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Gross primary production and ecosystem respiration of irrigated and rainfed maize–soybean cropping systems over 8 years

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Gross primary production and ecosystem respiration of irrigated and rainfed maize–soybean cropping systems over 8 years

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Abstract

The objective of this study is to examine interannual variability of carbon dioxide exchange and relevant controlling factors in irrigated and rainfed maize–soybean agroecosystems. The mean annual gross primary production (GPP) of irrigated and rainfed maize was 1796 ± 92 g C m^{-2} y^{-1} (±standard deviation) and 1536 ± 74 g C m^{-2} y^{-1}, respectively. Mean annual GPP of soybean (average of irrigated and rainfed crops) was about 56% that of maize. Light use efficiency of maize and soybean during clear sky conditions were 1.96 ± 0.10 and 1.37 ± 0.06 g C MJ^{-1}, respectively. A light use efficiency model, incorporating sensitivity to diffuse light, provided a reasonable simulation of daily GPP of maize and soybean (r^2 = 0.89–0.98 and 0.85–0.97, respectively). Simulated growing season GPP totals were within about 10% of the measured values. The green leaf area index (LAI) played a dominant role in explaining interannual variability of GPP in maize. For soybean, both LAI and PAR contributed to the interannual variability. Mean growing season ecosystem respiration (Re) totals were 1029 ± 46 g C m^{-2} for irrigated maize and 872 ± 29 g C m^{-2} for rainfed maize. The growing season Re total of soybean (average of irrigated and rainfed crops) was about 78% that of maize. A relationship, based on a reference soil respiration (Re_{20}), air temperature (T_a), and LAI, simulated daily growing season Re reasonably well for maize and soybean (r^2 = 0.77–0.91 and 0.51–0.94, respectively). Modeled Re totals during the growing season were generally within 10% of the measured values. Variations in the LAI and Re_{20} explained the majority of the interannual variability in growing season Re for maize. In addition to LAI and Re_{20}, T_a also contributed to the soybean Re variability. Non growing season Re contributed 10–20% and 17–24% of annual Re in maize and soybean, respectively and was primarily controlled by air temperature and residue biomass (r^2 ~ 81%). About 70% of maize GPP was lost in Re, resulting in the mean annual net ecosystem CO_2 production (NEP) of 552 ± 73 g C m^{-2} y^{-1} for irrigated maize and 471 ± 52 g C m^{-2} y^{-1} for rainfed maize. For soybean, however, most of the annual GPP was lost in Re resulting in a mean annual NEP of −57 ± 43 and 10 ± 52 g C m^{-2} y^{-1} for irrigated and rainfed soybean, respectively. In general, as compared to Re, GPP contributed more to explaining the departures (ΔNEP) of NEP from the 4-year mean for maize. Both GPP and Re contributed to the ΔNEP for soybean. Results on the net biome production (NBP) indicated that the irrigated maize–soybean rotation was initially a moderate source of carbon; however, the system appears to be approaching near C neutral recently. The rainfed maize–soybean rotation is approximately C neutral.

Keywords: Gross primary production, Ecosystem respiration, Net ecosystem production, Light use efficiency, Maize, Soybean

1. Introduction

Gross primary production (GPP) is the largest carbon flux on the global scale and drives ecosystem functions such as respiration (Re) and biomass accumulation (e.g., Beer et al., 2010). The North American Carbon Program Science Plan (Wofsy and Harriss, 2002) emphasized the quantification of the North American carbon sink which requires detailed measurements of CO_2 exchange in a variety of ecosystems for an extended period of time. Availability of several years of eddy covariance carbon exchange data (through flux networks such as Ameriflux and Euroflux) is beginning to allow thorough analyses of the climatic and biophysical factors that control the functioning of terrestrial ecosystems. Greater insight is being attained on how ecosystems may respond to short term changes in weather and biological variables in a given growing season and the related impacts in subsequent years (e.g., Urbanski et al., 2007). Factors such as canopy duration (Barr et al., 2007 and Dragoni et al., 2011), spring air temperatures (Krishnan et al., 2009 and Chen et al., 2009), and dry periods (Barr et al., 2007) have been identified as influencing interannual net ecosystem CO_2 production (NEP; Chapin et al., 2006), GPP and Re. Some studies (e.g., Richardson et al., 2007) indicate the impact of environmental variables (air/soil temperature, radiation, vapor pressure deficit) become

progressively less important at longer time scales. While most of these studies are from forest ecosystems, there are few similar long-term studies quantifying carbon exchange in agricultural ecosystems (e.g., Hernandez-Ramirez et al., 2011, Suyker and Verma, 2010, Hollinger et al., 2005 and Verma et al., 2005). Long-term flux data from many different ecosystems globally are needed to improve our understanding of how ecosystems respond to a wide range of atmospheric conditions in light of potential climate change.

The extent of maize-based agricultural crops in the US Corn Belt has been increasing over the last 20 years (about 263,000 ha per year; USDA National Agricultural Statistics Service: www.nass.usda.gov) and may continue to increase due to biomass requirements of the emerging biofuel industry. In 2010, across eight states of the Corn Belt (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, and Ohio), 83% of agricultural land area was planted in maize and soybean (http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-30-2011.pdf). Improved management practices (e.g., irrigation, fertilization, conservation tillage, etc.) have increased biomass accumulation and grain yield over the last few decades while minimizing soil disturbance (e.g., Cassman et al., 2003 and Lal et al., 1999). In recent years, a few studies have begun to quantify CO_2 exchange in these ecosystems (e.g., Hernandez-Ramirez et al., 2011, Suyker and Verma, 2010, Baker and Griffis, 2005, Bernacchi et al., 2005, Hollinger et al., 2005, Suyker et al., 2005 and Verma et al., 2005). Long-term studies, which focus on factors influencing the interannual variability of GPP and Re in these extensive cropping systems are needed to help develop information on regional and continental carbon budgets and relevant controlling factors.

Models employing the concept of light use efficiency have the potential to address the spatial and temporal dynamics of GPP globally (e.g., Yuan et al., 2010). However, previous studies examining agricultural ecosystems assume one value of light use efficiency for all C_3 and C_4 crops which can lead to significant errors in daily and growing season totals of GPP (e.g., Yuan et al., 2010). Secondly, these models use a maximum value for a growing season which is then decreased depending on stress conditions. This procedure ignores the increase of light use efficiency due to cloudy conditions (e.g., Jenkins et al., 2007 and Turner et al., 2003).

Given the dominance of maize-soybean cropping systems in the north-central USA and the interest of scientists and policy makers in their role in the carbon budget of the region, we initiated mass and energy exchange studies in these ecosystems in 2001. The primary objective of this paper is to quantify the seasonal and interannual variability of CO_2 exchange in these cropping systems. We examine the first 8 years of continuous measurements and address the following questions: (a) What are the annual magnitudes of GPP, Re, and NEP and associated interannual variability in these irrigated and rainfed cropping systems? and (b) What is the relationship between key environmental and biophysical variables (e.g., light, leaf area index, air temperature, dryness) and the interannual variability of GPP and Re in different management practices (irrigated and rainfed) of these two important crops? Measurements made in this study were used to examine the ability of a light use efficiency model to predict GPP on a daily basis. Light use efficiency of each crop was determined and the impact of diffuse light was evaluated.

2. Materials and methods

2.1. Study sites

The study sites are located at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Both sites, planted in maize–soybean rotation (*Zea mays*, L.; *Glycine max* [L.] Merr.), are large production fields (49 and 65 ha) that provide sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using tower eddy covariance systems (e.g., Baldocchi et al., 1988). The irrigated site (41°09′53.5″N, 96°28′12.3″W, 362 m) is equipped with center pivot irrigation. The rainfed site (41°10′46.8″N, 96°26′22.7″W, 362 m) relies on rainfall. Prior to initiation of the study, the irrigated site had a 10-year history of maize–soybean rotation under no-till. The rainfed site had a variable cropping history of primarily wheat, soybean, oats, and maize grown in 2–4 ha plots with tillage. Both sites were uniformly tilled by disking prior to initiation of the study in 2001 to homogenize the top 0.1 m of soil and incorporate fertilizers as well as previously accumulated surface residues. The sites have been in no-till since 2001. The soil is a deep silty clay loam, typical of eastern Nebraska, consisting of four soil series: Yutan (fine-silty, mixed, superactive, mesic Mollic Hapludalfs), Tomek (fine, smectitic, mesic Pachic Argialbolls), Filbert (fine, smectitic, mesic Vertic Argialbolls), and Filmore (fine, smectitic, mesic Vertic Argialbolls). The irrigated field consists of 50% Tomek, 27% Filbert/Filmore, and 23% Yutan. The rainfed site consists of 70% Tomek, 20% Filbert/Filmore, and 10% Yutan. Volumetric soil moisture of the top 1 m layer at field capacity is 0.41 and 0.39 $m^3\ m^{-3}$ at the irrigated and rainfed sites, respectively. Crop management practices (i.e., plant populations, herbicide and pesticide applications, irrigation) have been employed in accordance with the standard best management practices (BMPs) prescribed for production-scale maize–soybean systems in the region. Nitrogen (N) was applied as urea ammonium nitrate solution after measuring residual nitrate from spring soil samples. For the irrigated maize field, typically 180 kg N/ha was applied in three applications (2/3 preplant and 1/3 as two fertigations through the sprinkler system). In contrast, a single preplant N fertilizer application (typically 120 kg N/ha) was made to maize in the rainfed system. Table 1 summarizes information on the study sites, dates of planting/emergence/harvest, cultivars planted, plant population, and yield.

