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Growing season variability in carbon dioxide exchange of irrigated and rainfed soybean in the southern United States

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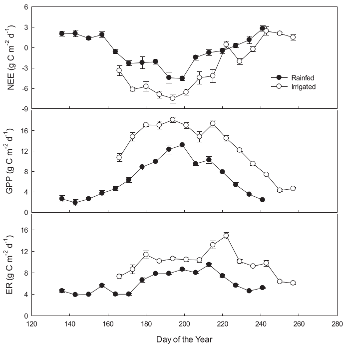
HIGHLIGHTS

- We compared CO_2 fluxes between rainfed and irrigated soybean in the southern U.S.
- Peak daily NEE reached up to -4.55 g C m^{-2} d^{-1} in rainfed soybean.
- Peak daily NEE reached up to -7.48 g C m^{-2} d^{-1} in irrigated soybean.
- Optimum air temperature and VPD were ~30 C and ~2.5 kPa, respectively, at both sites.
- Irrigated soybean was a net carbon sink (~3 months) for about a month longer period.

GRAPHICAL ABSTRACT



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ABSTRACT

Measurement of carbon dynamics of soybean (*Glycine* max L.) ecosystems outside Corn Belt of the United States (U.S.) is lacking. This study examines the seasonal variability of net ecosystem CO_2 exchange (NEE) and its components (gross primary production, GPP and ecosystem respiration, ER), and relevant controlling environmental factors between rainfed (El Reno, Oklahoma) and irrigated (Stoneville, Mississippi) soybean fields in the southern U.S. during the 2016 growing season. Grain yield was about 1.6 t ha^{-1} for rainfed soybean and 4.9 t ha^{-1} for irrigated soybean. The magnitudes of diurnal NEE (~2-weeks average) reached seasonal peak values of -23.18 and -34.78 μmol m^{-2} s^{-1} in rainfed and irrigated soybean, respectively, approximately two months after planting (i.e., during peak growth). Similar thresholds of air temperature (T_a, slightly over 30 °C) and vapor pressure deficit (VPD, ~2.5 kPa) for NEE were observed at both sites. Daily (7-day average) NEE, GPP, and ER reached seasonal peak values of -4.55, 13.54, and 9.95 g C m^{-2} d^{-1} in rainfed soybean and -7.48, 18.13, and 14.93 g C m^{-2} d^{-1} in irrigated soybean, respectively. The growing season (DOY 132–243) NEE, GPP, and ER totals were -54, 783, and 729 g C m^{-2}, respectively, in rainfed soybean. Similarly, cumulative NEE, GPP, and ER totals for DOY 163–256 (flux measurement was initiated on DOY 163, missing first 45 days after planting) were -291, 1239, and 948 g C m^{-2}, respectively, in irrigated soybean. Rainfed soybean was a net carbon sink for only two months, while irrigated soybean appeared to be a net carbon sink for about three months. However, grain yield and the magnitudes and seasonal sums of CO_2 fluxes for irrigated soybean in this study were comparable to those for soybean in the U.S. Corn Belt, but they were lower for rainfed soybean.

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1. Introduction

Atmospheric concentration of carbon dioxide (CO_2) has been rising continuously as a result of anthropogenic activities. For a better understanding of the portion of anthropogenic CO_2 that remains in the atmosphere, the North American Carbon Program (NCAP) identifies the need for in-depth carbon accounting at large scales (i.e., regional and global scales) (Wofsy and Harriss, 2002). Thus, information on exchange of CO_2 fluxes across space is necessary for major agroecosystems not only to develop, test, and improve crop models (Suyker et al., 2005) and satellite-based production efficiency models (Running et al., 1999; Wagle et al., 2014; Xiao et al., 2004) and ET models (Glenn et al., 2007; Wagle et al., 2016; Wagle et al., 2017), but also to better understand the potential of those ecosystems to mitigate climate change and rising CO_2 concentration (Robertson et al., 2000).

Eddy covariance (EC) measurements provide a great opportunity to quantify the exchange of energy, CO_2, and water vapor (H_2O) for a variety of ecosystems. Several EC studies have mainly been reported for soybean (*Glycine* max L.) ecosystems in the north-central United States (i.e., U.S. Corn Belt) (Baker and Griffis, 2005; Hollinger et al., 2005; Suyker and Verma, 2009; Suyker and Verma, 2012; Wagle et al., 2015c). These previous studies from the U.S. Corn Belt have shown that soybean ecosystems are near carbon neutral or small carbon source on annual scales. A comparison of CO_2 fluxes from soybean ecosystems in the U.S. Corn Belt under a range of hydrometeorological conditions showed that sum NEE ranged from -37 to -264 g C m^{-2} on seasonal scales (Wagle et al., 2015c). However, EC measurements in soybean ecosystems outside the U.S. Corn Belt, especially in the southern U.S., are lacking. Soybean has been a very valuable crop in the southern U.S. (Wrather et al., 1995). It is necessary to quantify carbon dynamics of major agroecosystems in all climatic regions and growing conditions to improve our understanding of how those globally important agroecosystems respond to a wide range of climatic conditions.

Both rainfed and irrigated, and conventional till and no-till management practices are common for maize (*Zea mays* L.) and soybean rotations in the U.S. It is well known that different management practices influence carbon dynamics of the ecosystems (Angers et al., 1997; Moinet et al., 2017; Winjum et al., 1992). Thus, it is necessary to accurately estimate carbon dynamics of soybean fields at large spatial scales under different climatic conditions (e.g., low and high precipitation) and management practices (e.g., rainfed and irrigated). Prior to development of early soybean production system (ESPS), growers in lower Mississippi River Valley (31° N–34° 30′ N) planted maturity group (MG) V thru VII soybean cultivars during mid-May to early June which experienced drought/heat stress and resulted in low yields (Bruns, 2016). In the last two decades, growers in the region started adopting ESPS and planting MG IV and V soybean cultivars prior to May 1 along with supplemental irrigation in the region (Bruns, 2016).

While producers in the Mississippi River Valley utilize irrigation to grow soybean, producers in Oklahoma largely function within rainfed environments. Many producers in Oklahoma double-crop soybean with winter wheat (*Triticum aestivum* L.) to improve land and equipment use. Soybean double-cropped with winter wheat in Oklahoma are generally MG IV and V (early maturing, 110–120 days) to fit within the summer period when lands planted to wheat are generally fallowed (Rao and Northup, 2008).

There is limited information comparing CO_2 fluxes of soybean among different agrometeorological and management conditions, especially outside the U.S. Corn Belt. This study reports CO_2 fluxes from a rainfed soybean field in El Reno, Oklahoma and an irrigated soybean field in Stoneville, Mississippi during a growing season. In addition to irrigation treatment, these two sites represent a large climatic gradient (temperate continental climate with mean annual precipitation of 925 mm in Oklahoma site and warm-humid climate with mean annual precipitation of 1300 mm in Mississippi site). The following questions are addressed in this study: (a) how do net ecosystem CO_2 exchange (NEE) and its components (gross primary production, GPP and ecosystem respiration, ER) compare between rainfed and irrigated, and low and high precipitation sites? (b) how do the responses of NEE to major environmental factors [photosynthetically photon flux density (PPFD), air temperature (T_a), vapor pressure deficit (VPD), and soil water content (SWC)] differ between two sites? and (c) what are the differences in seasonal dynamics of ecosystem water use efficiency (EWUE) and ecosystem light use efficiency (ELUE) between two sites?

2. Materials and methods

2.1. Study sites

The rainfed soybean site (~10 ha) was located at the USDA-ARS Grazinlands Research Laboratory, El Reno, Oklahoma (35° 34′N, 98° 1′ W, ~420 m elevation above sea level). The climate is temperate continental, and average annual precipitation is approximately 925 mm, with about 40% received during the soybean growing season from May to August. The dominant soil type is Dale silt loam complex (fine-silty, mixed, superactive, thermic Pachic Haplustolls) situated on the upper terrace of a flood plain along a major stream. These were among the more productive agricultural soils available in central Oklahoma (USDA-NRCS, 1999). Historically (1940–2000), the site was used to produce both row and cereal crops with conventional tillage (combinations of deep plowing, offset disking, and harrowing). The primary use of the site during the 1970's through 2015 was as conventionally tilled winter wheat (*Triticum aestivum* L.) and paddocks of introduced perennial cool-season grasses (2000–2007) that were grazed by yearling stocker cattle. Soybean (Midland 3746 NR2 – a glyphosate-tolerant mid-maturity group III cultivar) was planted (57 cm row spacing) on May 4, 2016 (DOY 125) and harvested on September 7, 2016 (DOY 251). Seedbed preparation prior to planting consisted of two passes with offset disk: one pass with vertical tillage implement and one pass with culti-packer. Phosphorus (~35 kg ha^{-1}) was applied at planting by side-banding (76 kg ha^{-1}) of 18-46-0 granular fertilizer. Glysphosate herbicide (2.3 L ha^{-1}) in aqueous solution was applied 27 and 70 days after planting to control grass and broadleaf weeds.

