

43 kg CO_2 ha^{-1} mm^{-1}, with the lowest value of 0 kg CO_2 ha^{-1} mm^{-1} and highest value of 119 kg CO_2 ha^{-1} mm^{-1} (Fig. 10b). In the case of cotton, average daily EWUE was 24 kg CO_2 ha^{-1} mm^{-1}, with a minimum of −5 kg CO_2 ha^{-1} mm^{-1} and a maximum of 82 kg CO_2 ha^{-1} mm^{-1} (Fig. 10c). The end of the season grain yield harvested from corn was 12,772 kg ha^{-1} and seasonal total ET exchanged from the cropping system was 483 mm (Fig. 9a, b). Hence, the corn crop's grain production WUE, expressed as the ratio of the weight of grain to the amount of ET, was 26 kg ha^{-1} mm^{-1} of water. With a grain yield of 4777 kg ha^{-1} and ET of 552 mm, WUE of soybean grain production was 9 kg ha^{-1} mm^{-1} of ET. Cotton seasonal ET was 367 mm that produced a lint yield of 1260 kg ha^{-1}, hence the WUE of cotton lint yield production was 3 kg ha^{-1} mm^{-1} of ET.

4. Conclusions

In this unique study, we quantified EWUE changes across irrigated C_3 (soybean and cotton) and C_4 (corn) crops in a humid climate of the MS Delta in a clay soil. Crop durations were 120, 135, and 137 days, respectively for corn, soybean, and cotton. Maximum LAI and average grain yield produced were 5.5 and 12,772 kg ha^{-1}, 5.5 and 4777 kg ha^{-1}, and 3.0 and 1260 kg lint ha^{-1}, respectively, for these crops. The NEE of CO_2 and ET from these cropping systems were measured using eddy covariance instrumentation. The daily non-closures of energy balances from the three cropping systems were between 4 and 8%. Estimated average daily ET of corn was 4.0 mm, soybean was 3.9 mm, and cotton was 3.0 mm. Seasonal ET for corn, soybean, and cotton was 483 mm, 552, and 367 mm, respectively. All the three crops were a net sink for CO_2 during the entire growth period, excepting the 3 to 4 weeks immediately after planting. Seasonal NEE of corn was 31,331 kg CO_2 ha^{-1}, and soybean and cotton NEE were 25% and 75% less than that of corn, respectively. Rg explained variations in the measured half-hourly NEE in corn, soybean, and cotton by 64, 66, and 51%, and VPD by 64, 63, and 32%, respectively. Estimated ET from these cropping systems explained variations in NEE by 41, 65, and 46%, respectively. The EWUE in C_4 corn was higher than in C_3 soybean and cotton, and between the two C_3 crops, soybean exhibited better EWUE than cotton. Average EWUE of corn, soybean, and cotton were 53, 43, and 24 kg CO_2 ha^{-1} mm^{-1} respectively. The WUE in grain production of corn was 26 kg ha^{-1} mm^{-1} and soybean was 9 kg ha^{-1} mm^{-1} of water. The WUE of cotton lint production was about 3 kg ha^{-1} mm^{-1} of water. Results of this investigation have the potential for decision support in choosing the right crop mix in the MS Delta for increased WUE while sequestering more CO_2 in cropping systems.

Disclaimer

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

References

Anapalli, S.S., Pettigrew, W.T., Reddy, K.N., Ma, L., Fisher, D.K., Sui, R., 2016. Climate optimized planting windows for cotton in the lower Mississippi Delta region. Agronomy 6 (46), 1–15.

Anapalli, S.S., Fisher, D.K., Reddy, K.N., Wagle, P., Gowda, P.H., Sui, R., 2018. Quantifying soybean evapotranspiration using an eddy covariance approach. Agric. Water Manag. 209, 228–239.

Anderson, R.G., Wang, D., 2014. Energy budget closure observed in paired eddy covariance towers with increased and continuous daily turbulence. Agric. For. Meteorol. 184, 204–209. https://doi.org/10.1016/j.agrformet.2013.09.012.

Arneth, A., Veenendaal, E.M., Best, C., Timmermans, W., Kolle, O., Montagnani, L., Shibistova, O., 2006. Water use strategies and ecosystem-atmosphere exchange of CO_2 in two highly seasonal environments. Biogeosciences 3, 421–437.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present, and future. Glob. Chang. Biol. 9, 479–492.

Baldocchi, D.D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, J.W., Oechel, W., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415–2435.

Beer, C., Ciais, P., Reichstein, M., Baldocchi, D., Law, B.E., Papale, D., Soussana, J.F., Ammann, C., Buchmann, N., Frank, D., Gianelle, D., Janssens, L.A., Knohl, A., Kostner, B., Moors, E., Roupsard, O., Verbeeck, H., Vesala, T., Williams, C.A., Wohlfahrt, G., 2009. Temporal and among-site variability of inherent water use efficiency at the ecosystem level. Glob. Biogeochem. Cycles 23, GB2018. https://doi.org/10.1029/2008GB003233.