2.2. Flux and supporting measurements

Eddy covariance measurements of CO_2 (F_c), latent heat (LE), sensible heat (H), and momentum fluxes were made using an omnidirectional three dimensional sonic anemometer (Model R3: Gill Instruments Ltd., Lymington, UK), a closed-path infrared CO_2/H_2O gas analysis system (Model LI6262: Li-Cor Inc., Lincoln, NE, USA), and an open-path infrared CO_2/H_2O gas analysis system (Model LI7500: Li-Cor Inc., Lincoln, NE, USA). Data from the closed-path system were the primary source of CO_2 fluxes (open-path CO_2 fluxes were used during the growing season only when closed-path fluxes were not available). A second closed-path infrared CO_2/H_2O gas analysis system (Model LI6262: Li-Cor Inc.) was employed to measure CO_2 profiles to estimate the CO_2 storage below the eddy covariance sensors. To have sufficient fetch (in all directions) representative of the cropping systems being studied, the eddy covariance sensors were mounted 3.0 m above the ground when the canopy was shorter than 1 m, and later moved to a height of 6.0 m until harvest (maize only). Fluxes were corrected for inadequate sensor frequency response (Moore, 1986, Massman, 1991 and Suyker and Verma, 1993; in conjunction with cospectra calculated from this study). Fluxes were adjusted for the variation in air density due to the transfer of water vapor and sensible heat (e.g., Webb et al., 1980). More details of the measurements and calculations are given in previous papers (e.g., Suyker et al., 2003). The CO_2 storage, calculated from CO_2 profiles, was incorporated with the eddy flux term (F_c) to calculate NEP (NEP is equal but opposite in sign to NEE, net ecosystem CO_2 exchange). Incident photosynthetically active radiation (PAR) was measured (Model LI-190: Li-Cor Inc., Lincoln, NE, USA)

Table 1. Site information, cultivars planted, plant populations, planting, emergence, harvest dates and yield at 15.5% and 13% moisture content for maize and soybean, respectively (M – maize; S – soybean).

Year	Crop/cultivar	Plant population (plants/ha)	Planting date	Emergence date	Harvest date	Yield (Mg ha^{-1})
Irrigated maize–soybean rotation (41°09′53.5′′N, 96°28′12.3′′W, 362 m)						
2001	M/Pioneer 33P67	80,900	May 11	May 18	October 22	13.41
2002	S/Asgrow 2703	333,100	May 20	May 28	October 7	3.99
2003	M/Pioneer 33B51	78,000	May 14	May 25	October 23	14.00
2004	S/Pioneer 93B09	296,100	June 2	June 8	October 18	3.71
2005	M/Pioneer 33B51	81,000	May 2	May 14	October 17	13.24
2006	S/Pioneer 93M11	318,800	May 12	May 23	October 5	4.36
2007	M/Pioneer 31N28	77,600	May 2	May 11	November 5	13.21
2008	S/Pioneer 93M11	318,000	May 15	May 25	October 9	4.22
Rainfed maize–soybean rotation (41°10′46.8′′N, 96°26′22.7′′W, 362 m)						
2001	M/Pioneer 33B51	52,600	May 14	May 21	October 29	8.72
2002	S/Asgrow 2703	304,500	May 20	May 28	October 9	3.32
2003	M/Pioneer 33B51	57,600	May 13	May 22	October 13	7.72
2004	S/Pioneer 93B09	264,700	June 2	June 8	October 11	3.41
2005	M/Pioneer 31G68	56,300	April 26	May 11	October 17	9.10
2006	S/Pioneer 93M11	288,200	May 11	May 22	October 8	4.31
2007	M/Pioneer 33H26	55,800	May 2	May 13	October 31	10.23
2008	S/Pioneer 93M11	313,000	May 14	May 25	October 8	3.97

along with diffuse PAR (PAR_d; Model BF-2 Sunshine sensor, Delta-T Devices, Cambridge, UK). The PAR absorbed by the canopy (APAR) was measured using six light-bar sensors (Model LI-191: Li-Cor Inc., Lincoln, NE, USA). To obtain the amount of PAR absorbed by green portions of the canopy ($APAR_{GRN}$), daily values of APAR were multiplied by the daily ratio of green to total leaf area index (LAI). Air temperature and humidity were measured at 3 and 6 m (Humitter 50Y, Vaisala, Helsinki, Finland) along with soil temperature measured at one location in row (at depths of 0.02, 0.04, 0.06, and 0.1 m) and one location between row (at depths of 0.02, 0.04, 0.06, 0.1, and 0.2 m; model TJ40044, Omega Engineering, Stamford, CT), net radiation at 5.5 m (CNR 1, Kipp and Zonen, Delft, NLD) and soil heat flux at 0.06 m depth (in two between- row locations: model HFT3, Radiation & Energy Balance Systems Inc., Seattle, WA and model HFP01SC, Hukseflux: Delft, NLD).

To fill in missing data due to sensor malfunction, power outages, unfavorable weather, etc., we adopted an approach that combined measurement, interpolation, and empirical data synthesis (e.g., Kim et al., 1992, Wofsy et al., 1993, Baldocchi et al., 1997 and Suyker et al., 2003). When daytime hourly values were missing, the CO_2 exchange was estimated as a function of PAR using measurements from that day (or the adjacent day, if needed). To minimize problems related to insufficient turbulent mixing at night, following an analysis similar to Barford et al. (2003), we selected a threshold mean wind speed (U) of 2.5 m s^{-1} (corresponding to a friction velocity, u* of approximately 0.25 m s^{-1}). For U < 2.5 m s^{-1}, data were filled in using CO_2 exchange-temperature relationships from windier conditions. Daytime estimates of ecosystem respiration (Re) were obtained from the nighttime CO_2 exchange adjusted to daytime temperatures (e.g., Xu and Baldocchi, 2003). The GPP was then obtained by adding Re and NEP (sign convention used here is such that GPP and Re are positive). To calculate growing season totals of GPP, Re, and NEP, the daily values were integrated from emergence to harvest in each year.

We compared the sum of sensible and latent heat fluxes (H + LE) measured by eddy covariance against the sum of R_n (net radiation) + storage terms, measured by other methods. To examine energy balance closure, we calculated a linear regression between the growing season totals of H + LE and $R_n + G$ during the 8 years of measurements (excluding periods with rain and irrigation). Here $G = G_s$ (soil heat storage) + G_c (canopy heat storage) + G_m (heat stored in the mulch) + G_p (energy used in photosynthesis). These terms were estimated using procedures similar to those outlined in Meyers and Hollinger (2004). The mean slope (±standard deviation) of the linear regression between H + LE and $R_n + G$ (i.e., closure) for all sites/years was 0.88 ± 0.04.

Aboveground biomass and leaf area index were determined from destructive samples at 10–14-day intervals until physiological maturity and again just prior to harvest. Six 1-m linear row sections were destructively sampled and measured in each field using a leaf area meter (Model LI3100C: Li-Cor Inc., Lincoln, NE, USA) to obtain green and total leaf area indices.

Measured precipitation and evaporative fraction (EF = LE/[H + LE]; e.g., Shuttleworth et al., 1989 and Schwalm et al., 2009) were used as indicators of dryness. For maize, major dry periods occurred during silking and/or reproductive stages in 2001 (July 31–August 15; R3–R4) and 2003 (July 18–28; V18 to R1 and August 5–September 29; R2 to senescence) and during vegetative/silking growth stages in 2005 (June 30–July 25; V12 to R1). For soybean, major dry periods occurred during the vegetative and reproductive growth in 2002 (July 14–August 5 and August 9–14; V7–V10 and V13–V14; R1 began early July for these indeterminate hybrids) and late in the season during reproductive growth stages in 2004 (September 9–26; R6 to senescence). There was no significant dry period in 2006, 2007 or 2008.

