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Abstract

Continuous measurements of CO_2 and water vapor exchanges made in three cropping systems (irrigated continuous maize, irrigated maize–soybean rotation, and rainfed maize–soybean rotation) in eastern Nebraska, USA during 6 years are discussed. Close coupling between seasonal distributions of gross primary production (GPP) and evapotranspiration (ET) were observed in each growing season. Mean growing season totals of GPP in irrigated maize and soybean were 1738 ± 114 and 996 ± 69 g C m^{-2}, respectively (±standard deviation). Corresponding mean values of growing season ET totals were 545 ± 27 and 454 ± 23 mm, respectively. Irrigation affected GPP and ET similarly, both growing season totals were about 10% higher than those of corresponding rainfed crops. Maize, under both irrigated and rainfed conditions, fixed 74% more carbon than soybean while using only 12–20% more water. The green leaf area index (LAI) explained substantial portions (91% for maize and 90% for soybean) of the variability in GPP_{PAR} (GPP over a narrow range of incident photosynthetically active radiation) and in ET/ET_o (71% for maize and 75% for soybean, ET_o is the reference evapotranspiration). Water productivity (WP or water use efficiency) is defined here as the ratio of cumulative GPP or above-ground biomass and ET (photosynthetic water productivity = $\sum$GPP/$\sum$ET and biomass water productivity = above-ground biomass/$\sum$ET). When normalized by ET_o, the photosynthetic water productivity (WP_{ETo}) was 18.4 ± 1.5 g C m^{-2} for maize and 12.0 ± 1.0 g C m^{-2} for soybean. When normalized by ET_o, the biomass water productivity (WP_{ETo}) was 27.5 ± 2.3 g DM m^{-2} for maize and 14.1 ± 3.1 g DM m^{-2} for soybean. Comparisons of these results, among different years of measurement and management practices (continuous vs rotation cropping, irrigated vs rainfed) in this study and those from other locations, indicated the conservative nature of normalized water productivity, as also pointed out by previous investigators.

Keywords: gross primary production, evapotranspiration, water productivity, maize, soybean, irrigated, rainfed

1. Introduction

Recent studies report changes in climatic conditions (e.g., air and water temperatures, precipitation patterns, sea ice cover, frost period durations) attributable to human-induced addition of heat-trapping gases from burning of fossil fuels as well as from forest clearing and changes in agricultural practices (Karl et al., 2009). Some studies (e.g., Schimel et al., 2001) also indicate an increase in the carbon sink capacity of natural ecosystems in the 1990s. To help analyze long-term behavior of regional and global carbon sources and sinks, continuous monitoring of carbon exchange in key ecosystems is needed. For example, agricultural ecosystems, which cover about 12% of the earth's surface (Wood et al., 2000), are more productive than natural ecosystems. In annual maize–soybean (*Zea mays*, L; *Glycine max* [L] Merr.) cropping systems, short-term carbon uptake may be two to three times greater than mature forest ecosystems (e.g., Falge et al., 2002). However, a large portion of net primary production is returned to the atmosphere from removal of the harvested grain carbon and post-harvest biomass decay, which limits long-term carbon storage (e.g., Verma et al., 2005; Baker and Griffis, 2005; Schimel et al., 2001). Research is underway to examine management practices that may be employed to increase carbon sequestration in agricultural ecosystems.

Impacts of potential climate change on agricultural ecosystems may include physiological effects on crops, pastures, changes in land-use, increased weed and pest challenges, and declines in yields (FAO report, 2007). Long-term, climate-induced changes in agriculture may affect the emission, uptake, and storage of carbon. Detailed, long-term studies in agricultural ecosystems documenting year-to-year variability in CO_2 and water vapor exchanges have the potential to reveal changes in the functioning of these systems and to understand the relevant biophysical factors driving these changes. This knowledge is necessary to estimate the contribution of agricultural ecosystems to regional and continental carbon balance now and in the future. Some of the negative effects of climate change may be mitigated by implementing new management strategies (e.g., conservation tillage, precision farming) but the interaction of climate in determining the long-term carbon balance and sustainable grain productivity requires further research.

Evapotranspiration (ET) contributes to the climate system in a significant manner by (a) returning 60% of land precipitation to the atmosphere (Oki and Kanae, 2006) and (b) linking the hydrological, carbon, and energy cycles (Pielke et al., 1998). For example, transpiration from crops is directly linked to plant CO_2 assimilation and thus changes in ET affect CO_2 uptake directly and indirectly through the depletion of plant available water. The competition for water resources for agriculture/livestock production and municipal/industrial needs is intense. Not only are increased populations putting a greater demand on water resources for food production, but climate change may have far-reaching, long-term impacts on both food production (yield) and the carbon cycle (Molden et al., 2007). Improving agricultural production while maintaining or reducing water required will mitigate competition for scarce water resources and reduce environmental degradation (Molden et al., 2003). Thus, studies of carbon exchange in agricultural ecosystems must also quantify evapotranspiration to provide a comprehensive determination of ecosystem behavior.