The irrigated soybean site (~30 ha) was located at the USDA-ARS Crop Production Systems Research, Stoneville, Mississippi (33° 42′ N, 90° 55′ W, ~32 m elevation above sea level). The climate is warm and humid, and average annual precipitation is approximately 1300 mm, with about 30% received during the soybean growing season from May to August (Kebede et al., 2014). Approximately 150 mm water was supplied through furrow irrigation to the field from May 24 to July 18, 2016. Dominant soil type is 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 has been planted for soybean since 2010. Soybean (cv. Dyna Grow 31RY45 – a mid-maturity group IV cultivar) was planted (97 cm row spacing) on April 28, 2016 (DOY 119) and was harvested on September 9, 206 (DOY 253). Fertilizers were not applied.

2.2. Eddy flux, meteorological, and biometric measurements

The EC system at the rainfed site comprised of CSAT3 sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA) and LI-7500-RS open-path infrared gas analyzer (IRGA, LI-COR Inc., Lincoln, Nebraska, USA). The EC system at the irrigated site comprised of Gill Wind Master sonic anemometer (Gill Instruments, Lymington, UK) and LI-7500-RS open-path infrared gas analyzer (IRGA, LI-COR Inc., Lincoln, Nebraska, USA). The sensors were mounted at a fixed height of a 2.5 at the rainfed site, while the sensor height was adjusted according to crop height to maintain 2 m height above the canopy at the irrigated site. Eddy fluxes were collected at 10 Hz frequency. The EC measurements were initiated on May 11 (DOY 132) at the rainfed site and on June 11 (DOY 163) at the irrigated site. Supplementary meteorological measurements included T_a, relative humidity (RH), soil temperature, SWC, net radiation, and PPFD.

We periodically took biometric measurements such as leaf area index (LAI) using a LAI-2200C plant canopy analyzer (LI-COR Inc., Lincoln, Nebraska, USA). Leaf chlorophyll content using a CCM-300 Chlorophyll Content Meter (Opti-Sciences Inc., Hudson, NH, USA) was also collected at the rainfed site.

2.3. Flux data processing and gap filling

The *EddyPro* software (LI-COR Inc., Lincoln, Nebraska, USA) was used to process raw eddy flux data to get 30-min fluxes. The *EddyPro* software provides a quality flag that ranges from 0 (best quality fluxes) to 2 (fluxes that should be discarded). The fluxes with a quality flag of 2 were discarded and unreliable fluxes and statistical outliers beyond ±3.5 SD (standard deviation) were removed from a 14-day running window (Wagle and Kakani, 2014). The *REddyProc* package (https://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWebR Package) on R-Forge, available online from the Max Planck Institute for Biogeochemistry, was used to fill gaps in flux data and to partition NEE into GPP and ER. This tool fills gaps using methods similar to Falge et al. (2001) but also considers the co-variation of fluxes with meteorological variables and the temporal auto-correlation of the fluxes (Reichstein et al., 2005). The tool partitions NEE into GPP and ER following the methods described in Reichstein et al. (2005). The ER was estimated based on the relationship between T_a and nighttime NEE using the Lloyd and Taylor (1994) model, and then NEE was partitioned into GPP and ER. The 30-min flux data were summed for each day to get daily fluxes. Daily flux data were summed over the growing season to get seasonal flux budgets. Sign convention for NEE is negative if the ecosystem is carbon sink and positive if the ecosystem is carbon source.

The NEE-PPFD relationship for different periods of the growing season was evaluated using the light-response function as:

$$\mathrm{NEE} = \frac{\alpha \times \mathrm{GPP_{max}} \times \mathrm{PPFD}}{\alpha \times \mathrm{PPFD} + \mathrm{GPP_{max}}} + \mathrm{ER} \tag{1}$$

where α is apparent quantum yield (mol CO_2 mol^{-1} of photons), PPFD is photosynthetic photon flux density (μmol m^{-2} s^{-1}), $\mathrm{GPP_{max}}$ is maximum canopy CO_2 uptake rate (μmol m^{-2} s^{-1}) at light saturation, and ER is ecosystem respiration (μmol m^{-2} s^{-1}) at zero PPFD.

2.4. Ecosystem water use efficiency (EWUE) and ecosystem light use efficiency (ELUE) estimates

The seasonal distributions of EWUE and ELUE were determined as the ratio between weekly sums of GPP and ET and between GPP and photosynthetically active radiation (PAR), respectively, as in Wagle et al. (2016). The EWUE at the seasonal scale was computed as the ratio between seasonal cumulative GPP and ET, and between seasonal cumulative net ecosystem production (NEP = −NEE) and ET. Similarly, the ELUE at the seasonal scale was computed as the ratio between seasonal cumulative GPP and PAR.

3. Results and discussion

3.1. Growing season weather conditions and crop growth

As compared to the 30-year (1981–2010) mean, May, June, and August 2016 were drier and July 2016 was wetter (1.86 times more rainfall) in El Reno, Oklahoma (Table 1). The rainfed site received 240 mm (62% of the 30-year mean) of rainfall from May to August in 2016. In comparison, the Stoneville, Mississippi site was drier in May 2016, but wetter during June to August as compared to the 30-year mean (Table 1). The irrigated site received 1.38 times more rainfall from May to August in 2016 as compared to the 30-year (1981–2010) mean May–August rainfall of 355 mm.

Evolution of LAI during the growing season is presented in Fig. 1. The maximum LAI was observed during mid- to late-July at both sites. The maximum recorded LAI was 3.4 m^2 m^{-2} for rainfed soybean and 5.71 m^2 m^{-2} for irrigated soybean. The maximum LAI was recorded up to 4.5 and 5.5 m^2 m^{-2} at rainfed and irrigated soybean flux sites, respectively, at Mead, Nebraska (Suyker and Verma, 2010). Total grain yield was ~1.6 t ha^{-1} for rainfed soybean, which was similar to the county-average. The county-average (Canadian county, Oklahoma) soybean yields in 2014 and 2015 were approximately 1.8 and 1.6 t ha^{-1}, respectively (USDA-NASS, 2016). Early-maturing soybean varieties usually have short plants and low yields. Further, the occurrence of above-average temperatures (>35 °C) during late-July and early-August reduced yield by causing some flower abortion. Total grain yield was ~4.9 t ha^{-1} for irrigated soybean.

As compared to the soybean yields in the U.S. Corn Belt, grain yield of <2 t ha^{-1} for rainfed soybean in Oklahoma was lower, but grain yield of ~4.9 t ha^{-1} for irrigated soybean in Mississippi was similar to the county-average maximum soybean yields in the U.S. Corn Belt. County-average soybean yields in 2015 were up to 4.87 t ha^{-1} in the Midwest U.S., and many counties had soybean yields above 3.67 t ha^{-1} (Schnitkey, 2016). Total grain yields of 3.19–3.44 t ha^{-1} (3-years average = 3.33 t ha^{-1}) had been reported for a rainfed soybean flux site at Champaign, Illinois (Hollinger et al., 2005). Similarly, grain yields of 3.32–4.31 t ha^{-1} (4-years average = 3.75 t ha^{-1}) and 3.71–4.36 t ha^{-1} (4-years average = 4.07 t ha^{-1}) had been reported for rainfed and irrigated soybean flux sites, respectively, at Mead, Nebraska (Suyker and Verma, 2012).

3.2. Diurnal patterns of NEE

Diurnal NEE trends (~2-weeks average) in rained and irrigated soybean across the growing season are shown in Fig. 2. The NEE rates were higher in irrigated soybean than in rainfed soybean throughout the growing season. The NEE rates were maximum during July 1–15 in irrigated soybean and July 13–20 in rainfed soybean (NEE measurements were missing for a period of July 1–12 in rainfed soybean due to a malfunctioning sonic anemometer). The magnitude of diurnal peak NEE reached up to −23.18 ± 1.63 (standard error) μmol m^{-2} s^{-1} in rainfed soybean and −34.78 ± 2.04 μmol m^{-2} s^{-1} in irrigated soybean. Results showed that peak NEE occurred approximately two months after planting, corresponded with peak vegetation growth as reflected by maximum LAI and chlorophyll content (Fig. 1). These time periods also correspond to the approximate time of soybean pod setting.