Carrara, A., Janssens, I.A., Curiel, Y.J., Ceulemans, R., 2004. Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. Agric. For. Meteorol. 126 (1), 15–31. https://doi.org/10.1016/j.agrformet.2004.05.002.

Clark, B.R., Hart, R.M., 2009. The Mississippi Embayment Regional Aquifer Study (MERAS): documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment. U.S. Geological Survey Scientific Investigations Report 2009–5172 (61 p.).

Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Ground water depletion embedded in international food trade. Nat. Lett. 543, 700–706.

de Vries, D.A., 1963. Thermal properties of soils. In: van Wijk, W.R. (Ed.), Physics of Plant Environment. Wiley, New York, pp. 137–160.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. For. Meteorol. 107, 43–69.

Foken, T., Aubinet, M., Leuning, R., 2011. The eddy-covariance method. In: Aubinet, M., Vesala, T., Papale, D. (Eds.), Eddy Covariance: a Practical Guide to Measurement and Data Analysis. Springer, 57 Berlin, Heidelberg.

Hall, A.E., 1979. A model of leaf photosynthesis and respiration for predicting carbon dioxide assimilation in different environments. Oecologia (Beri.) 143, 299–316.

Hanifzadeh, M., Garcia, E.C., Viamajala, S., 2018. Production of lipid and carbohydrate from microalgae without compromising biomass productivities: role of Ca and Mg. Renew. Energy 127, 989e997.

Hatfield, J.L., Sauer, T.J., Prueger, J.H., 2001. Managing soils to achieve greater water use efficiency: a review. Publications from USDA-ARS/UNL Faculty , p. 1341. http://digitalcommons.unl.edu/usdaarsfacpub/1341.

Hesketh, J.D., 2017. Predicting Photosynthesis for Ecosystem Models. vol. 1. CRC Press, p. 283 (ISBN 9781315896861 - CAT# K348020).

Kebede, H., Fisher, D.K., Sui, R., Reddy, K.N., 2014. Irrigation methods and scheduling in the Delta region of Mississippi: current status and strategies to improve irrigation efficiency. Am. J. Plant Sci. 5, 2917–2928. https://doi.org/10.4236/ajps.2014.520307.

Kimball, B.A., LaMorte, R.L., Pinter Jr., P.J., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D., Brooks, T.J., 1999. Free-air CO2 enrichment (FACE) and soil nitrogen effects on energy balance and evapotranspiration of wheat. Water Resour. Res. 35 (4), 1179–1190.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A.D., Arneth, A., Barr, A., Stoy, P., Wohlfahrt, G., 2010. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. Glob. Chang. Biol. 16 (1), 187–208. https://doi.org/10.1111/j.1365-2486.2009.02041.x.

Lei, H.M., Yang, D.W., 2010. Seasonal and interannual variations in carbon dioxide exchange over a cropland in the North China Plain. Glob. Chang. Biol. 16 (11), 2944–2957. https://doi.org/10.1111/j.1365-2486.2009.02136.x.

Leuning, R., van Gorsel, E., Massman, W., Isaac, P., 2012. Reflections on the surface energy imbalance problem. Agric. For. Meteorol. 156, 65–74.

Liu, X., Yang, S., Xu, J., Zhang, J., Liu, J., 2017. Effects of heat storage and phase shift correction on energy balance closure of paddy fields. Atmosfera 30 (1), 39–52.

Mauder, M., Foken, T., 2011. Documentation and Instruction Manual of the Eddy-Covariance Software Package TK3. Universität Bayreuth, Abteilung Mikrometeorologie, p. 46 ISSN 1614-8924. (60 pp.).

Mauder, M., Oncley, S.P., Vogt, R., Weidinger, T., Ribeiro, L., Bernhofer, C., Foken, T., Kohsiek, W., de Bruin, H.A.R., Liu, H., 2007. The energy balance experiment EBEX-2000. Part II: inter-comparison of eddy-covariance sensors and post-field data processing methods. Bound.-Layer Meteorol. 123, 29–54. https://doi.org/10.1007/s10546-006-9139-4.

Meek, W.M., 1997. Estimaion of maximum possible daily gloval solar radiation. Agric. For. Meteorol. 87, 223–241.

Meyers, T.P., Hollinger, S.E., 2004. An assessment of storage terms in the surface energy balance of maize and soybean. Agric. For. Meteorol. 125, 105–115.

Moncrieff, J.B., Masheder, J.M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, S., Verhoef, A., 1997. A system to measure surface flux momentum, sensible heat, water vapor and carbon dioxide. J. Hydrol. 188–189, 589–611.

Moncrieff, J.B., Clement, R., Finnigan, J., Meyers, T., 2004. Averaging, detrending and filtering of eddy covariance time series. In: Lee, X., Massman, W.J., Law, B.E. (Eds.), Handbook of Micrometeorology: a Guide for Surface Flux Measurements. Kluwer Academic, Dordrecht, pp. 7–31.

