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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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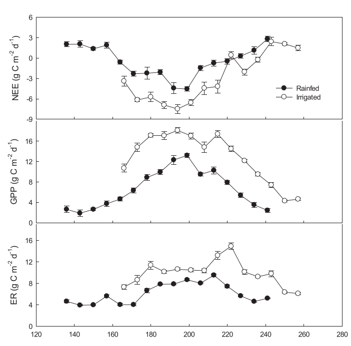
HIGHLIGHTS

- 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