Table 1
Monthly total rainfall (mm) in the 2016 growing season in comparison with the 30-year mean (1981–2010) for the study sites.

Month	30-year mean	2016	Proportion in 2016
El Reno, Oklahoma			
May	124	34	0.27
June	113	34	0.30
July	65	121	1.86
August	87	51	0.59
Growing season total	389	240	0.62
Stoneville, Mississippi			
May	116	65	0.56
June	93	121	1.30
July	88	166	1.89
August	58	139	2.40
Growing season total	355	491	1.38

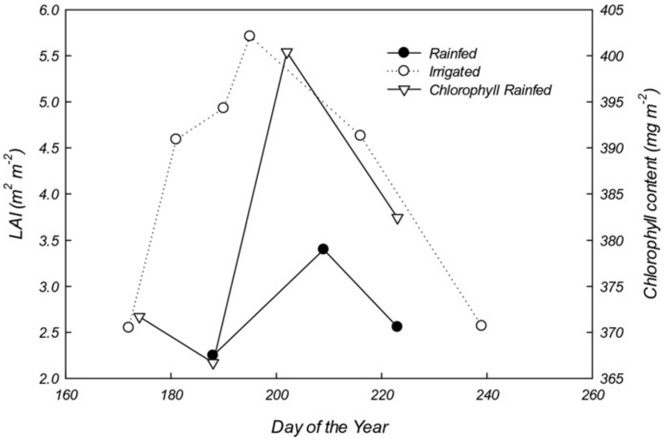

Fig. 1. Seasonal evolution of leaf are index (LAI) in rainfed and irrigated soybean, and chlorophyll content in rainfed soybean.

3.3. Seasonal patterns, magnitudes, and sums of NEE, GPP, and ER

Growing season distributions of daily (7-day average) NEE, GPP, and ER in rainfed and irrigated soybean across the growing season are shown in Fig. 3. Daily NEE, GPP, and ER followed the similar seasonal dynamics at both sites, but they were higher in irrigated soybean than in rainfed soybean throughout the growing season. The magnitude of daily peak NEE reached up to −4.55 ± 0.31 and −7.48 ± 0.65 g C m^{-2} d^{-1} in rainfed and irrigated soybean, respectively. Table 2 shows that peak daily NEE ranged from −4.65 to −5.06 g C m^{-2} d^{-1} in rainfed soybean at Rosemount, Minnesota and −5.16 to −5.79 g C m^{-2} d^{-1} in irrigated soybean at Mead, Nebraska (Wagle et al., 2015c). However, peak daily NEE ranged from −5.65 (in a dry year) to −9.16 (in a year with well-distributed seasonal rainfall) g C m^{-2} d^{-1} in rainfed soybean at Bondville, Illinois (Wagle et al., 2015c). Peak daily NEE in rainfed soybean reached up to −8.9 g C m^{-2} d^{-1} at Champaign, Illinois as well (Hollinger et al., 2005).

Rainfed soybean was a sink of carbon between DOY 162 (June 10) and 223 (August 10), while irrigated soybean was a sink of carbon between DOY 163 (June 11, the first day of flux measurement) to DOY 235 (August 22). The irrigated soybean was planted about a week earlier and could have been a sink of carbon approximately 1–2 weeks earlier. Results indicated that irrigated soybean could be a sink of carbon for about 3–4 weeks longer (~3 months) than the rainfed soybean (60 days). Soybean ecosystems in Nebraska, Illinois, and Minnesota were also sinks of carbon for 65 to 89 days (Wagle et al., 2015c).

The magnitude of daily peak GPP reached up to 13.54 ± 0.44 and 18.13 ± 0.54 g C $m^{-2}d^{-1}$ in rainfed and irrigated soybean, respectively. Table 2 shows that daily peak GPP reached up to ~18 g C m^{-2} d^{-1} in both rainfed and irrigated soybean in the U.S. Corn Belt, similar to the peak daily GPP (18.13 g C m^{-2} d^{-1}) in irrigated soybean in this study. The magnitude of daily peak ER reached up to 9.95 ± 0.20 and 14.93 ± 0.63 g C m^{-2} d^{-1} in rainfed and irrigated soybean, respectively. Table 2 shows that daily peak ER reached up to 13–14 g C m^{-2} d^{-1} in both rainfed and irrigated soybean in the U.S. Corn Belt, similar to the peak daily ER (14.93 g C m^{-2} d^{-1}) in irrigated soybean in this study.

Seasonal (DOY 132–243) sums of NEE, GPP, and ER were −54, 783, and 729 g C m^{-2}, respectively, in rainfed soybean. Seasonal (DOY 163–253, measurements initiated on DOY 163) sums of NEE, GPP, and ER were −296, 1225, and 929 g C m^{-2}, respectively, in irrigated soybean. For the overlapping period (DOY 163–243), sums of NEE, GPP, and ER were lower in rainfed than in irrigated soybean approximately by 67%

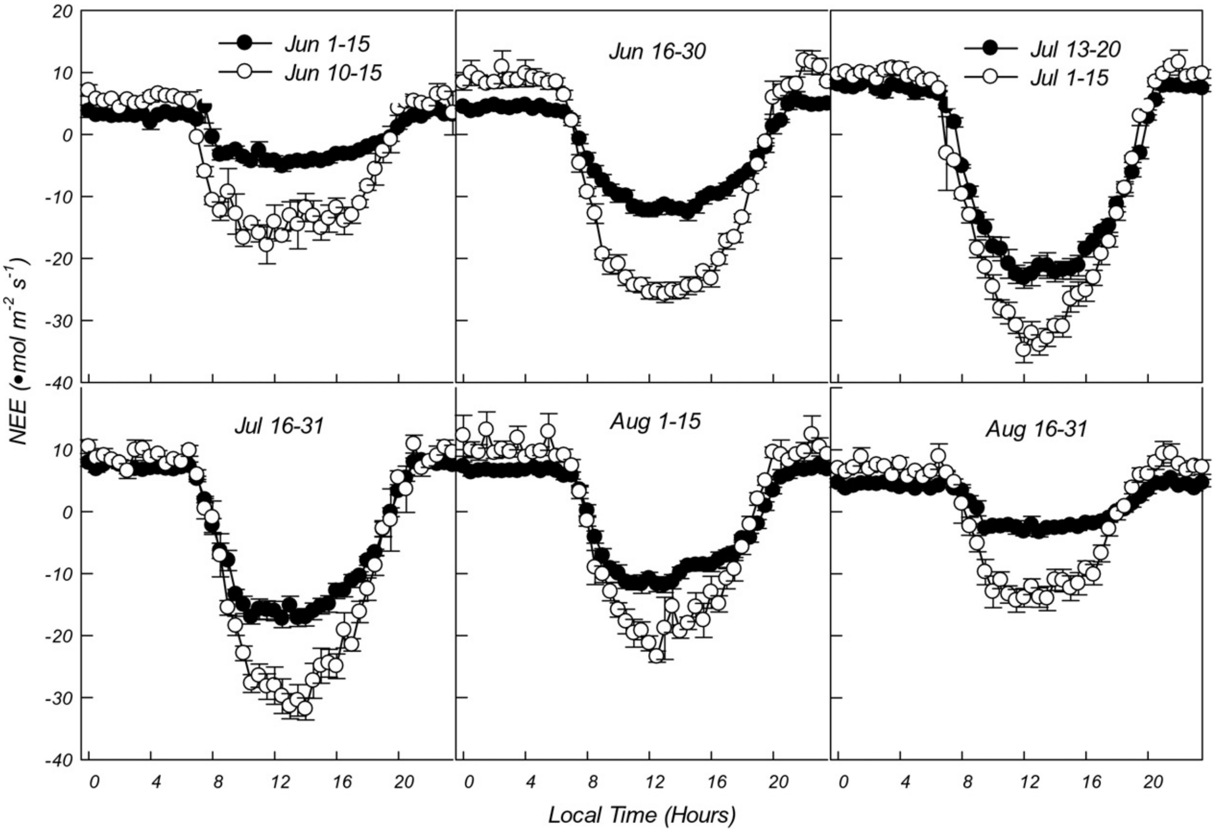

Fig. 2. Half-hourly binned diurnal courses of net ecosystem CO_2 exchange (NEE) in rainfed (closed circles) and irrigated (open circles) soybean. Bars represent standard errors of the means.