Maize-based cropping systems dominate agricultural land-use in the north-central United States. Since 2001, we have been making continuous measurements of CO_2 and water vapor fluxes in these systems in eastern Nebraska. The objectives of the study reported here are to (a) quantify magnitudes and seasonal distributions of CO_2 and water vapor exchanges in irrigated and rainfed maize–soybean cropping systems, (b) examine the impact of dry periods on CO_2 and water vapor fluxes and investigate the role of leaf area in controlling these fluxes, and (c) quantify water productivity (WP or water use efficiency) of these crops using both gross primary production and above-ground biomass. Availability of several years of concurrent measurements of CO_2 and water vapor fluxes in different management practices (irrigated vs rainfed, continuous cropping vs rotation) of these two important crops allowed us to compare and contrast the role of key biophysical parameters in regulating photosynthesis and evapotranspiration.

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. These sites are large production fields, each 49–65 ha, that provide sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using tower eddy covariance systems. One site (#1: 41°09′ 54.2′′N, 96°28′35.9′′W, 361 m) is equipped with center pivot irrigation and is planted in continuous maize. The second site (#2: 41°09′53.5′′N, 96°28′12.3′′W, 362 m), also equipped with center pivot irrigation is planted in maize–soybean rotation. The third site (#3: 41°10′46.8′′N, 96°26′22.7′′W, 362 m) relies on rainfall and is planted in maize–soybean rotation. Prior to initiation of the study, the irrigated sites 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. All three 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. Results from the first 4 years documented declining yields with continuous irrigated maize (Site 1) because of difficulties in achieving uniform and adequate plant population due to a heavy litter layer. To address these constraints in our continuous irrigated maize system (Site 1), starting in the autumn of 2005, we began to utilize a conservation plow that does not completely invert the topsoil layer as happens with conventional plowing (conservation plowing was done each fall only at Site 1). 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). Within each site, six small measurement areas (intensive measurement zones, IMZs) 20 m × 20 m each, were established for detailed process-level studies of soil C dynamics, crop growth and biomass partitioning. Crop management practices (i.e., plant populations, herbicide and pesticide applications, irrigation)

Table 1. Crop management details, site information, and peak green leaf area index during 2001–2006 (M – maize; S – soybean).

Year	Crop/cultivar	Plant population (plants/ha)	Planting date	Harvest date	Peak green leaf area index ($m^2\ m^{-2}$)
Irrigated continuous maize (41°09′54.2′′N, 96°28′35.9′′W, 361 m)					
2001	M/Pioneer 33P67	82,000	May 10	October 18	6.0
2002	M/Pioneer 33P67	82,000	May 9	November 4	6.0
2003	M/Pioneer 33B51	77,000	May 15	October 27	5.5
2004	M/Pioneer 33B51	79,800	May 3	October 15	5.2
2005	M/Dekalb 63-75 CRW	70,800	May 4	October 13	5.2
2006	M/Pioneer 33B53	80,200	May 5	October 4	4.9
Irrigated maize–soybean rotation (41°09′53.5′′N, 96°28′12.3′′W, 362 m)					
2001	M/Pioneer 33P67	80,900	May 11	October 22	6.1
2002	S/Asgrow 2703	333,100	May 20	October 7	5.5
2003	M/Pioneer 33B51	78,000	May 14	October 23	5.5
2004	S/Pioneer 93B09	296,100	June 2	October 18	4.4
2005	M/Pioneer 33B51	81,000	May 2	October 17	4.8
2006	S/Pioneer 93M11	318,800	May 12	October 5	5.0
Rainfed maize–soybean rotation (41°10′46.8′′N, 96°26′22.7′′W, 362 m)					
2001	M/Pioneer 33B51	52,600	May 14	October 29	3.9
2002	S/Asgrow 2703	304,500	May 20	October 9	3.0
2003	M/Pioneer 33B51	57,600	May 13	October 13	4.3
2004	S/Pioneer 93B09	264,700	June 2	October 11	4.5
2005	M/Pioneer 31G68	56,300	April 26	October 17	4.3
2006	S/Pioneer 93M11	288,200	May 11	October 8	4.5

have been employed in accordance with standard best management practices (BMPs) prescribed for production-scale maize systems. Table 1 summarizes major crop management information (including site information, the dates of planting/harvest, cultivars planted, plant population, and peak green leaf area index).