2.3. Modeling gross primary production

Employing the measurements from this study, we examined the ability of a light use efficiency model to predict GPP of maize and soybean on a daily basis:

$$GPP = \varepsilon \cdot APAR_{GRN} \quad (1)$$

where ε is the light use efficiency and $APAR_{GRN}$ is the absorbed PAR by the green fraction of the canopy. In some previous studies (e.g., Heinsch et al., 2003 and Xiao et al., 2005), light use efficiency was assigned a constant (maximum) value for the entire growing season irrespective of sky conditions. However, cloudy skies impact the daily light use efficiency which consequently affects GPP (e.g., Gu et al., 2003). Therefore, we expressed the light use efficiency as:

$$\varepsilon = \varepsilon_c \cdot f_1 \quad (2)$$

where ε_c is the light use efficiency under clear skies and no stress. The function f_1 includes the impact of diffuse light on ε. Also, we assumed that, for the range of temperatures experienced, the effect on photosynthesis was small and the impact of dryness was incorporated through its effect on leaf area (e.g., Suyker and Verma, 2010). We used a linear

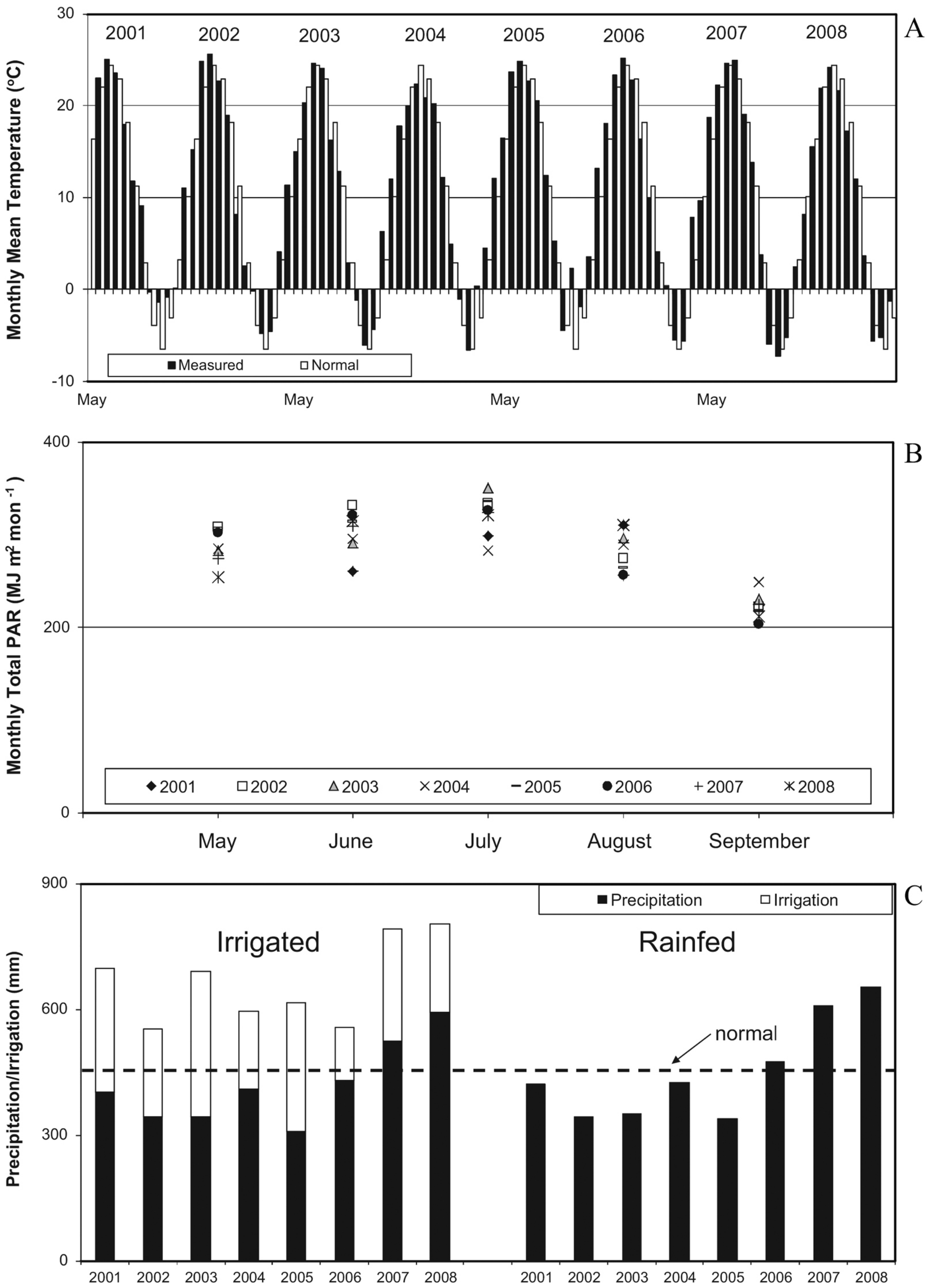


Figure 1.
(A) Monthly mean air temperature,
(B) monthly accumulated photosynthetically active radiation (PAR) from May to September, and
(C) May–September accumulated precipitation plus irrigation totals. Normal values (measured at a nearby weather station, 1971–2000 Climate Normals; HPRCC, 2006) for air temperature and precipitation are included. Data for PAR and T_a are from the irrigated site—the rainfed site data were very similar.

expression for f_1 (Turner et al., 2003 and Jenkins et al., 2007), adjusted to have a minimum value of 1 during clear skies (ratio of PAR_d/PAR was measured to be approximately 0.17 during a completely clear day):

$$f_1\left(\frac{PAR_d}{PAR}\right) = 1 + \beta \cdot \left(\frac{PAR_d}{PAR} - 0.17\right) \quad (3)$$

where β is the sensitivity of light use efficiency to diffuse PAR. The $APAR_{GRN}$, may be expressed following the Beer–Lambert law as:

$$APAR_{GRN} = PAR(1 - e^{-k\,LAI}) \quad (4)$$

where k is the light extinction coefficient. We used our measurements of APAR and LAI to calculate k ($k = 0.484$ for maize and 0.576 for soybean determined from all years of data in this study). The light use efficiency relationship (Equations (1–4)) is thus expressed in terms of two environmental parameters (PAR, PAR_d), a biophysical parameter (LAI), and two regression coefficients (ε_c, β).

2.4. Modeling ecosystem respiration

Growing season ecosystem respiration was considered as the sum of two components: (a) the contribution of heterotrophic respiration from

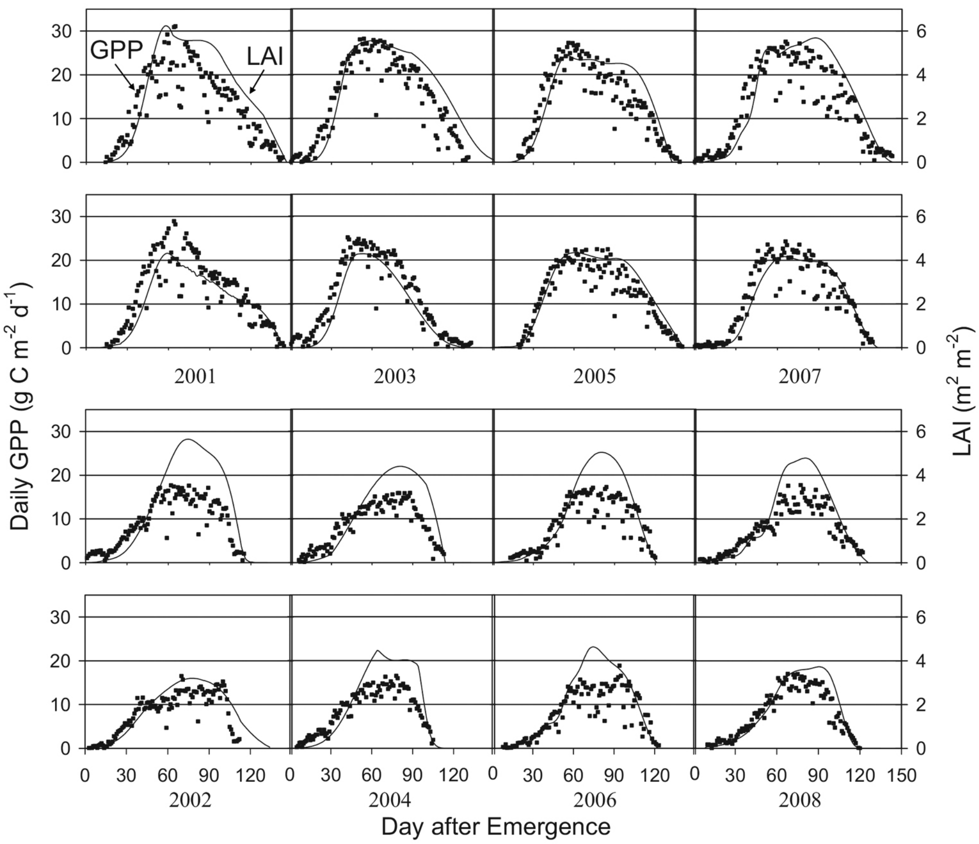


Figure 2. Growing season distributions of measured daily gross primary production (■ GPP) and green leaf area index (— LAI) for each year for irrigated maize (top row), rainfed maize (second row), irrigated soybean (third row) and rainfed soybean (bottom row).

the soil and the surface residue in the absence of the canopy and (b) the combined contribution of the above and below-ground autotrophic respiration from the canopy and the increased heterotrophic soil CO_2 emission as a result of canopy growth (Kuzyakov, 2002). Accordingly, the following relationship was examined to evaluate its potential for predicting growing season ecosystem respiration of maize and soybean:

$$\mathrm{Re} = (\mathrm{Re}_{20} + \lambda \mathrm{LAI}) \cdot e^{\gamma (T_a - 20)} \quad (5)$$

where λ is the sensitivity to LAI, γ is the temperature sensitivity coefficient, T_a is air temperature, and Re_{20} is a reference soil respiration at 20 °C. The value of Re_{20} could vary from year to year and between sites depending on how much residue was left after harvest and how much was respired during the non growing season (e.g., more residue would decay during a warm spring and Re_{20} would be higher). We evaluated Re_{20} each spring as the average Re measured during the three weeks prior to canopy emergence (and adjusted to a temperature of 20 °C using a Q_{10} factor of 2). For this model, three parameters (LAI, T_a, and Re_{20}) and two regression coefficients (λ, γ) are required to estimate daily ecosystem respiration.