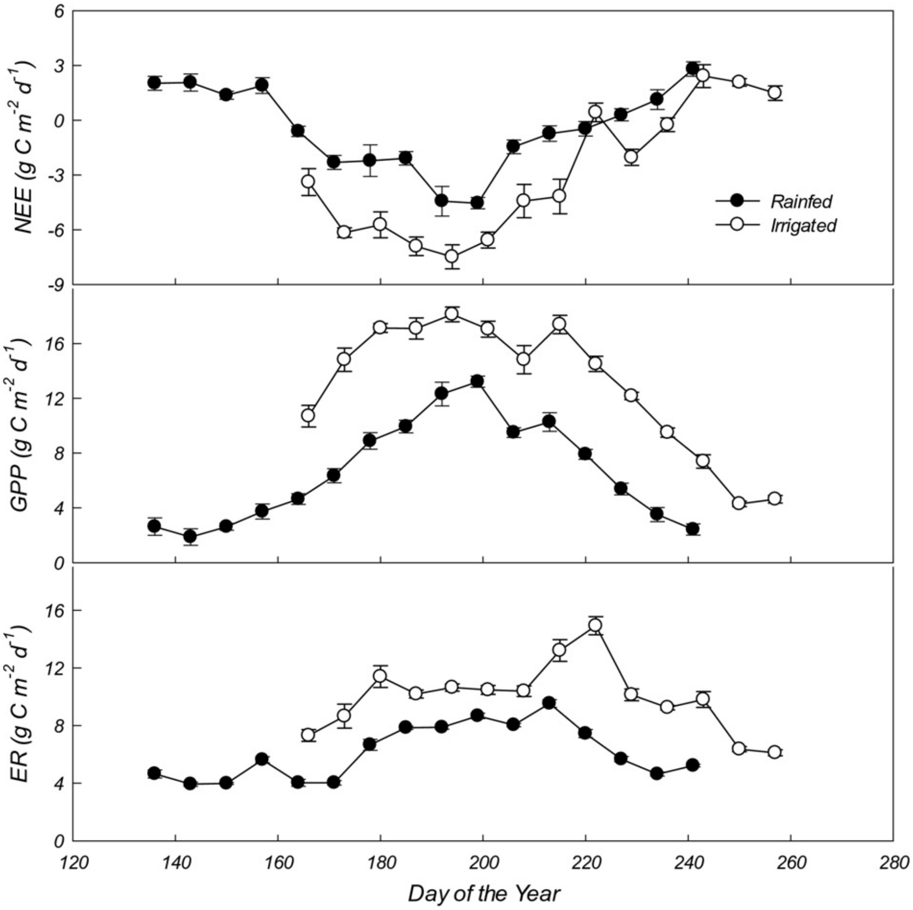

Fig. 3. Seasonal changes (7-day averages) of net ecosystem CO_2 exchange (NEE), gross primary production (GPP), and ecosystem respiration (ER) in rainfed and irrigated soybean. Bars represent standard errors of the means.

(−308 vs. −103 g C m^{-2}), 43% (1176 vs. 671 g C m^{-2}), and 35% (868 vs. 568 g C m^{-2}), respectively. Table 3 shows that seasonal sums of NEE, GPP, and ER for rainfed soybean in the U.S. Corn Belt ranged from −37 to −264, 586 to 1195, and 549 to 931 g C m^{-2}, respectively. Similarly, seasonal sums of NEE, GPP, and ER for irrigated soybean in the U.S. Corn Belt ranged from −48 to −170, 877 to 972, and 795 to 829 g C m^{-2}, respectively. Note that soybean planted in the U.S. Corn Belt was late MG and the growing season extended approximately from mid-May to mid-October.

When calculated for the entire growing season (or study period), the ratio of ER to GPP was approximately 0.93 for rainfed soybean and 0.76 for irrigated soybean. Suyker and Verma (2012) reported the growing season ER/GPP ratio of 0.76 for soybean and 0.56 for maize. Growing season ER/GPP ratios of 0.6 for winter wheat, 0.4 for potato (*Solanum tuberosum* L.) and sugarbeets (*Beta vulgaris* L.) (Aubinet et al., 2009), and 0.76–0.78 for switchgrass (*Panicum virgatum* L.) and high biomass sorghum (*Sorghum bicolor* L. Moench) (Wagle et al., 2015a) have been reported. The higher ER/GPP ratio of 0.93 for rainfed soybean in El Reno, Oklahoma as compared to other ecosystems was likely due to higher respiration rates and the limitation of photosynthesis during warm and dry periods during June through August.

Cumulative NEE from carbon sink to source period (DOY 162–223) was −131 g C m^{-2} in rainfed soybean, while cumulative NEE from carbon sink to source period (DOY 163–235, missing 1–2 weeks of a sink period before initiation of flux measurements) was −325 g C m^{-2} in irrigated soybean. The 3-years mean cumulative NEE from carbon sink to source period in rainfed soybean at Champaign, Illinois was −313 g C m^{-2} (Hollinger et al., 2005). These results indicate that the magnitudes and seasonal sums of CO_2 fluxes in rainfed soybean can be similar to those of the irrigated soybean if rainfed soybean fields receive timely and sufficient rainfall

Table 2
Comparison of daily maximum net ecosystem CO_2 exchange (NEE), gross primary productivity (GPP), and ecosystem respiration (ER) (g C m^{-2} d^{-1}) in soybean.

Site	Max. NEE (-ve)	Max. GPP	Max ER	Reference
Rosemount, MN – rainfed soybean	4.65–5.06	9.6–11.35		(Wagle et al., 2015c)
Bondville, IL – rainfed soybean	5.65–9.16	13.31–17.96		(Wagle et al., 2015c)
Mead, NE – rainfed soybean		16–17	9–14	(Suyker and Verma, 2012)
Champaign, IL – rainfed soybean	8.9			(Hollinger et al., 2005)
El Reno, OK – rainfed soybean	4.55	13.54	9.95	This study
Mead, NE – irrigated soybean (2002–2004)	5.16–5.79	13.76–14.26		(Wagle et al., 2015c)
Mead, NE – irrigated soybean (2002–2008)		16–18	10–13	(Suyker and Verma, 2012)
Stoneville, MS – irrigated soybean	7.48	18.13	14.93	This study

Table 3
Comparison of seasonal sums (g C m^{-2}) of net ecosystem CO$_2$ exchange (NEE), gross primary productivity (GPP), and ecosystem respiration (ER) in soybean.

Site	Sum NEE (-ve)	Sum GPP	Sum ER	Reference
Rosemount, MN – rainfed soybean	37–59	586–742	549–683	(Wagle et al., 2015c)
Bondville, IL – rainfed soybean	127–264	684–1195	557–931	(Wagle et al., 2015c)
Mead, NE – rainfed soybean (2002–2008)	−209 (average)	894	685	(Suyker and Verma, 2012)
Champaign, IL – rainfed soybean	272–339[a]			(Hollinger et al., 2005)
El Reno, OK – rainfed soybean	−54	783	729	This study
Mead, NE – irrigated soybean (2002–2004)	48–141	877–936	795–829	(Wagle et al., 2015c)
Mead, NE – irrigated soybean (2002–2008)	−170 (average)	972	802	(Suyker and Verma, 2012)
Stoneville, MS – irrigated soybean	−296	1225	929	This study

[a] Only for carbon sink to source period.

during the growing season. According to Wagle et al. (2015b), rainfed soybean systems in the U.S. Corn Belt needed about 450–500 mm of seasonally (May to October) well-distributed rainfall to maximize productivity and net carbon uptake. Our rainfed site received only 240 mm (38% less than the 30-year mean, 1981–2010) of seasonal rainfall (May to August).