2.2. Flux and supporting measurements

Eddy covariance measurements (e.g., Baldocchi et al., 1988) 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), and an open-path infrared CO_2/H_2O gas analysis system (Model LI7500: Li-Cor Inc., Lincoln, NE). Data from the closed-path system were the primary source of CO_2 fluxes; the open-path fluxes used occasionally to fill in data gaps. 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 m above the ground when the canopy was shorter than 1 m, and later moved to a height of 6 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). Air temperature and humidity were measured at 3 and 6 m (Humitter 50Y, Vaisala, Helsinki, Finland) along with soil temperature at 0.06, 0.1, and 0.2 m depths (upper two depths measured in-row and between-row; 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; Suyker et al., 2003). When daytime hourly values were missing, the net ecosystem exchange (NEE = CO_2 flux + CO_2 storage) was estimated as a function of photosynthetically active radiation (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 windspeed (*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 monthly NEE–temperature relationships from windier conditions. Daytime estimates of ecosystem respiration (Re) were obtained from the night NEE–temperature Q_{10} relationship and adjusted to daytime temperatures (e.g., Xu and Baldocchi, 2003). The gross primary production (GPP) was then obtained by subtracting Re from NEE (sign convention used here is such that GPP is always positive and Re is always negative). When hourly values were missing (day or night), the LE was estimated as a function of available energy. Linear regressions between LE and available energy were determined (separately for dry and wet conditions) for 3-day intervals, and used to fill in missing fluxes. We compared the sum of latent and sensible heat fluxes (LE + H) measured by eddy covariance against the sum of R_n (net radiation) + storage terms, measured by other methods. We calculated a linear regression between the growing season totals of H + LE and $R_n + G$ during the 6 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 and standard deviation of regression slopes between $R_n + G$ and H + LE (i.e., closure) for all sites/years was 0.88 ± 0.04. In view of the difficulties associated with accurately estimating the storage and other relevant terms, the "energy balance closure" at our study site seems reasonable. Above-ground biomass and green leaf area were determined from destructive samples at 10- to 14-day intervals until physiological maturity and again just prior to harvest. One-meter linear row sections were destructively sampled in each IMZ using a leaf area meter (Model LI3100C: Li-Cor Inc., Lincoln, NE).

3. Results and discussion

3.1. Weather conditions during the growing season

Mean monthly temperatures in June, July and August were generally above normal (Mead, NE; *1971–2000 Climate Normals*; HPRCC, 2006; Figure 1A). The temperature in June of 2002 was about 3.0 °C above normal. In 2004, however, the temperature was cooler (by 2.0–2.3 °C) during these 3 months. In 2003, June

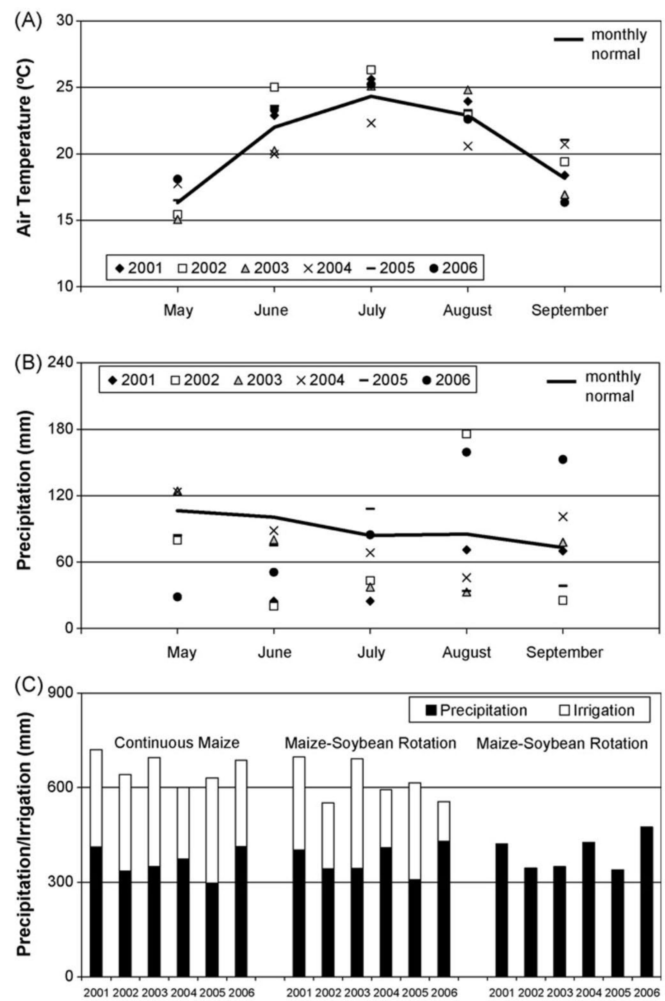

Figure 1. (A) Monthly mean temperature measured at the rainfed site and climate normals (measured at a nearby weather station at Mead, NE; *1971–2000 Climate Normals*; HPRCC, 2006), **(B)** monthly precipitation totals measured at the rainfed site and climate normals, and **(C)** growing season totals of precipitation/irrigation for each site during 2001–2006.