3. Results and discussion

3.1. Relevant meteorological information

During the growing season, the monthly mean air temperatures were generally close (within 2.0 °C) to normal (Figure 1), except for slightly warmer temperatures during 2002 and cooler temperatures during 2004. The monthly total incident PAR had peak values between 300 and 350 MJ m^{-2} mon^{-1} in July. Precipitation received during the growing season was generally lower than normal in 2002, 2003, and 2005. Precipitation was within 50 mm of normal in 2001, 2004, and 2006, and more than 75 mm above normal in 2007 and 2008. Irrigation totals ranged from 270–350 mm in maize years to 125–210 mm in soybean years.

3.2. Gross primary production

3.2.1. Measured seasonal distributions

Growing season distributions of daily GPP for irrigated and rainfed maize and soybean are shown in Figure 2. Peak GPP values ranged from 28 to 30 g C m^{-2} d^{-1} for irrigated maize. These peaks occurred about 50–60 days after emergence, and this period corresponded to the approximate time of peak green leaf area index (LAI). Values of peak LAI ranged from 4.8 to 6.2 m^2 m^{-2}. Peak GPP of rainfed maize was slightly lower (22–27 g C m^{-2} d^{-1}), and the peak LAI ranged from 4.2 to 4.3 m^2 m^{-2}. For irrigated soybean, peak GPP values were from 16 to 18 g C m^{-2} d^{-1} and occurred at about the same time (about 60 days after emergence) as the peak LAI, which varied from 4.4 to 5.6 m^2 m^{-2}. Peak GPP of rainfed soybean was from 16 to 17 g C m^{-2} d^{-1} and the peak LAI was from 3.2 to 4.6 m^2 m^{-2}.

Mean growing season GPP total (or annual totals since GPP = 0 during the non-growing season) of irrigated maize was 1796 ± 92 g C m^{-2} y^{-1} (±standard deviation). On average, the GPP total (1536 ± 74 g C m^{-2} y^{-1}) of rainfed maize was about 85% that of irrigated maize. Mean growing season GPP of irrigated soybean was 972 ± 74 g C m^{-2} y^{-1}. The GPP of rainfed soybean (894 ± 8 g C m^{-2} y^{-1}) was on average 92% that of irrigated soybean. Soybean GPP (average of irrigated and rainfed crops) was about 56% of maize GPP. The yield (R^2 = 0.94) and above ground biomass (R^2 = 0.95) of both irrigated and rainfed crops (Figure 3) was closely related to the growing season GPP.

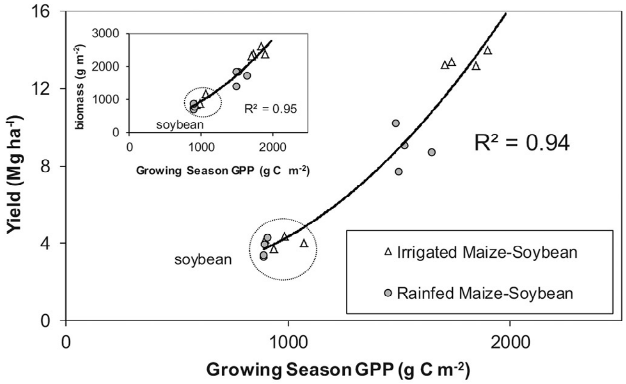


Figure 3. Yield plotted as a function of growing season totals of gross primary production (GPP) for irrigated and rainfed maize and soybean crops from 2001 to 2008. The inset shows the relationship with above ground biomass and GPP.

3.2.2. GPP modeling results

To evaluate the modeling capability of the light use efficiency relationship, we fit Equations (1–4) to our measurements using nonlinear regression (SAS 9.1; SAS Institute, Cary, NC, USA) to determine ε_c and β. One typical year from each crop at the irrigated site (2005 for maize and 2006 for soybean) were used to minimize the confounding effects of moisture stress. The values (±95% confidence intervals) of ε_c were determined to be 1.96 ± 0.10 and 1.37 ± 0.06 g C MJ^{-1} for maize and soybean, respectively. The larger ε_c for maize is expected as the C_4 crop is more photosynthetically efficient than soybean (e.g., Long et al., 2006). The values of β were 0.487 ± 0.190 and 0.877 ± 0.184 for maize and soybean, respectively, implying greater sensitivity of the soybean canopy GPP to diffuse light compared to maize. The larger β for soybean may be related to factors such as canopy structure (e.g., vertical profile of leaf area density, leaf inclination angle). These coefficients in conjunction with the measured values of LAI, PAR and PAR_d were used to calculate GPP in the other years (6 years in the irrigated crops and 8 years in the rainfed crops). On a daily basis, the modeled GPP underestimated the measured GPP in the irrigated and rainfed maize fields (slopes were 0.84–0.98, intercepts generally within ±1.5 g C m^{-2} d^{-1}, and r^2 values ranged from 0.89 to 0.98: Table 2). Some of the underestimation may be a result of poor model fit later in the growing season due to lower chlorophyll content at the same value of LAI in the spring (Peng et al., 2011). For irrigated and rainfed soybean, there was a slightly better fit with slopes ranging from 0.92 to 1.10 and r^2 from 0.85 to 0.97. Data points during dry periods (2001, 2003, and 2005 for maize and 2002 and 2004 for soybean) generally fell within the overall data scatter, perhaps indicating that most of the impact of the dry periods was manifested through the effect on LAI (Figure 4). On a growing season basis (Figure 5), the modeled GPP totals were generally within 10% of the measured values for both irrigated and rainfed crops.

Increases in GPP and light use efficiency due to diffuse light have been reported in maize and other ecosystems (e.g., Knohl and Baldocchi, 2008, Alton et al., 2007a, Alton et al., 2007b, Gu et al., 2003, Gu et al., 2002, Turner et al., 2003 and Choudhury, 2001), but not quantified on a growing season basis. The light use efficiency relationship can be used to separate the contribution of direct and diffuse light to GPP. Using Equations (1–4), GPP may be expressed as:

$$\mathrm{GPP} = \varepsilon_c \cdot \mathrm{PAR} \cdot (1 - e^{-k\,\mathrm{LAI}}) + \varepsilon_c \cdot \mathrm{PAR} \cdot (1 - e^{-k\,\mathrm{LAI}}) \cdot \beta \cdot \left(\frac{\mathrm{PAR_d}}{\mathrm{PAR}} - 0.17\right) \quad (6)$$

where the first term is the GPP resulting from the incident PAR and the second term is the "GPP advantage" due to diffuse PAR (e.g., Gu et al., 2002). Integrating the daily values of the second term in Equation (6) over the entire growing season indicated a GPP advantage (due to diffuse light) of 9–14% for maize and 18–20% for soybean.

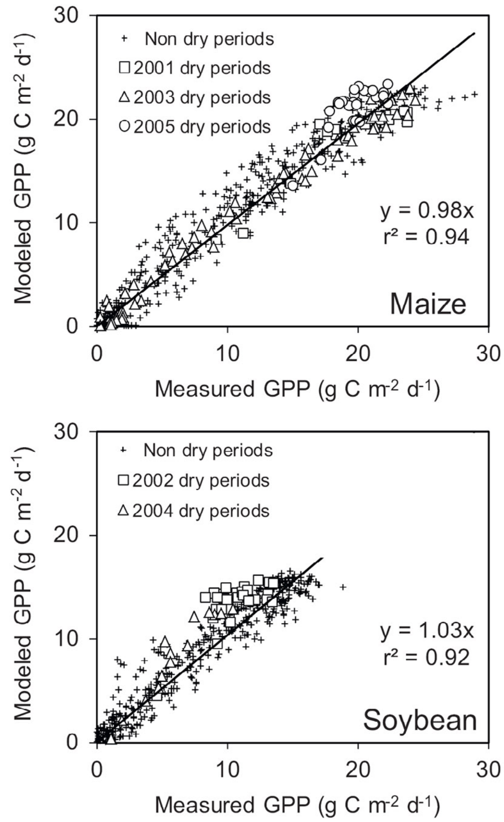


Figure 4. Comparison of rainfed measured and modeled daily gross primary production (GPP) for all years of (A) maize and (B) soybean. Dry periods in each year are noted.