3.4. Response of NEE to PPFD for different periods of the growing season

The response of daytime NEE (PPFD > 5 μmol m^{-2} s^{-1}) to PPFD is evaluated in Fig. 4 and light-response function parameters are presented in Table 4 for different periods of the growing season. The NEE-PPFD relationships varied for different periods within the site. The NEE-PPFD relationship was weaker in early and late growing seasons, but it was stronger when green LAI and NEE were around the maximum. At the rainfed site, NEE reached a maximum at around 1000 μmol m^{-2} s^{-1} and it did not increase much when PPFD increased further for all selected periods in May, June, and August even though the mean relative SWC, which was computed as [relative SWC = $(\theta - \theta_{\min})/(\theta_{\max} - \theta_{\min})$, where $\theta_{\max}$ and $\theta_{\min}$ are maximum and minimum values of volumetric SWC at each site], for the selected period in May (May 24–31) was 0.86. However, there was no indication of NEE saturation up to PPFD of 2000 μmol m^{-2} s^{-1} for the selected period of peak NEE and LAI in July (July 13–20) when the mean relative SWC was only 0.47. As a result, the highest GPP$_{\max}$ (~46 μmol m^{-2} s^{-1}) was observed during July 13–20 at the rainfed site (Table 4). At the irrigated site, NEE reached a maximum at around 1000 μmol m^{-2} s^{-1} for a selected period in August (August 18–25) and declined thereafter when the mean relative SWC was 0.69. However, no indication of NEE saturation was observed up to PPFD of 2000 μmol m^{-2} s^{-1} for selected periods in June and July when the mean relative SWC was only 0.35. As a result, GPP$_{\max}$

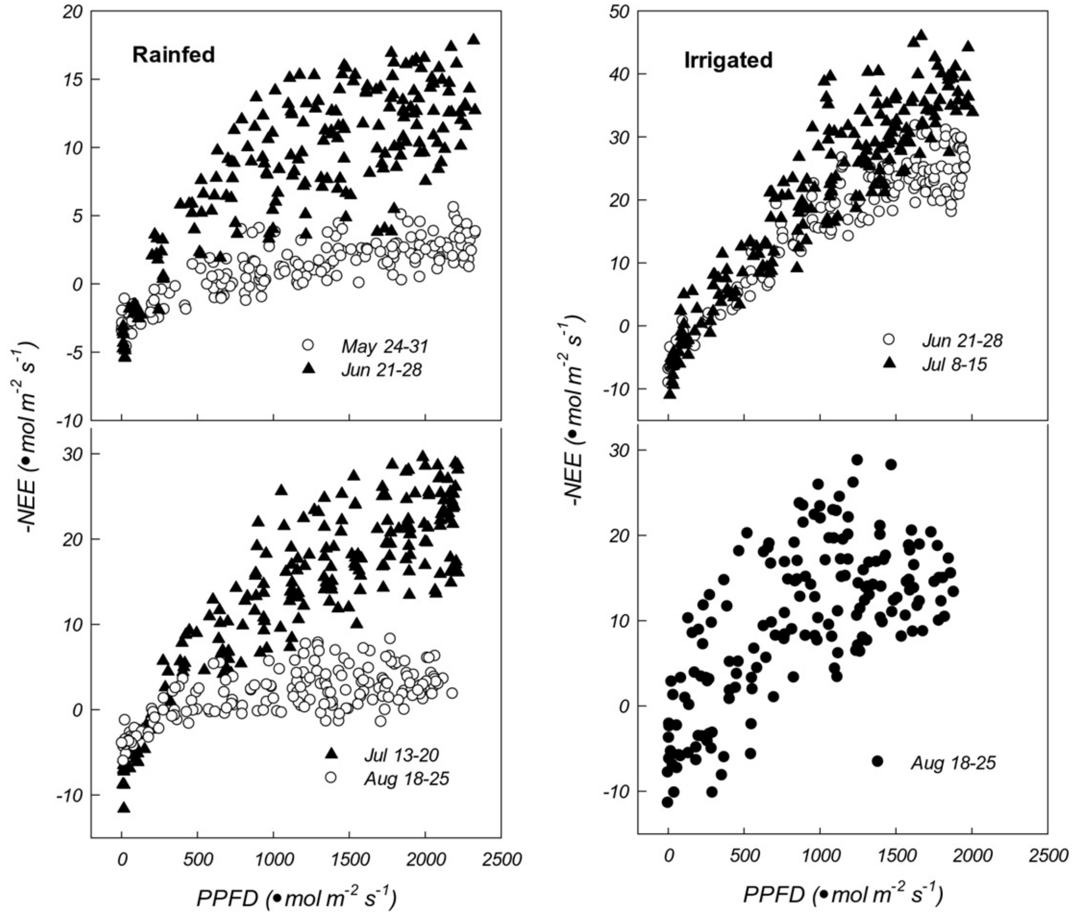

Fig. 4. Comparison of relationship between daytime net ecosystem CO$_2$ exchange (NEE) and photosynthetic photon flux density (PPFD) for selected periods during the growing season.

Table 4
Light-response function parameters estimated from rectangular hyperbolic light-response function (Eq. (1)) for selected periods during the growing season.

Period	α	GPP_{max}	ER	R^2
Rainfed				
May 24–31	0.008 ± 0.001	8.75 ± 0.72	−3.07 ± 0.34	0.69
June 21–28	0.037 ± 0.007	22.71 ± 1.12	−4.89 ± 0.87	0.74
July 13–20	0.042 ± 0.005	46.07 ± 2.49	−7.96 ± 0.95	0.85
August 18–25	0.029 ± 0.009	9.55 ± 0.64	−4.85 ± 0.69	0.56
Irrigated				
June 21–28	0.041 ± 0.004	58.99 ± 3.99	−7.45 ± 1.0	0.90
July 8–15	0.041 ± 0.004	99.9 ± 11.62	−6.73 ± 1.02	0.89
August 18–25	0.054 ± 0.017	30.07 ± 2.74	−6.39 ± 1.81	0.54

Here α = apparent quantum yield (mol CO_2 mol^{-1} of photons), PPFD = photosynthetic photon flux density (μmol m^{-2} s^{-1}), GPP_{max} = maximum canopy CO_2 uptake rate (μmol m^{-2} s^{-1}) at light saturation, ER = ecosystem respiration rate (μmol m^{-2} s^{-1}) at zero PPFD, and R^2 = the coefficient of determination.

reached up to approximately 59 and 100 μmol m^{-2} s^{-1} during June 21–28 and July 8–15, respectively. These results illustrated that the NEE-PPFD relationships varied with crop growth stages, and the irrigated site had greater photosynthetic capacity (i.e., GPP_{max}).

The maximum value of α was about 0.042 mol CO_2 mol^{-1} photons during peak NEE in July (the period of maximum LAI) at both sites. Although the fit of the Eq. (1) resulted α of 0.054 mol CO_2 mol^{-1} photons during August 18–25 at the irrigated site, it had larger uncertainty (95% confidence limit for α ranged from 0.02 to 0.088) due to the poor NEE-PPFD relationship. The largest observed α value during peak NEE for soybean was about 0.07 mol CO_2 mol^{-1} photons at AmeriFlux soybean sites (US-Ro1 and US-Bo1) in Minnesota and Illinois (Wagle et al., 2015c). The mean relative SWC was about 0.47 at the rainfed site and 0.35 at the irrigated site during peak NEE periods in this study. Thus, smaller α values during peak NEE in this study can partly be attributed to limitation of the carbon uptake by SWC.

3.5. Response of NEE to T_a, VPD, and SWC

Scatter plots of NEE against T_a and VPD showed that NEE increased rapidly with increasing T_a and VPD up to certain thresholds (Fig. 5) because T_a and VPD increase simultaneously, and RuBISCO activity is enhanced by increasing T_a, resulting in higher carbon uptake (Sage and Kubien, 2007). Results showed similar threshold values of T_a and VPD for NEE at both rainfed and irrigated sites. The NEE reached a maximum value at slightly over 30 °C of T_a and ~2.5 kPa of VPD, and plateaued or declined thereafter at both sites (Fig. 5). These results are further supported by Fig. 6. We created diurnal trends of NEE, T_a, and VPD for selected time periods in Fig. 6 to further examine the response of NEE to T_a and VPD. Results