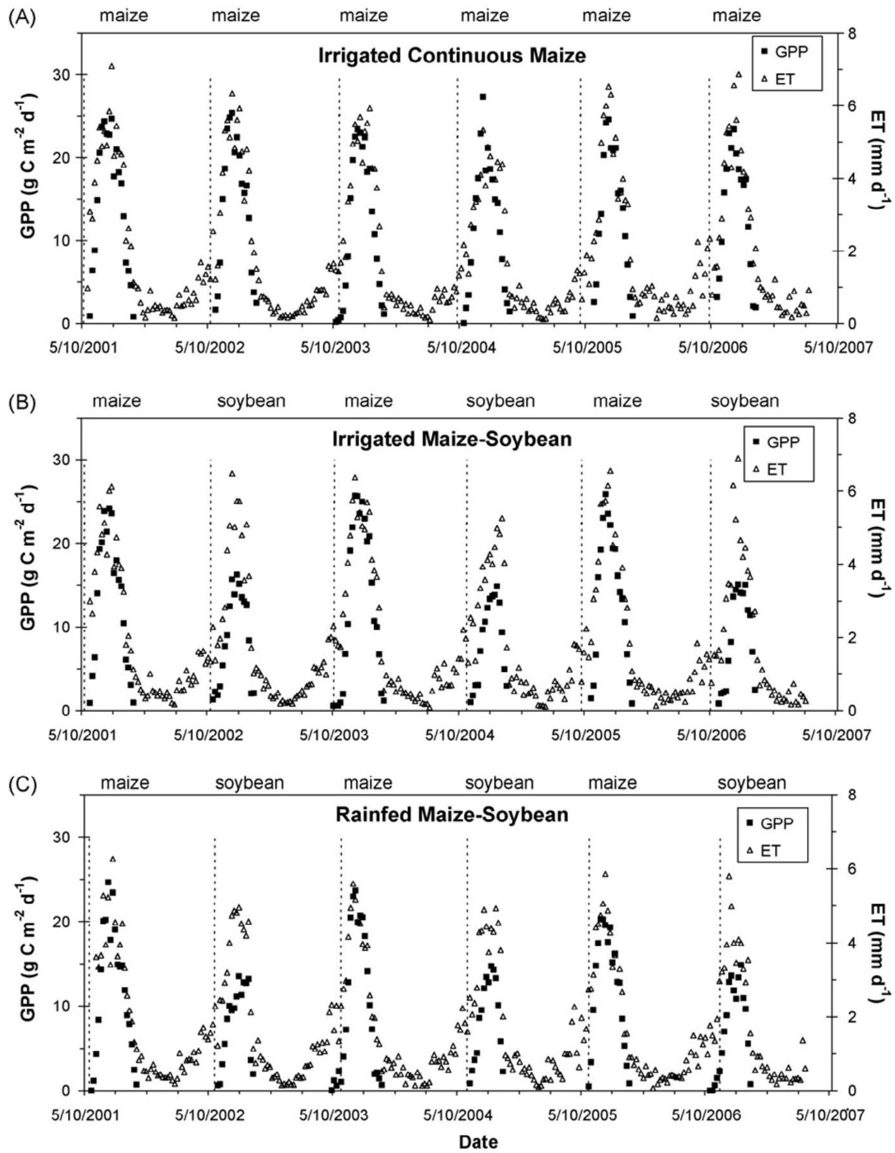

Figure 2. Seasonal distributions of daily gross primary production (GPP) and evapotranspiration (ET) for **(A)** irrigated continuous maize, **(B)** irrigated maize–soybean rotation, and **(C)** rainfed maize–soybean rotation from 2001 to 2007. Each datum point represents a weekly average. Dashed lines are dates of canopy emergence.

was 1.8 °C cooler than normal but July and August were warmer (0.8 and 1.9 °C above normal, respectively). Precipitation was quite variable and was generally below normal, sometimes by as much as 80 mm/month (Figure 1B). Irrigation provided about 40–50% of the total water received for maize and 25–40% of the total water received for soybean (Figure 1C).

3.2. Annual distributions of gross primary production and evapotranspiration

3.2.1. Maize

Daily gross primary production (GPP) and evapotranspiration (ET) during 6 years of our study are plotted in Figure 2. Prior to emergence of both crops (late May to early June), the ET gradually increased concurrently with available energy. In this period, mulch biomass plays a dominant role in controlling normalized surface evaporation (E/E_{eq}) (e.g., Suyker and Verma, 2008), where E and E_{eq} are the non-growing season evaporation and equilibrium evaporation, respectively (e.g., Slayter and McIlroy, 1961). Once the canopy emerged, the GPP and ET began increasing rapidly. Peak GPP values in irrigated maize were reasonably steady, ranging from 23.4 to 27.3 g C m^{-2} d^{-1} (mean = 24.9 g C m^{-2} d^{-1}) during the six growing seasons in irrigated continuous maize and the three growing seasons in irrigated maize in rotation. The peak ET ranged from 5.3 to 7.1 mm d^{-1} (mean = 6.4 mm d^{-1}). As compared to irrigated maize, the peak GPP under rainfed conditions was smaller, ranging from 20.3 to 24.6 g C m^{-2} d^{-1} (mean = 22.9 g C m^{-2} d^{-1}). Peak ET in rainfed maize was also slightly lower (5.6–6.3 mm d^{-1}, with a mean of 5.9 mm d^{-1}). With the onset of senescence, the GPP and ET values began to decline during mid-September/early October. By mid-October, the GPP was near-zero while ET continued to slowly decrease during November through February. Peak winter ET was typically 10–20% of growing season peak values.

3.2.2. Soybean

For irrigated and rainfed soybean, peak GPP ranged from 14.8 to 16.2 g C m^{-2} d^{-1} (mean = 15.4 g C m^{-2} d^{-1}) and 13.5 to 14.9 g C m^{-2} d^{-1} (mean = 14.4 g C m^{-2} d^{-1}), respectively. Peak irrigated and rainfed ET ranged from 5.3 to 6.9 and 4.9 to 5.8 mm d^{-1}, respectively (means were 6.2 and 5.2 mm d^{-1}, respectively). Again,

Table 2. Average growing season totals (planting to harvest) of gross primary production (GPP) and evapotranspiration (ET) and ratios for irrigated/rainfed and maize/soybean (data from continuous and rotation maize crops are included in the averages).