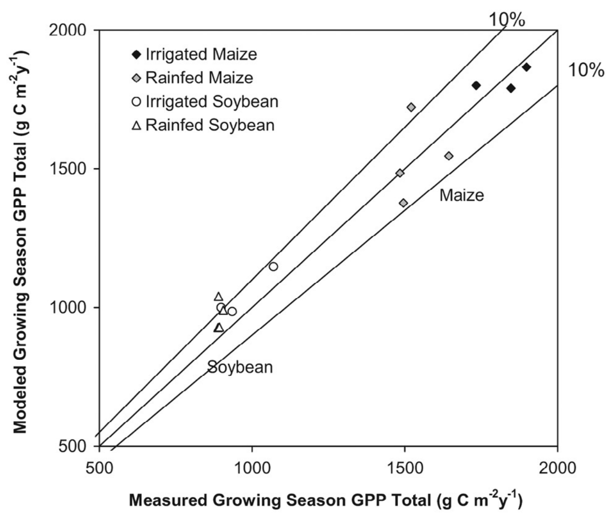


Figure 5. Comparison of modeled and measured growing season (or annual) totals of gross primary production (GPP) for irrigated and rainfed maize and soybean.

3.2.3. Interannual GPP variability: role of controlling factors

To evaluate the role of key controlling variables (PAR and LAI) in explaining the interannual variability of GPP, we compared 2 years of data employing the light use efficiency relationship (Equations (1–4)).

Table 2. Linear regression coefficients and root mean square error (g C m^{-2} d^{-1}) of measured vs. modeled daily gross primary production (GPP) for irrigated and rainfed maize and soybean.

Site	Year	Daily GPP Slope	Daily GPP Intercept	Daily GPP r^2	Daily GPP RMSE
Irrigated maize	2001	0.84	2.65	0.89	2.84
	2003	0.87	1.53	0.91	2.86
	2007	0.89	1.04	0.95	2.20
Rainfed maize	2001	0.84	1.23	0.94	2.12
	2003	0.98	−0.60	0.98	1.48
	2005	0.94	2.41	0.94	2.37
	2007	0.95	0.57	0.98	1.24
Irrigated soybean	2002	1.04	0.32	0.90	2.04
	2004	1.03	0.19	0.88	1.95
	2008	1.08	0.24	0.94	1.74
Rainfed soybean	2002	0.92	1.95	0.85	2.35
	2004	1.10	−0.49	0.93	1.58
	2006	0.93	1.25	0.90	1.84
	2008	0.97	0.57	0.97	1.03

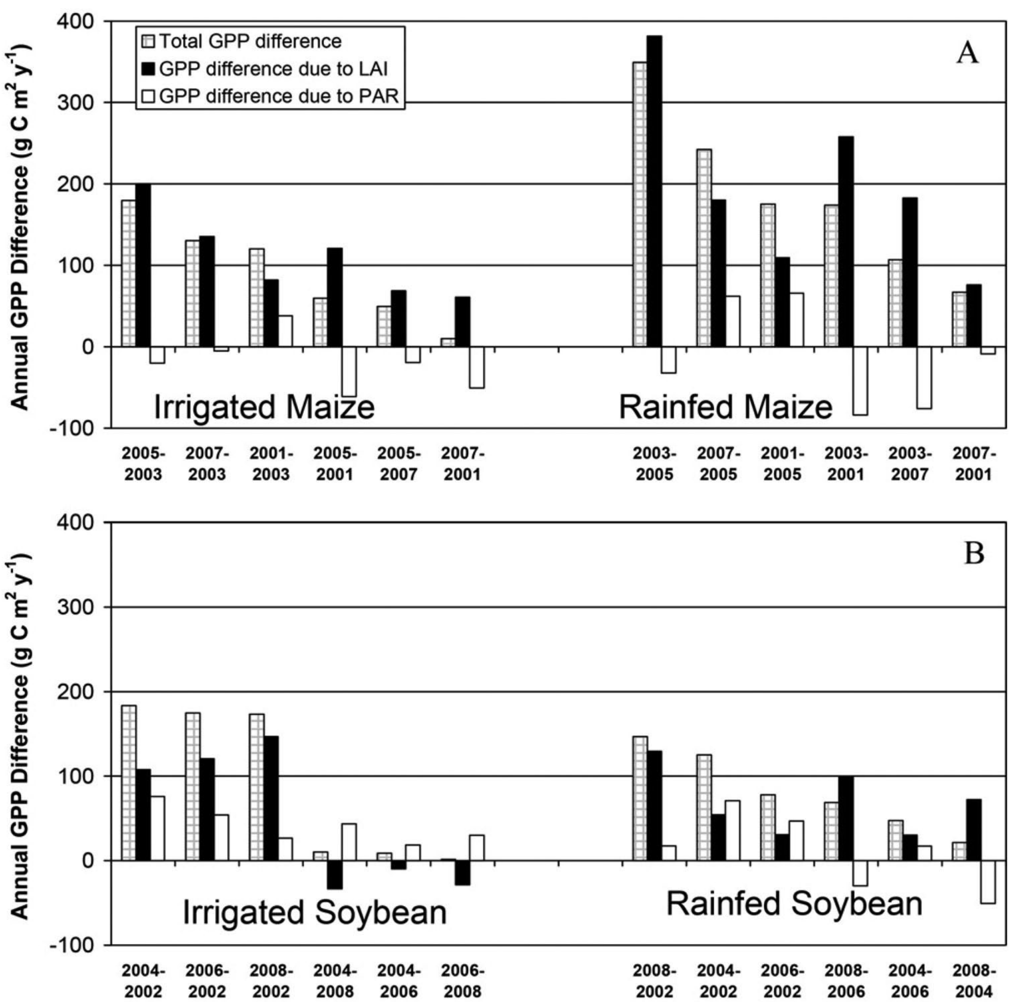


Figure 6. Differences in annual gross primary production (GPP) for different combinations of years attributable to differences in green leaf area (LAI) and differences in PAR (incident and diffuse photosynthetically active radiation) for (A) irrigated and rainfed maize and (B) irrigated and rainfed soybean. Values of the total GPP difference are arranged largest to smallest for each management and crop. For maize, LAI dominates the change in growing season GPP between the 2 years.

By exchanging the controlling variables between these 2 years, we attempted to separate the influence of PAR and LAI on annual GPP. Changes in PAR and LAI include not only differences in magnitudes but also their seasonal distributions. This approach implicitly accounts for various factors which affect PAR and LAI distributions (e.g., length of growing season, dry periods, cloud cover). We also assume the LAI distribution is generally independent of the distribution of PAR. A comparison of relevant data from irrigated maize during 2 years (for example 2001 and 2003) indicated that the difference in the annual (modeled) GPP was 120 g C m^{-2} y^{-1} (the 2003 value was larger). When the daily LAI distribution in 2001 was replaced by the daily LAI distribution in 2003, the GPP increased by 80 g C m^{-2} y^{-1}. When the daily