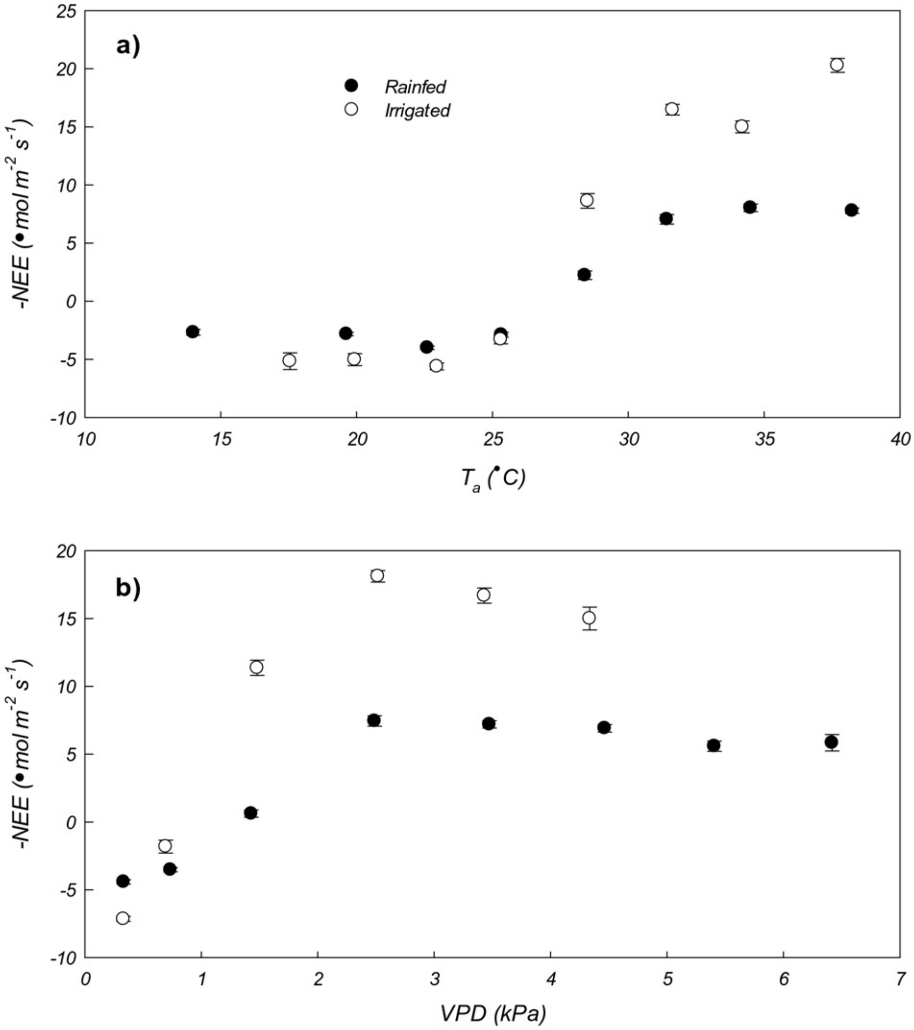

Fig. 5. Response of net ecosystem CO_2 exchange (NEE) to air temperature (T_a) and vapor pressure deficit (VPD) in rainfed and irrigated soybean. Half-hourly NEE data for the entire study period were aggregated in classes of increasing T_a and VPD. Bars represent standard errors of the means.

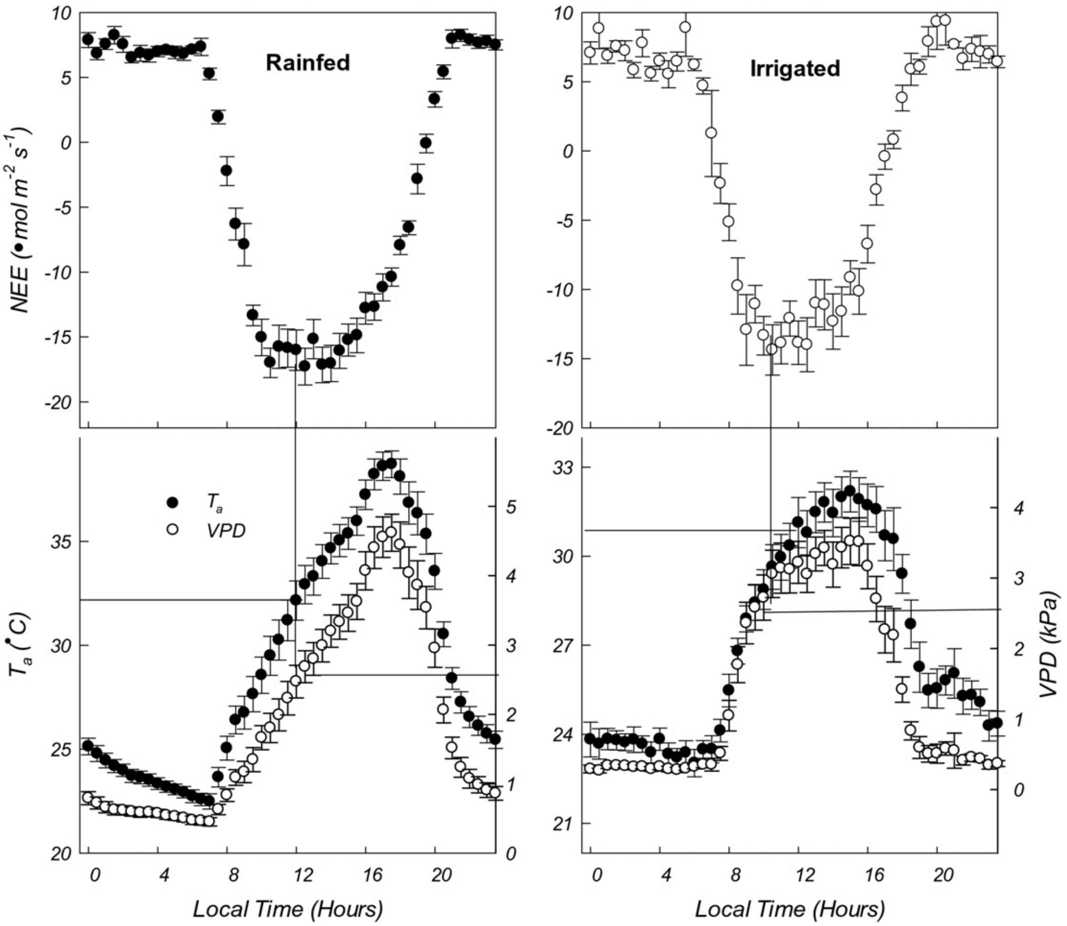

Fig. 6. Half-hourly binned diurnal courses of net ecosystem CO_2 exchange (NEE), air temperature (T_a), and vapor pressure deficit (VPD) for selected periods (July 16–31 for rainfed and August 16–31 for irrigated soybean). Bars represent standard errors of the means. Optimum T_a and VPD thresholds for peak NEE are shown by horizontal lines.

illustrated that NEE reached peak values when T_a was slightly over 30 °C and VPD was ~2.5 kPa. These results are consistent with the findings of previous studies. The optimum T_a range for soybean plant development was 28–30 °C (Brown, 1960). The optimum T_a for GPP at few soybean sites in the U.S. Corn Belt was approximately 28 °C (Wagle et al., 2015c). Transpiration rate in the commercial soybean cultivars continued to increase beyond 2.0 kPa (Fletcher et al., 2007). Reduction in NEE at higher T_a and VPD is because of the fact that higher T_a is associated with higher VPD which suppresses carbon assimilation via stomatal closure (Turner et al., 1984) or non-stomatal effect (Morison and Gifford, 1983).

To examine the effect of SWC on NEE, the seasonal distributions of daily averaged NEE at a given PPFD range (1200–1500 μmol m^{-2} s^{-1}) were evaluated against the seasonal distributions of daily average relative SWC (Fig. 7). Seasonal (DOY 133–244) average relative SWC was 0.36 for rainfed site, while seasonal (DOY 172–264) average relative SWC was 0.40 for irrigated site. Like rainfed site, the irrigated site had large fluctuations in SWC during the growing season. Daily average volumetric SWC ranged from 0.14 to 0.39 m^3 m^{-3} for rainfed site, while it ranged from 0.15 to 0.65 m^3 m^{-3} for irrigated site. As a result, NEE declined during dry periods and increased when SWC increased after rainfall or irrigation events. Relative SWC decreased at both sites to about 0.2 during peak crop growth in July (after DOY 200 at the rainfed site and DOY 210 at the irrigated site). The irrigated site was not irrigated after July 18 (DOY 200). The results indicated that NEE at both sites was limited by SWC, especially during peak growth.

3.6. Seasonal patterns and magnitudes of EWUE and ELUE

The magnitude of EWUE (weekly sums of GPP/ET) at the rainfed site was mostly between 2 and 2.5 g C mm^{-1} ET throughout the growing season, reaching up to ~2.7 g C mm^{-1} ET during peak growth. The magnitude of EWUE at the irrigated site was >3 g C mm^{-1} ET during the active growth phase, with maximum reaching up to ~3.7 g C mm^{-1} ET (Fig. 8). The ELUE increased with increasing crop growth, reached a maximum during peak growth, and then declined during crop senescence. The maximum ELUE reached about 0.22 and 0.44 g C mol^{-1} PAR for rainfed and irrigated soybean, respectively.