Crop	GPP g C m^{-2} Irrigated	GPP g C m^{-2} Rainfed	ET mm Irrigated	ET mm Rainfed	GPP ratio Maize Irrigated/Rainfed	ET ratio Soybean Irrigated/Rainfed
A						
Maize (2001–2006)	1738	1553	545	482	1.12	1.13
Soybean (2002–2006)	996	895	454	430	1.11	1.06
Management			GPP ratio Maize/soybean			ET ratio Maize/soybean
B						
Irrigated (2001–2006)			1.74			1.20
Rainfed (2001–2006)			1.74			1.12

the peak GPP and ET showed little variability among years. Soybean GPP and ET values decreased rapidly during the first half of September as the canopy senesced. The GPP approached zero and the ET followed similar patterns and magnitudes as in maize from October to April.

The seasonal distributions in each year reflect a close coupling between GPP and ET of both crops. Growing season GPP and ET (planting to harvest) totals for each crop under irrigated and rainfed conditions are given in Table 2. Irrigated maize had the highest GPP and ET (1738 g C m^{-2} and 545 mm) and rainfed soybean the lowest (895 g C m^{-2} and 430 mm). Two significant features emerge. Compared to rainfed values, the GPP and ET totals in each crop are higher by about 10% for irrigated conditions. Irrigation seems to have similar effects on both quantities. Secondly, maize fixes 74% more carbon in photosynthesis as compared to soybean, but uses only about 12–20% more water under irrigated or rainfed conditions (Table 2B).

3.3. Impact of dry periods

Measured precipitation and evaporative fraction (EF = LE/[H + LE]; e.g., Shuttleworth et al., 1989 and Schwalm et al., 2010) were used as indicators of dryness (Figure 3). For maize, major dry periods occurred during silking and/or reproductive stages in 2001 (July 31–August 15; R3 to 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 to V10 and V13 to 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.

In Figure 4, we examine daily GPP and ET of the rainfed crops in relation to those of the respective irrigated crops (maize: 2001, 2003, and 2005 and soybean: 2002, 2004 and 2006). Differences in daily GPP and ET (ΔGPP and ΔET) increased during the dry periods for both maize and soybean and reached peak values of 9.3 g C m^{-2} d^{-1} and 3.0 mm d^{-1}, respectively. On a cumulative basis, during the 2003 dry period which occurred primarily during the reproductive growth stages, the difference in cumulative GPP (ΔCum GPP) was 360 g C m^{-2} or about 24% of the irrigated growing season total (Table 3). The corresponding difference in cumulative ET (ΔCum ET) was 100 mm or 22% of the irrigated growing season total. The next longest dry period for maize occurred earlier in the growth cycle in 2005 and had a smaller impact on ΔCum GPP and ΔCum ET (7% and 5% of the respective irrigated growing season totals) while the shortest dry period in 2001 showed a very small impact (about 2% of the irrigated growing season totals for both GPP and ET). For soybean, during the dry period in vegetative growth in 2002, the ΔCum GPP and ΔCum ET were respectively 13% and 7% of irrigated growing season totals. During the dry period in reproduction/senescence stages in 2004, ΔCum GPP and ΔCum ET were both approximately 7% of irrigated growing season totals. These results indicate that for both maize and soybean, the percentage impact of dry periods on cumulative GPP and ET was of similar order in each year (Table 3). Also, these impacts were reasonably correlated with the duration of the dry period (Figure 5).

3.4. Role of leaf area in controlling GPP and ET

3.4.1. GPP vs LAI

To minimize confounding effects of varying light, we examined GPP over a narrow range of incident PAR (GPP_{PAR}: GPP when PAR was between 1400 and 1500 µmol m^{-2} s^{-1}) as a function of LAI. Likelihood ratio tests (LRT) showed that, for irrigated conditions (Figure 6A), the GPP_{PAR}–LAI relationship was not significantly different among years for continuous maize or maize in rotation ($p < 0.01$). Likewise for irrigated soybean, there was no significant difference ($p < 0.01$) in the GPP_{PAR}–LAI relationship over three growing seasons (Figure 6B).

In rainfed maize and soybean, the GPP_{PAR} values during adequate moisture were generally within the 95% confidence bands of "irrigated values" (Figure 6C and D). During the dry periods, the maize GPP_{PAR} values tended to remain within these confidence bands of the irrigated values. For soybean, the GPP_{PAR} values during the dry period tended to congregate in the lower range of irrigated values at the same LAI. This subtle difference may be related to the degree soybean tolerates drought compared to maize (e.g., Boyer, 1970).