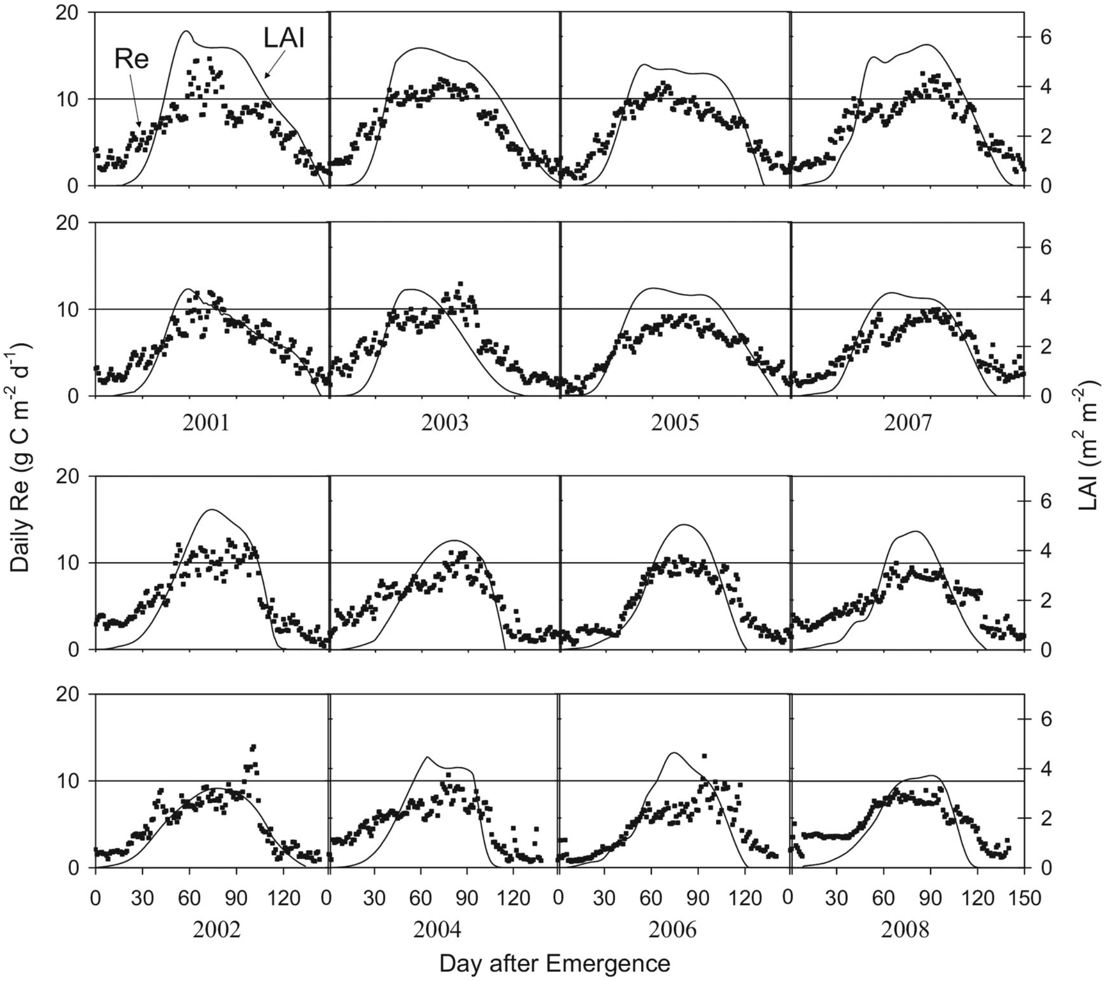


Figure 7. Growing season distributions of measured ecosystem respiration (■ Re) and green leaf area index (___ LAI) for each year for irrigated maize (top row), rainfed maize (second row), irrigated soybean (third row) and rainfed soybean (bottom row).

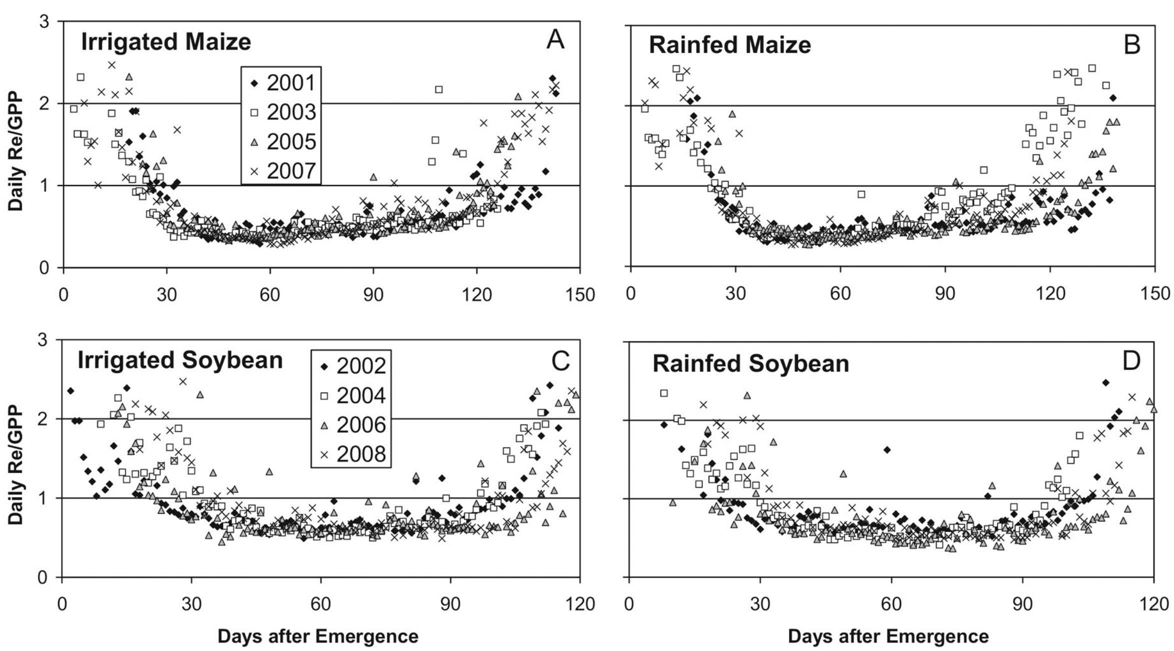


Figure 8. Seasonal distributions of daily Re/GPP for 4 years of (A) irrigated maize, (B) rainfed maize, (C) irrigated soybean, and (D) rainfed soybean.

Table 3. Linear regression coefficients and root mean square error (g C m^{-2} d^{-1}) of measured vs. modeled daily ecosystem respiration (Re) for irrigated and rainfed maize and soybean.

	Year	Daily Re Slope	Daily Re Intercept	Daily Re r^2	Daily Re RMSE
Irrigated maize	2001	1.10	−0.65	0.89	1.35
	2003	1.03	−0.53	0.91	1.16
	2007	1.03	−0.33	0.89	1.33
Rainfed maize	2001	0.83	0.87	0.86	1.16
	2003	0.87	0.11	0.77	1.64
	2005	1.13	0.04	0.90	1.24
	2007	1.00	−0.21	0.89	1.03
Irrigated soybean	2002	1.26	−1.19	0.94	1.43
	2006	1.04	−0.44	0.82	1.60
	2008	1.22	−2.13	0.78	1.81
Rainfed soybean	2002	0.73	1.69	0.80	1.37
	2004	1.16	−1.42	0.81	1.48
	2006	0.87	0.56	0.51	2.40
	2008	1.13	−1.38	0.86	1.26

PAR distribution in 2001 was replaced by the daily PAR distribution in 2003, the GPP further increased by 40 g C m^{-2} y^{-1}. Thus, the majority of the change in the annual GPP was attributable to the change in LAI. Comparison of data from different combination of years (Figure 6) indicated three general kinds of impacts for both crops: (a) changes in LAI and PAR each caused GPP to increase, (b) changes in LAI and PAR partially or almost totally offset the increase in GPP, and (c) changes in LAI or PAR predominantly caused GPP to increase. For maize (irrigated and rainfed), LAI was consistently the largest factor explaining the interannual GPP variability. However, for soybean (irrigated and rainfed), both LAI and PAR contributed to the interannual variability of GPP.

3.3. Ecosystem respiration

3.3.1. Measured growing season distributions

Growing season distributions of daily ecosystem respiration (Re) of irrigated and rainfed maize and soybean are shown in Figure 7. Peak Re ranged from about 12 to 15 g C m^{-2} d^{-1} for irrigated maize and slightly lower for rainfed maize (9–13 g C m^{-2} d^{-1}). For soybean, Re peaked from 10–13 and 9–14 g C m^{-2} d^{-1} in the irrigated and rainfed fields, respectively. In both crops, peak Re generally occurred about 60–75 days after emergence, about 15 days after the occurrence of peak LAI.

For irrigated maize, average growing season Re total (± standard deviation) was 1029 ± 46 g C m^{-2}. Average Re total (872 ± 29 g C m^{-2}) for rainfed maize was 85% that of the irrigated crop. For rainfed soybean, the average Re total (685 ± 36 g C m^{-2}) was also 85% that of the irrigated crop (802 ± 61 g C m^{-2}). The growing season Re of soybean was about 78% of maize Re.

Figure 8 includes the growing season distributions of the daily Re to GPP ratio. Except for early and late in the season (when LAI was less than 1), the daily Re/GPP ratio was fairly steady during most of the growing season (30–110 days after maize emergence and 30–90 days after soybean emergence). During this period, the mean daily Re/GPP (±standard deviation) was 0.49 ± 0.12 for irrigated maize and 0.48 ± 0.14 for rainfed maize. A two factor ANOVA (year × management practice) indicated no significant difference in mean of daily growing season Re/GPP ratios for maize or soybean ($\alpha = 0.025$) among years or management practices (irrigated or rainfed). Correspondingly, the mean Re/GPP was 0.67 ± 0.12 for irrigated soybean and 0.62 ± 0.14 for rainfed soybean. Again, no significant difference was observed among 8 years of irrigated and rainfed soybean (two factor ANOVA; $\alpha = 0.025$). When calculated for the entire growing season, the Re/GPP ratio (±standard deviation) was 0.56 ± 0.02 for maize and 0.76 ± 0.05 for soybean. The C input to soil from previous crop residues likely contributed to the higher Re/GPP values for soybean. Growing season Re/GPP of 0.6 for winter wheat and 0.4 for potato have been reported (Aubinet et al., 2009 and Moureaux et al., 2008).

3.3.2. Growing season Re modeling results

We calculated the coefficients (λ, γ) using a typical year of measurements for each crop from the irrigated site (2005 for maize and 2004 for soybean) using nonlinear regression (SAS 9.1; SAS Institute, Cary, NC, USA). For maize, regression values for λ and γ were 1.328 ± 0.084 g C m^{-2} d^{-1} and 0.0345 ± 0.0083 °C^{-1}, respectively. Corresponding soybean values were 1.594 ± 0.085 g C m^{-2} d^{-1} and 0.0421 ± 0.0100 °C^{-1}. These coefficients were then used to calculate the 'modeled' daily Re in the other 6 years in the irrigated crops and 8 years in the rainfed crops (Table 3). On a daily basis, the modeled daily Re of maize was generally within about 15% of measured values and r^2 ranged from 0.77 to 0.91 (Table 3). For soybean, the modeled-measured Re agreement was worse: slopes ranged from 0.73 to 1.26 and r^2 ranged from 0.51 to 0.86. On a growing season basis, for both crops, the modeled and measured Re totals generally agreed within 10% (Figure 9).