Norman, J.M., Campbell, G.S., 1989. Canopy structure. In: Pearcy, R.W., Ehleringer, J.R., Mooney, H.A., Rundel, P.W. (Eds.), Plant Physiological Ecology: Field Methods and Instrumentation. Chapman and Hall, London, pp. 301–325 https://doi.org/10.1007/978-94-009-2221-1_14.

Parent, A.C., Anctil, F., 2012. Quantifying evapotranspiration of a rainfed potato crop in South-Eastern Canada using eddy covariance techniques. Agric. Water Manag. 113, 45–56.

Pielke, R.A., Avissar, R., Raupach, M., Dolman, H., Zeng, X., Denning, S., 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Glob. Chang. Biol. 4, 461–475.

Powers, S., 2007. Agricultural water use in the Mississippi Delta. Delta Ground Water. 37th Annual Mississippi Water Resources Conference Proceedings, pp. 47–51.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439. https://doi.org/10.1111/j.1365-2486.2005.001002.x.

Runkle, B.R., Rigby, J.R., Reba, M.L., Anapalli, S.S., Bhattacharjee, J., Krauss, K.W., Liang, L., Locke, M.A., Novick, K.A., Sui, R., Suvočarev, K., White, P.M., 2017. Deltaflux: an eddy covariance network for a climate-smart lower Mississippi Basin. Agric. Environ. Lett. 2, 170003.

Sage, R.F., Sage, T.L., Kocacinar, F., 2012. Photorespiration and the evolution of C_4 photosynthesis. Annu. Rev. Plant Biol. 63, 19–47.

Schulze, E.D., Hall, E.A., 1982. Stomatal resposes, water loss and CO_2 assimilation rates of plants in contrasting envirnments. In: Lange, O.L., Nobel, P.S., Osmond, C.B., Ziegler, H. (Eds.), Encyclopedia of Plant Physiology, Physiological Ecology II: Water Relations and Carbon Assimilation. Springer-Verlag, Berlin, Heidelberg, New York, pp. 181–230.

Shurpali, N.J., Biasi, C., Jokinen, S., Hyvönen, N., Martikainen, P.J., 2013. Linking water vapor and CO_2 exchange from a perennial bioenergy crop on a drained organic soil in eastern Finland. Agric. For. Meteorol. 168, 47–58.

Sun, G., Noormets, A., Gavazzi, M., McNulty, S.G., Chen, J., Domec, J.C., King, J.S., Amatya, D.M., Skaggs, R.W., 2010. Energy and water balances of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA. For. Ecol. Manag. 259, 1299–1310.

Tallec, T., Béziat, P., Jarosz, N., Rivalland, V., Ceschia, E., 2013. Crop's water use efficiencies in a temperate climate: comparison of stand, ecosystem and agronomical approaches. Agric. For. Meteorol. 168, 69–81. https://doi.org/10.1016/j.agrformet.2012.07.008.

Uddin, J., Hancock, N.H., Smith, R.J., Foley, J.P., 2013. Measurement of evapotranspiration during sprinkler irrigation using a precision energy budget (Bowen ratio, eddy covariance) methodology. Agric. Water Manag. 116, 89–100.

Van Dijk, A., Moene, A.F., de Bruin, H.A.R., 2004. The principles of surface flux physics: theory, practice and description of the EC pack library. Meteorology and Air Quality Group. Wageningen University, Wageningen, The Netherlands, p. 99.

VanLoocke, A., Twine, T.E., Zeri, M., Bernacchi, C.J., 2012. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric. For. Meteorol. 164, 82–95. https://doi.org/10.1016/j.agrformet.2012.05.016.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean. Technol. 14. https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2.

Vickers, D., Thomas, C.K., Martin, J.G., Law, B.E., 2009. Self-correlation between assimilation and respiration resulting from flux partitioning of eddy-covariance CO_2 fluxes. Agric. For. Meteorol. 149, 1552–1555.

Wagle, P., Kakani, V.G., 2014. Seasonal variability in net ecosystem carbon dioxide exchange over a young switchgrass stand. GCB Bioenergy 6 (4), 339–350.

Wagle, P., Kakani, V.G., Huhnke, R.L., 2015. Net ecosystem carbon dioxide exchange of dedicated bioenergy feedstocks: switchgrass and high biomass sorghum. Agric. For. Meteorol. 207, 107–116.

Wagle, P., Kakani, V.G., Huhnke, R.L., 2016. Evapotranspiration and ecosystem water use efficiency of switchgrass and high biomass sorghum. Agron. J. 108 (3), 1007–1019.

Way, D.A., Katul, G.G., Manzoni, S., Vico, G., 2014. Increasing water use efficiency along the C_3 to C_4 evolutionary pathway: a stomatal optimization perspective. J. Exp. Bot. 65 (13), 3683–3693. https://doi.org/10.1093/jxb/eru205.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Q. J. R. Meteorol. Soc. 106, 85–100.