3.4.2. ET vs LAI

To examine the dependence of ET on LAI (Figure 7), we normalized daily ET with reference evapotranspiration (ET_o – e.g., Allen et al., 1998). The role of LAI in controlling ET and GPP are similar in some ways. As for GPP_{PAR}, there was no statistical difference in the ET/ET_o–LAI relationship among years for irrigated maize or soybean ($p < 0.05$; Figure 7A and B). Also, for a given LAI, the ET/ET_o values of rainfed crops in relation to irrigated conditions were similar (generally within the confidence bands) during adequate moisture and dry periods (Figure 7C and D). Overall, the LAI explained substantial portions of the variability in GPP_{PAR} (91% and 90% for maize and soybean, respectively) and ET/ET_o (71% and 75% for maize and soybean, respectively). However, there was a subtle difference as well. The canopy did not seem to approach GPP saturation at the highest leaf area for either crop. In contrast, the ET/ET_o at higher LAI seemed to approach an asymptotic value (e.g., Kristensen, 1974; Steduto and Hsiao, 1998) – the LAI threshold was slightly lower for soybean compared to maize.

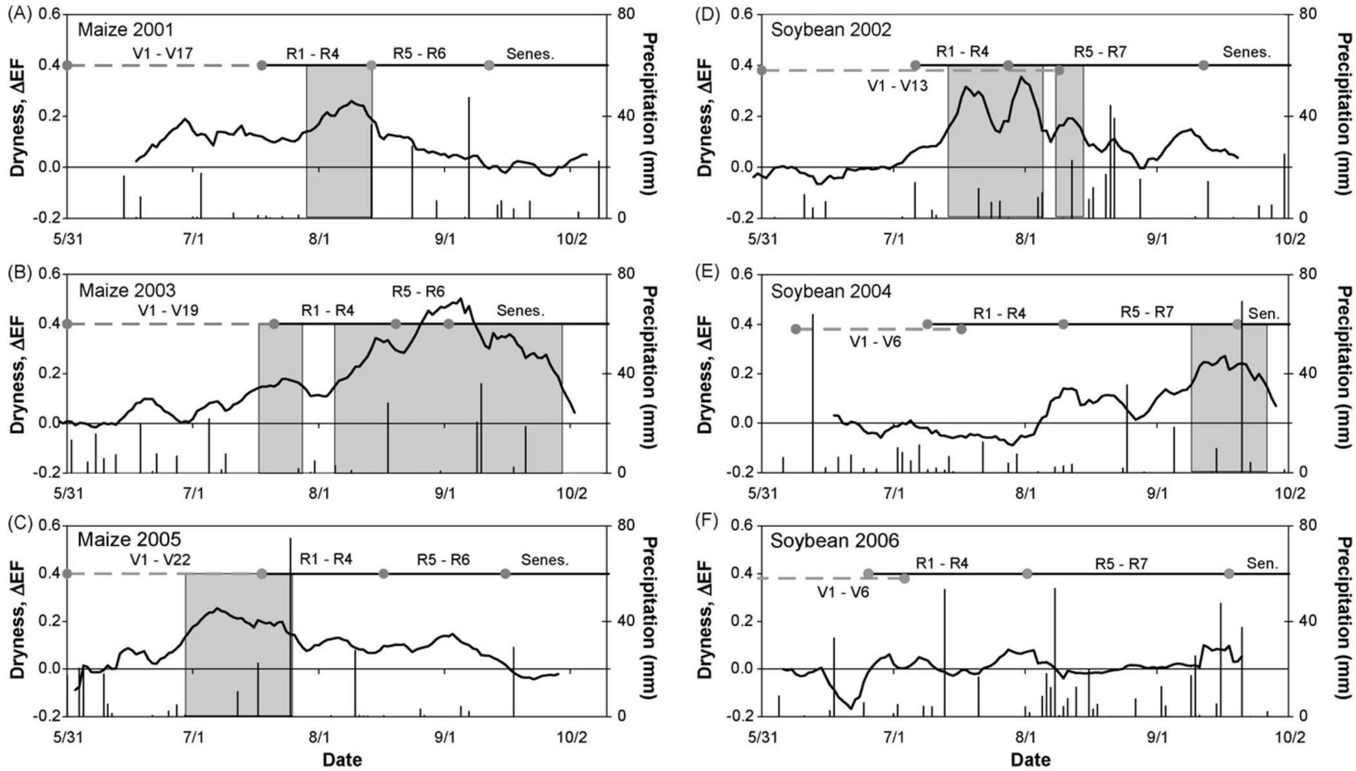

Figure 3. Seasonal distributions of ΔEF: ΔEF is the difference between irrigated and rainfed EF (evaporative fraction) for **(A)** maize in 2001, **(B)** maize in 2003, **(C)** maize in 2005, **(D)** soybean in 2002, **(E)** soybean in 2004, and (F) soybean in 2006. Major dry periods (shaded areas) and growth stages (for the rainfed site) are noted. The solid points (●) indicate the separation of the growth stages.