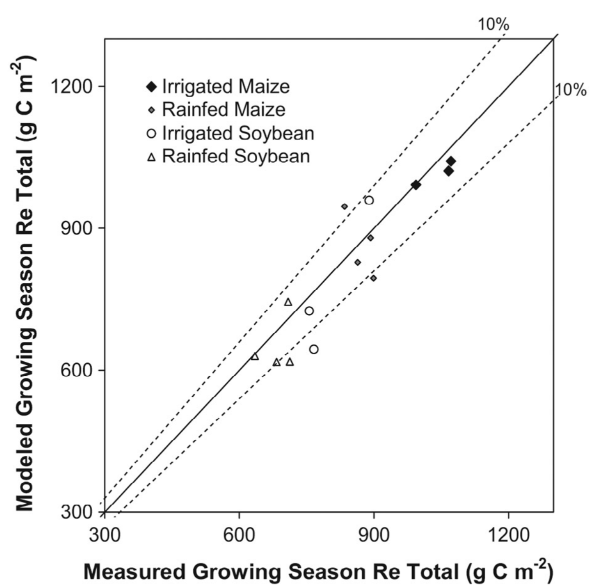


Figure 9. Comparison of modeled and measured growing season totals of ecosystem respiration (Re) for irrigated and rainfed maize and soybean.

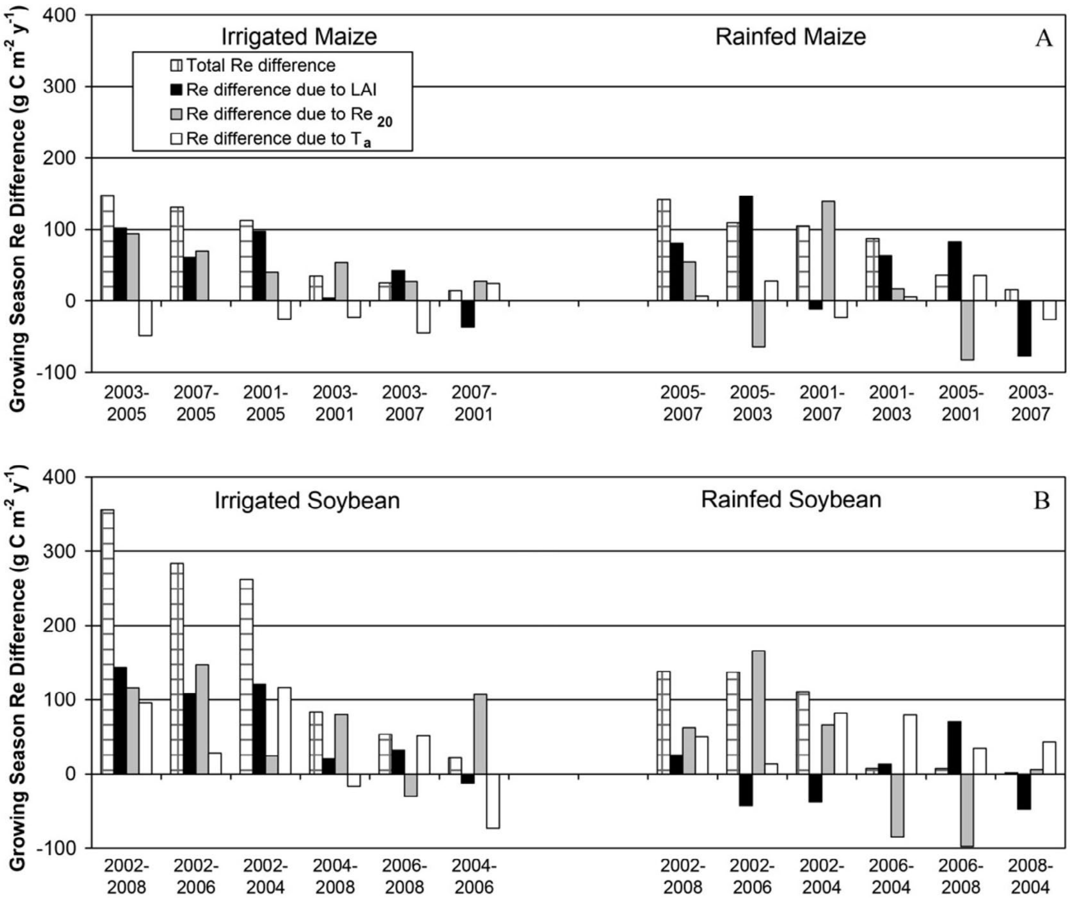


Figure 10. Differences in growing season ecosystem respiration (Re) for different combination of years attributable to differences in green leaf area (LAI), differences in reference soil surface respiration (Re_{20}), and differences in air temperature (T_a) for (A) irrigated and rainfed maize and (B) irrigated and rainfed soybean. Values of the total Re difference are arranged largest to smallest for each management and crop.

3.3.3. Interannual variability of growing season Re: role of controlling factors

To evaluate the role of key controlling variables (LAI, T_a, and Re_{20}) in explaining the interannual variability of growing season Re, we compared 2 years of data employing Equation (5). By exchanging each input parameter in a similar manner outlined in Section 3.2.3, we separated the impact on the growing season Re due to changes in LAI, T_a, and Re_{20}. Comparison of data from different combination of years is shown in Figure 10. The results indicated two features: (a) generally, Re_{20} and LAI contributed to variability in growing season Re, and (b) in some cases, the influence of Re_{20}, LAI or T_a offset each other. For maize, LAI and Re_{20} explained most of the interannual variability in growing season Re. In addition to LAI and Re_{20}, T_a was also important in contributing to the interannual growing season Re variability.

3.3.4. Ecosystem respiration during the non growing season

Non growing season Re was accumulated from the day after harvest to subsequent spring planting. The non-growing season Re contributed 10–20% and 17–24% of annual Re in maize and soybean, respectively. However, the soybean crop is harvested earlier than maize and planted later so comparisons among years will be biased due to different integration periods. Accordingly, the daily Re was accumulated during identical durations (Re_{NGS}: November 1–April 30). Average Re_{NGS} (±standard deviation) following irrigated and rainfed maize harvest was 157 ± 26 and 152 ± 34 g C m^{-2}, respectively (Figure 11). Following soybean harvest, corresponding values were135 ± 22 and 124 ± 19 g C m^{-2}, respectively. The Re_{NGS} values are generally consistent with (a) greater above ground biomass for maize and thus greater residue left on the surface and (b) expected higher respiration from the irrigated field. The interannual variability in Re_{NGS} was generally small (<25% of average Re_{NGS}).

Work at the study sites by Kochsiek (2010) suggested temperature, residue biomass left after harvest, and surface moisture content were the most important factors influencing Re_{NGS}. Thus, we employed three variables: (a) seasonally averaged air temperature, (b) the residue biomass left at harvest (G_{Res}: determined as the difference between total

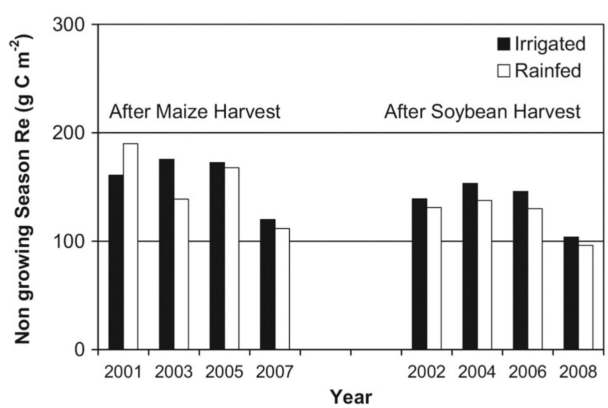


Figure 11. Non growing season Re integrated from November 1 to April 30 for irrigated and rainfed maize and soybean.