Different methods of EWUE and ELUE calculations by different studies make it complicated to directly compare EWUE and ELUE values. The same method of EWUE and ELUE computations showed that the peak ELUE ranged from 0.40 to 0.55 g C mol^{-1} PAR and peak EWUE ranged from 4.22 to 5.81 g C mm^{-1} ET in maize at three adjacent AmeriFlux maize sites (US-Ne1, US-Ne2, and US-Ne2) in Nebraska (Wagle et al., 2016). Larger EWUE and ELUE values are expected in maize than soybean due to greater photosynthetic capacity of the C_4 maize as compared to C_3 soybean.

The ratio of seasonal (DOY 133–243) sums of GPP to ET and NEP to ET yielded EWUE of 2.42 and 0.17 g C mm^{-1} ET for rainfed soybean, respectively. Similarly, the ratio of seasonal (DOY 163–253) sums of GPP to ET and NEP to ET yielded EWUE of 2.96 and 0.71 g C mm^{-1} ET for irrigated soybean, respectively. The ratio of seasonal sums of GPP to PAR yielded ELUE of 0.14 and 0.31 g C mol^{-1} PAR for rainfed and irrigated soybean, respectively.

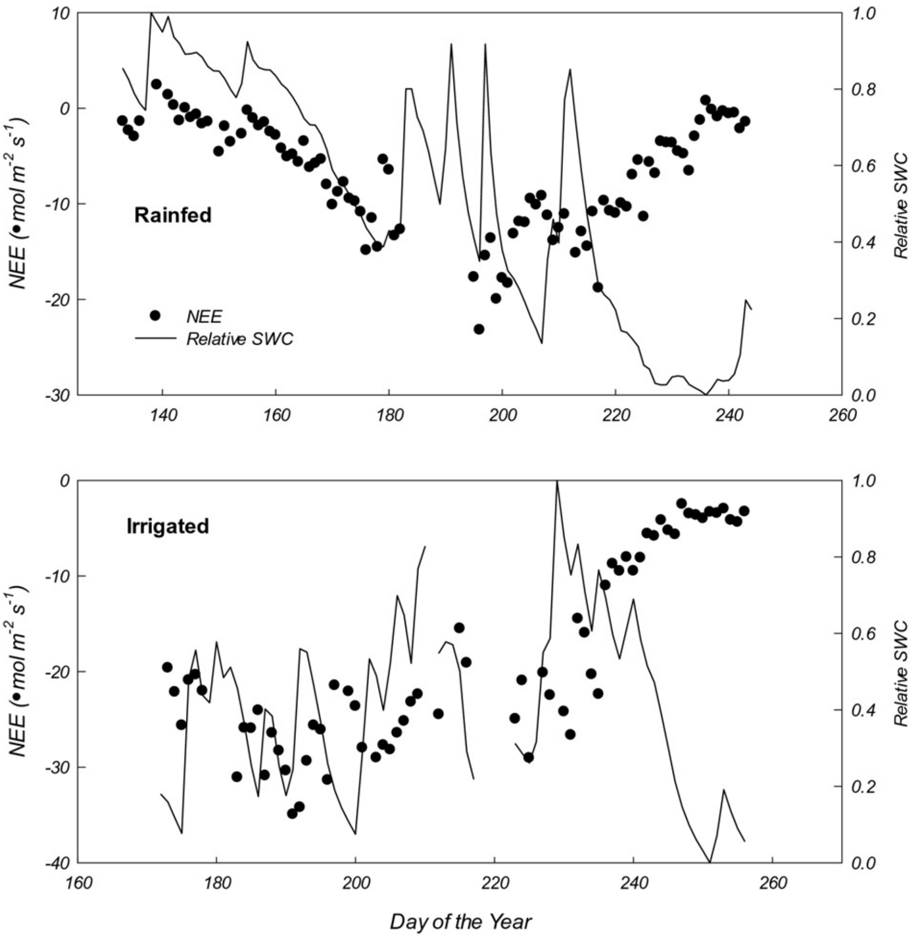

Fig. 7. Seasonal distributions of daily averaged net ecosystem CO_2 exchange (NEE) at a given photosynthetic photon flux density (PPFD) range (1200–1500 μmol m^{-2} s^{-1}) and relative soil water content (SWC) in rainfed and irrigated soybean.

The results showed that the irrigated soybean was more light and water use efficient than the rainfed soybean due to larger differences in carbon uptake than the use of water and light.

To further investigate the influence of water stress on EWUE and ELUE, we computed EWUE and ELUE for two SWC classes (relative SWC < 0.4 and >0.4) during peak growth (the entire month of July) at the irrigated site. The EWUE values were 3.05 and 3.41 g C mm^{-1} ET at relative SWC < 0.4 and >0.4, respectively. Similarly, ELUE values were 0.35 and 0.40 g C mol^{-1} PAR at relative SWC < 0.4 and >0.4, respectively. The results illustrated that EWUE and ELUE values were higher at higher SWC. During dry periods, GPP is reduced more than ET in grasslands and croplands, resulting in lower EWUE (Wagle et al., 2015b), while several studies have reported the opposite results (i.e., increase in EWUE during drought) in forests (Krishnan et al., 2006; Wolf et al., 2013). Negligible amount of soil evaporation under canopy-covered forest but considerable amount in grasslands and croplands can lead to this contrasting result.

When EWUE and ELUE values were computed for the month of July at the irrigated site for days with PAR < 45 and >45 mol m^{-2} d^{-1} to examine the influence of clear or partly cloudy periods on EWUE and ELUE, we found that EWUE and ELUE values were higher under cloudy conditions (PAR < 45 mol m^{-2} d^{-1}). The EWUE values were 3.73 and 3.0 g C mm^{-1} ET and ELUE values were 0.43 and 0.34 g C mol^{-1} PAR for cloudy and clear periods, respectively. These results are consistent with the findings that EWUE and ELUE increase under diffuse sky radiance (cloudy) conditions as compared to direct sunlight (clear days) via increment in GPP due to sharing of the canopy radiation-load (Alton et al., 2007; Turner et al., 2003). In contrast, ET is higher during sunny periods than cloudy periods.

4. Conclusion

This study examines CO_2 fluxes between irrigated and rainfed soybean in the southern U.S. in response to controlling factors during a growing season. Grain yield and the magnitudes and seasonal sums of CO_2 fluxes for irrigated soybean in this study were comparable to those for soybean in the U.S. Corn Belt, but they were lower in rainfed soybean. Our results indicated that CO_2 fluxes were limited by soil water content, especially during peak growth, at both sites. Rainfed soybean was a net carbon sink for only two months, but irrigated soybean appeared to be a net carbon sink for about three months. The NEE-PPFD relationships varied with crop growth stages. The NEE had similar response to T_a and VPD at both sites. The NEE reached peak values when T_a was slightly over 30 °C and VPD was ~2.5 kPa, consistent with the findings of previous soybean studies from the U.S. Corn Belt. To sum up, this study provides some guidance on the seasonal carbon dynamics of rainfed and irrigated soybean in the southern U.S. and their responses to major climatic variables. However, multiple year measurements are necessary to examine how long-term carbon dynamics and budgets might compare with this one year measurement, especially for rainfed soybean since fluxes in irrigated soybean might remain more stable among wet and dry years if enough irrigation is supplied.