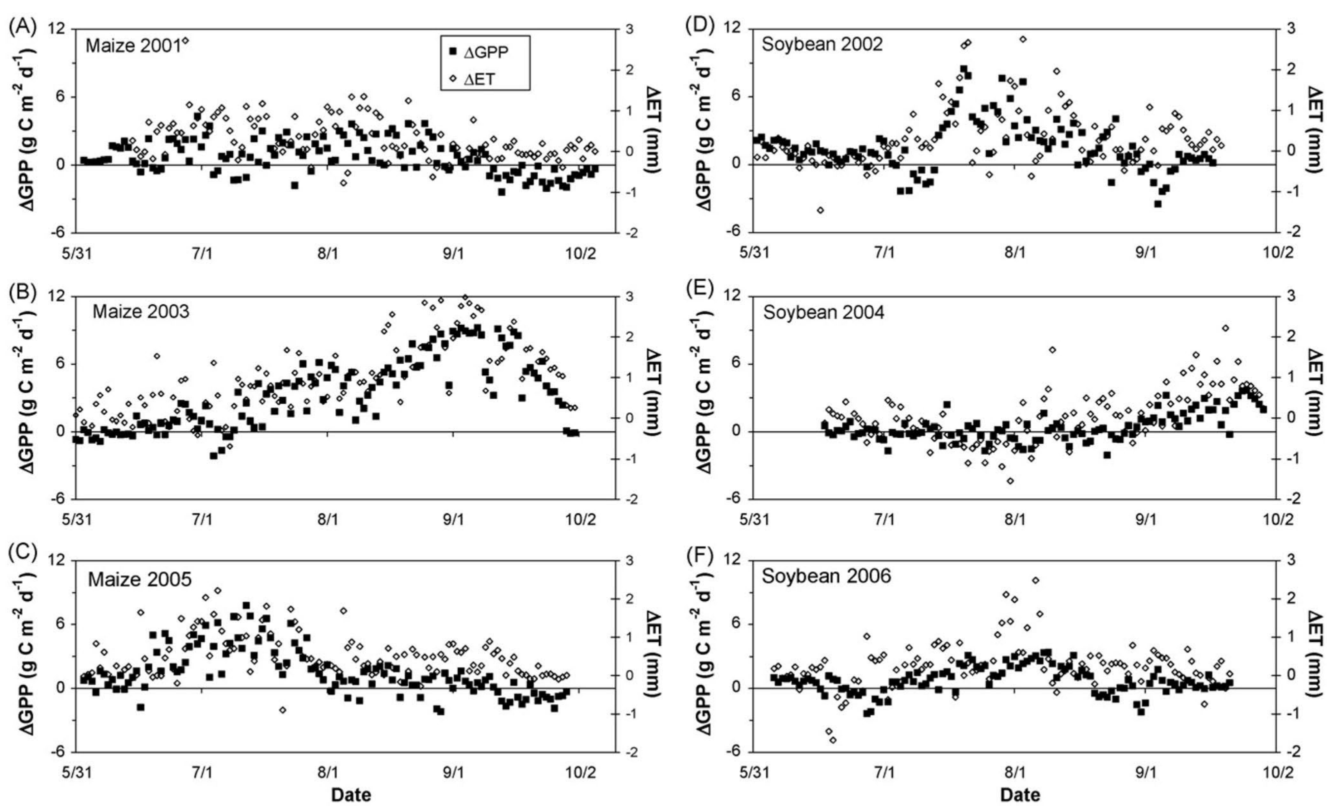

Figure 4. Difference (ΔGPP) between the daily gross primary production of irrigated and rainfed crops and difference (ΔET) between the daily evapotranspiration of irrigated and rainfed crops for **(A)** maize in 2001, **(B)** maize in 2003, **(C)** maize in 2005, **(D)** soybean in 2002, **(E)** soybean in 2004, and (F) soybean in 2006.

Table 3. Cumulative gross primary production (GPP) and evapotranspiration (ET) of the irrigated and rainfed maize–soybean during the major dry periods (see text for details). Dry period durations and percent differences (in relation to the irrigated growing season totals) of GPP and ET are included.

Crop	Year	Dry period	Cumulative GPP			Cumulative ET		
		Duration	Irrigated $g\ C\ m^{-2}\ d^{-1}$	Rainfed $g\ C\ m^{-2}\ d^{-1}$	% Seasonal difference	Irrigated $mm\ d^{-1}$	Rainfed $mm\ d^{-1}$	% Seasonal difference
Maize	2001	7/31–8/15	336	310	2	87	77	2
	2003	7/18–28; 8/5–9/29	1106	746	24	295	195	22
	2005	6/30–7/25	626	514	7	160	133	5
Soybean	2002	7/14–8/5; 8/9–14	429	309	13	166	137	7
	2004	9/9/2026	122	56	7	77	49	7

3.5. Water productivity

Water productivity (WP) or water use efficiency can be defined as the ratio of cumulative carbon (expressed as GPP or biomass) and transpiration (T) during the growing season. Accurately measuring or modeling T at the ecosystem scale is difficult. In Figure 8, we show typical examples of the cumulative GPP–ET and above-ground biomass–ET relationships for maize and soybean. Non-linearity in the relationship early and late in the season is likely related to the contribution of soil water evaporation (Hsiao, 1993) and possibly decreasing chlorophyll content and photosynthetic activity during senescence (Ciganda et al., 2008). Accordingly, to minimize the contribution of soil water evaporation in our analysis, we calculated cumulative GPP, ET, and above-ground biomass during the period that started when LAI > 2 $m^2\ m^{-2}$ and ended approximately a week before physiological maturity (PM). During this period, the ∑GPP vs ∑ET and above-ground biomass vs ∑ET were nearly linear ($r^2 > 0.99$: Figure 8). As pointed out by Steduto et al. (2007), the linearity of the GPP–ET and biomass–ET relationships indicates the "constancy" of WP during the growing season.