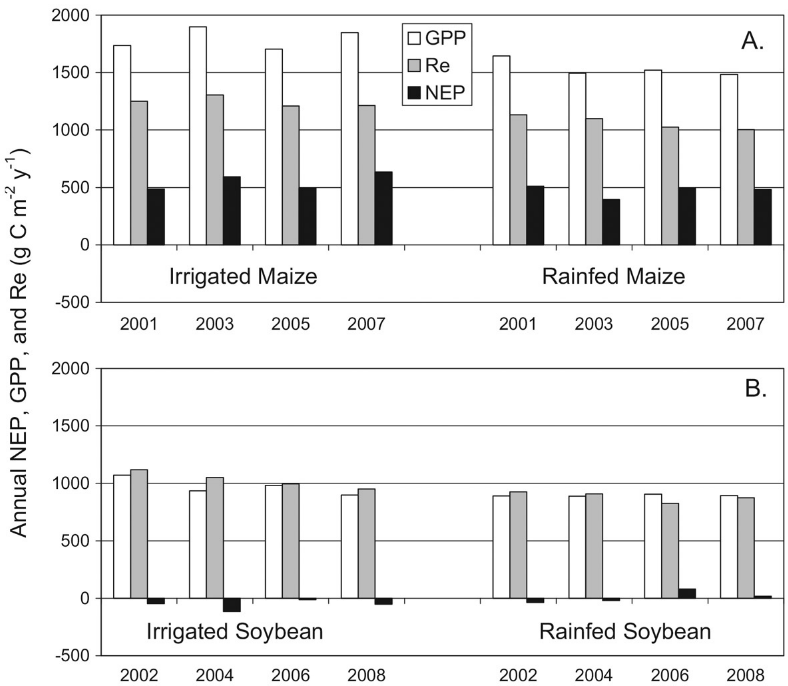
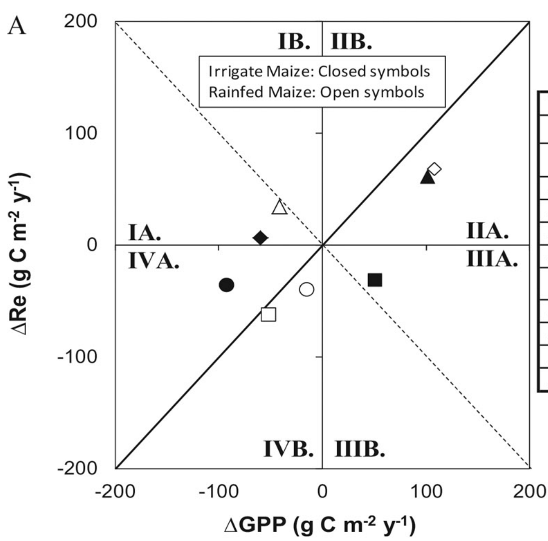
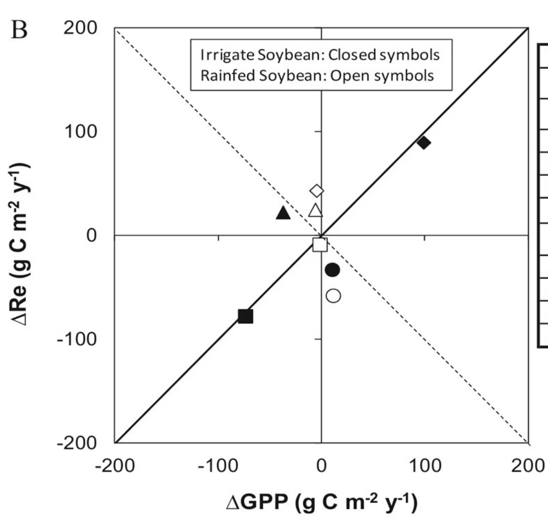


Figure 12. Annual net ecosystem production (NEP), gross primary production (GPP), and ecosystem respiration (Re) for (A) irrigated/rainfed maize and (B) irrigated/rainfed soybean.



Year	Symbol	ΔGPP	ΔRe	ΔNEP
		(g C m^{-2} y^{-1})		
		Irrigated Maize		
2001	◆	-60	6	-66
2003	▲	102	61	41
2005	●	-92	-36	-57
2007	■	51	-31	82
		Rainfed Maize		
2001	◇	108	68	40
2003	△	-41	34	-76
2005	○	-15	-40	25
2007	□	-52	-62	10



Year	Symbol	ΔGPP	ΔRe	ΔNEP
		(g C m^{-2} y^{-1})		
		Irrigated Soybean		
2002	◆	99	89	10
2004	▲	-37	22	-59
2006	●	11	-33	44
2008	■	-73	-78	4
		Rainfed Soybean		
2002	◇	-4	43	-47
2004	△	-6	24	-30
2006	○	11	-58	70
2008	□	-1	-9	8

Figure 13. Departures in annual gross primary production (ΔGPP) and ecosystem respiration (ΔRe) from their respective 4-year means for (A) irrigated and rainfed maize and (B) irrigated and rainfed soybean. ΔNEP = ΔGPP − ΔRe. Data below the solid diagonal line implies above average NEP (below average NEP above the line). Data in quadrants I and III indicate both GPP and Re contributed to NEP (data points on the dashed line imply equal contribution). Data in quadrants II and IV indicate GPP and Re had offsetting impacts (data points on the solid line imply equally offsetting contributions). Data in "A" portion of each quadrant indicate greater contribution by GPP and data in "B" portion indicate greater contribution by Re. Tables include values of ΔGPP, ΔRe, and ΔNEP.

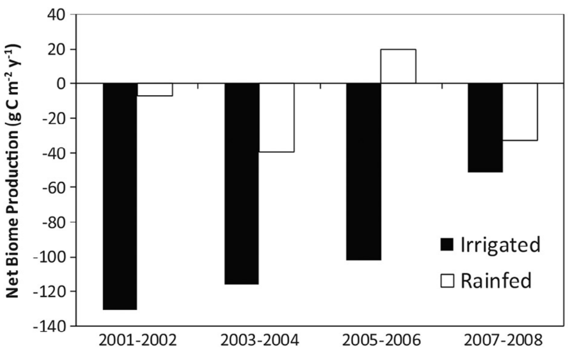


Figure 14. Net biome production (NBP = NEP − grain C removed during harvest) for the combined cycle of maize and soybean for irrigated and rainfed crops. Each bar is a 2-year average of NBP.

aboveground plant biomass and grain biomass), and (c) the cumulative difference between precipitation and evapotranspiration (∑[P-ET]: as an indicator of surface moisture) in a stepwise multiple regression of Re_{NGS}. Average air temperature explained 68% and residue biomass explained 13% of interannual variability in Re_{NGS} (∑[P-ET] was not significant).

3.4. Annual net ecosystem production and net biome production

Annually integrated GPP, Re, and NEP are depicted in Figure 12. About 70% of maize GPP was lost in ecosystem respiration resulting in the mean annual NEP (± standard deviation) of 552 ± 73 g C m^{-2} y^{-1} for irrigated maize and 471 ± 52 g C m^{-2} y^{-1} for rainfed maize. In contrast, in the case of soybean, most of the annual GPP was lost as ecosystem respiration resulting in a mean annual NEP for rainfed and irrigated soybean of 10 ± 52 and −57 ± 43 g C m^{-2} y^{-1}, respectively.

To examine the role of GPP and Re in explaining departures of NEP from the mean (ΔNEP), following a method used by Chen et al. (2009), we plotted the departures (ΔGPP, ΔRe) in annual GPP and Re from their respective 4-year means (Figure 13; ΔNEP = ΔGPP − ΔRe). For irrigated maize, the GPP generally contributed more to ΔNEP (i.e., ΔGPP generally larger than ΔRe). During 2001 and 2003, rainfed maize results were similar to those from irrigated maize. However, during 2005 and 2007, both GPP and Re seem to make similar contributions with offsetting impacts on ΔNEP. Data from irrigated soybean indicated nearly equal contributions of GPP and Re to the ΔNEP, with 2 years (2002 and 2008) of essentially offsetting impacts on ΔNEP. In rainfed soybean, there seems to be an indication of somewhat greater contribution of Re (the ΔGPP were very small and ΔRe was slightly larger). Overall, GPP tended to contribute more than Re to the ΔNEP of maize. For soybean, both GPP and Re seem important.

Net biome production (NBP = NEP − grain C removed during harvest) was calculated for each year (Figure 14). The irrigated maize–soybean rotation began as a moderate source of carbon. However, more recently, it appears to be nearly C neutral. The rainfed maize–soybean rotation is approximately C neutral, consistent with the results of Hollinger et al. (2005).

4. Summary and conclusions

This paper includes an examination of 8 years of measurements of carbon exchange in an irrigated and rainfed maize–soybean rotation cropping system. Peak daily gross primary production (GPP) ranged from about 28–30 g C m^{-2} d^{-1} for irrigated maize, occurring about 50–60 days after emergence. This period corresponded to the approximate time of peak green leaf area index (LAI). Peak GPP was slightly lower for rainfed maize (22–27 g C m^{-2} d^{-1}). For soybean (irrigated and rainfed), peak GPP was between 16 and 18 g C m^{-2} d^{-1} and also corresponded to the period of peak LAI occurring about 60–70 days after emergence. Examination of the role of quality of light in relation to the annual GPP of these crops indicated a GPP advantage due to diffuse light of 9–14% for maize and 18–20% for soybean. Peak daily values of growing season ecosystem respiration (Re) ranged from about 12 to 15 g C m^{-2} d^{-1} for irrigated maize and slightly lower for rainfed maize (9–13 g C m^{-2} d^{-1}). For soybean, Re values peaked from 10 to 14 g C m^{-2} d^{-1} in the irrigated and rainfed fields. In both crops, peak Re values generally occurred about two weeks after the occurrence of peak LAI. Comparison of growing season results among different years of measurement and management practices (irrigated, rainfed) indicated a conservative nature of the Re/GPP ratio for each crop. When calculated for the entire growing season, the Re/GPP ratio (±standard deviation) was 0.56 ± 0.02 for maize and 0.76 ± 0.05 for soybean.

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