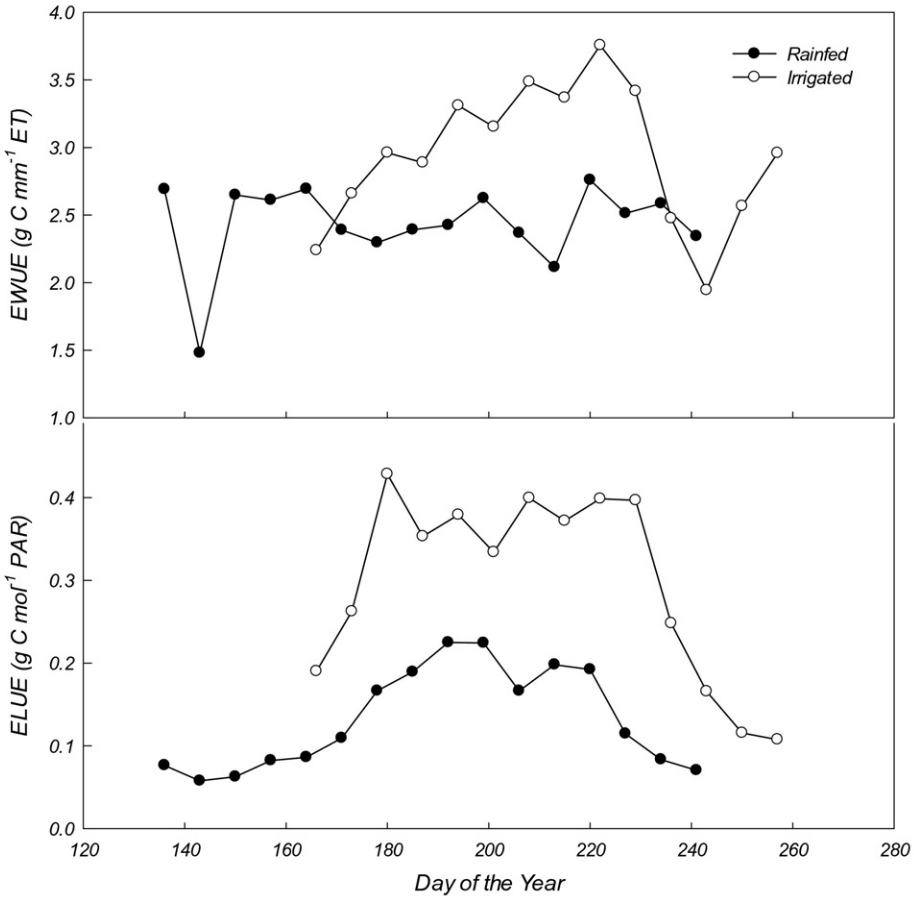

Fig. 8. Seasonal dynamics of ecosystem water use efficiency (EWUE) and ecosystem light use efficiency (ELUE) in rainfed and irrigated soybean.

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References

Alton, P., North, P., Los, S., 2007. The impact of diffuse sunlight on canopy light-use efficiency, gross photosynthetic product and net ecosystem exchange in three forest biomes. Glob. Chang. Biol. 13 (4), 776–787.

Angers, D., et al., 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res. 41 (3), 191–201.

Aubinet, M., et al., 2009. Carbon sequestration by a crop over a 4-year sugar beet/winter wheat/seed potato/winter wheat rotation cycle. Agric. For. Meteorol. 149 (3), 407–418.

Baker, J., Griffis, T., 2005. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. Agric. For. Meteorol. 128 (3), 163–177.

Brown, D.M., 1960. Soybean ecology. I. Development-temperature relationships from controlled environment Studies 1. Agron. J. 52 (9), 493–496.

Bruns, H.A., 2016. Macro-nutrient concentration and content of irrigated soybean grown in the early production system of the Midsouth. Commun. Soil Sci. Plant Anal. 47 (17), 2008–2016.

Falge, E., et al., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. For. Meteorol. 107 (1), 43–69.

Fletcher, A.L., Sinclair, T.R., Allen, L.H., 2007. Transpiration responses to vapor pressure deficit in well watered ‘slow-wilting’ and commercial soybean. Environ. Exp. Bot. 61 (2), 145–151.

Glenn, E.P., Huete, A.R., Nagler, P.L., Hirschboeck, K.K., Brown, P., 2007. Integrating remote sensing and ground methods to estimate evapotranspiration. Crit. Rev. Plant Sci. 26 (3), 139–168.

Hollinger, S.E., Bernacchi, C.J., Meyers, T.P., 2005. Carbon budget of mature no-till ecosystem in North Central Region of the United States. Agric. For. Meteorol. 130 (1), 59–69.

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 (20), 2917.

Krishnan, P., et al., 2006. Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought. Agric. For. Meteorol. 139 (3), 208–223.

Lloyd, J., Taylor, J., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 315–323.

Moinet, G.Y., Cieraad, E., Turnbull, M.H., Whitehead, D., 2017. Effects of irrigation and addition of nitrogen fertiliser on net ecosystem carbon balance for a grassland. Sci. Total Environ. 579, 1715–1725.

Morison, J.I., Gifford, R.M., 1983. Stomatal sensitivity to carbon dioxide and humidity a comparison of two C3 and two C4 grass species. Plant Physiol. 71 (4), 789–796.

Rao, S., Northup, B., 2008. Forage and grain soybean effects on soil water content and use efficiency. Crop Sci. 48 (2), 789–793.

Reichstein, M., et al., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob. Chang. Biol. 11 (9), 1424–1439.

Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289 (5486), 1922–1925.

Running, S.W., Nemani, R., Glassy, J.M., Thornton, P.E., 1999. MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOD17) Algorithm Theoretical Basis Document. University of Montana, SCF At-Launch Algorithm ATBD Documents (available online at: www.ntsg.umt. edu/modis/ATBD/ATBD_MOD17_v21.pdf).

Sage, R.F., Kubien, D.S., 2007. The temperature response of C3 and C4 photosynthesis. Plant Cell Environ. 30 (9), 1086–1106.

Schnitkey, G., 2016. County corn and soybean yields in 2015. Farmdoc Daily (6):61, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, March 29, 2016 http://farmdocdaily.illinois.edu/2016/03/county-corn-and-soybean-yields-in-2015.html.

Suyker, A.E., Verma, S.B., 2009. Evapotranspiration of irrigated and rainfed maize–soybean cropping systems. Agric. For. Meteorol. 149 (3), 443–452.

Suyker, A.E., Verma, S.B., 2010. Coupling of carbon dioxide and water vapor exchanges of irrigated and rainfed maize–soybean cropping systems and water productivity. Agric. For. Meteorol. 150 (4), 553–563.

Suyker, A.E., Verma, S.B., 2012. Gross primary production and ecosystem respiration of irrigated and rainfed maize–soybean cropping systems over 8 years. Agric. For. Meteorol. 165, 12–24.

Suyker, A.E., Verma, S.B., Burba, G.G., Arkebauer, T.J., 2005. Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. Agric. For. Meteorol. 131 (3), 180–190.

Turner, D.P., et al., 2003. A cross-biome comparison of daily light use efficiency for gross primary production. Glob. Chang. Biol. 9 (3), 383–395.

Turner, N.C., Schulze, E.-D., Gollan, T., 1984. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content. Oecologia 63 (3), 338–342.

USDA-NASS, 2016. Oklahoma Soybean County Estimates. https://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/County_Estimates/2016/ok_ce_soybean_2016.pdf.

Wagle, P., Gowda, P.H., Xiao, X., Kc, A., 2016. Parameterizing ecosystem light use efficiency and water use efficiency to estimate maize gross primary production and evapotranspiration using MODIS EVI. Agric. For. Meteorol. 222, 87–97.

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., 2015a. Net ecosystem carbon dioxide exchange of dedicated bioenergy feedstocks: Switchgrass and high biomass sorghum. Agric. For. Meteorol. 207, 107–116.

Wagle, P., et al., 2017. Analysis and estimation of tallgrass prairie evapotranspiration in the central United States. Agric. For. Meteorol. 232, 35–47.

Wagle, P., et al., 2015b. Biophysical controls on carbon and water vapor fluxes across a grassland climatic gradient in the United States. Agric. For. Meteorol. 214, 293–305.

Wagle, P., Xiao, X., Suyker, A.E., 2015c. Estimation and analysis of gross primary production of soybean under various management practices and drought conditions. ISPRS J. Photogramm. Remote Sens. 99 (0), 70–83.

Wagle, P., et al., 2014. Sensitivity of vegetation indices and gross primary production of tallgrass prairie to severe drought. Remote Sens. Environ. 152 (0), 1–14.

Winjum, J.K., Dixon, R.K., Schroeder, P.E., 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. Natural Sinks of CO2. Springer, pp. 213–227.

Wofsy, S., Harriss, R., 2002. The North American Carbon Program (NACP). Report of the NACP Committee of the US Interagency Carbon Cycle Science Program. 59. US Global Change Research Program, Washington, DC.

Wolf, S., et al., 2013. Contrasting response of grassland versus forest carbon and water fluxes to spring drought in Switzerland. Environ. Res. Lett. 8 (3), 035007.

Wrather, J.A., Chambers, A., Fox, J., Moore, W., Sciumbato, G., 1995. Soybean disease loss estimates for the southern United States, 1974 to 1994. Plant Dis. 79 (10), 1076–1099.

Xiao, X., et al., 2004. Satellite-based modeling of gross primary production in an evergreen needleleaf forest. Remote Sens. Environ. 89 (4), 519–534.