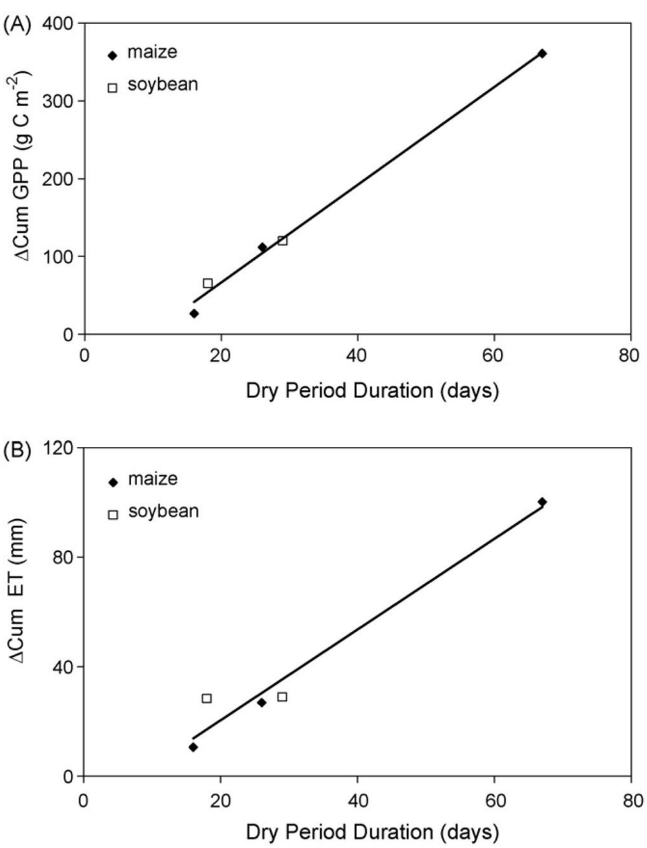

Figure 5. Differences between **(A)** irrigated and rainfed cumulative GPP (ΔCum GPP) and **(B)** irrigated and rainfed cumulative ET (ΔCum ET) for both maize and soybean during major dry periods plotted against dry period durations.

When examining WP from different locations (climates) or different years, previous research has shown it necessary to normalize the daily T (or ET) by daytime average vapor pressure deficit (D – e.g., Tanner and Sinclair, 1983) or by daily reference evapotranspiration, ET_o (e.g., Steduto et al., 2007 and Steduto and Albrizio, 2005). Although some analyses (e.g., Steduto and Albrizio, 2005 and Steduto et al., 2007) suggest that normalizing by ET_o is "more robust," here we present results that include normalizing both ways (by daily ET_o and daytime average D).

Photosynthetic water productivity (normalized by ET_o):

$$WP_{ETo} = \frac{\sum GPP}{\sum(ET/ET_o)} \quad (1)$$

Photosynthetic water productivity (normalized by D):

$$WP_D = \frac{\sum GPP}{\sum(ET/D)} \quad (2)$$

Biomass water productivity (normalized by ET_o):

$$WP_{ETo} = \frac{\text{above-ground biomass}}{\sum(ET/ET_o)} \quad (3)$$

Biomass water productivity (normalized by D):

$$WP_D = \frac{\text{above-ground biomass}}{\sum(ET/D)} \quad (4)$$

where the summation period starts when LAI > 2 $m^2\ m^{-2}$ and ends a week before PM.

3.5.1. Photosynthetic water productivity

The mean photosynthetic WPETo was 17.6 ± 1.2 g C m^{-2} (mean ± standard deviation) for irrigated continuous maize and 18.6 ± 1.1 g C m^{-2} for irrigated maize in rotation during 6 years of our study (Figure 9A, Table 4). The rainfed maize mean value was 20.0 ± 1.3 g C m^{-2}. Considering all management practices studied here, the maize photosynthetic WPETo was 18.4 ± 1.5 g C m^{-2}. For years when maize was grown at all three sites (2001, 2003, and 2005), a two factor ANOVA (year × management practice) indicated no significant difference in photosynthetic WPETo ($\alpha = 0.025$) among years or management practices (continuous vs rotation, irrigated vs rainfed).

The mean photosynthetic WPETo was 12.1 ± 1.3 g C m^{-2} during 3 years of irrigated soybean and 11.8 ± 0.7 g C m^{-2} for 3 years of rainfed soybean (Figure 9A, Table 4). Considering all soybean data, mean photosynthetic WPETo was 12.0 ± 1.0 g C m^{-2}. Again, no significant difference was observed among 6 years of irrigated and rainfed photosynthetic WPETo (two factor ANOVA; $\alpha = 0.025$). Values of photosynthetic WP_D (normalized by daytime D) for maize and soybean are also given in Table 4.

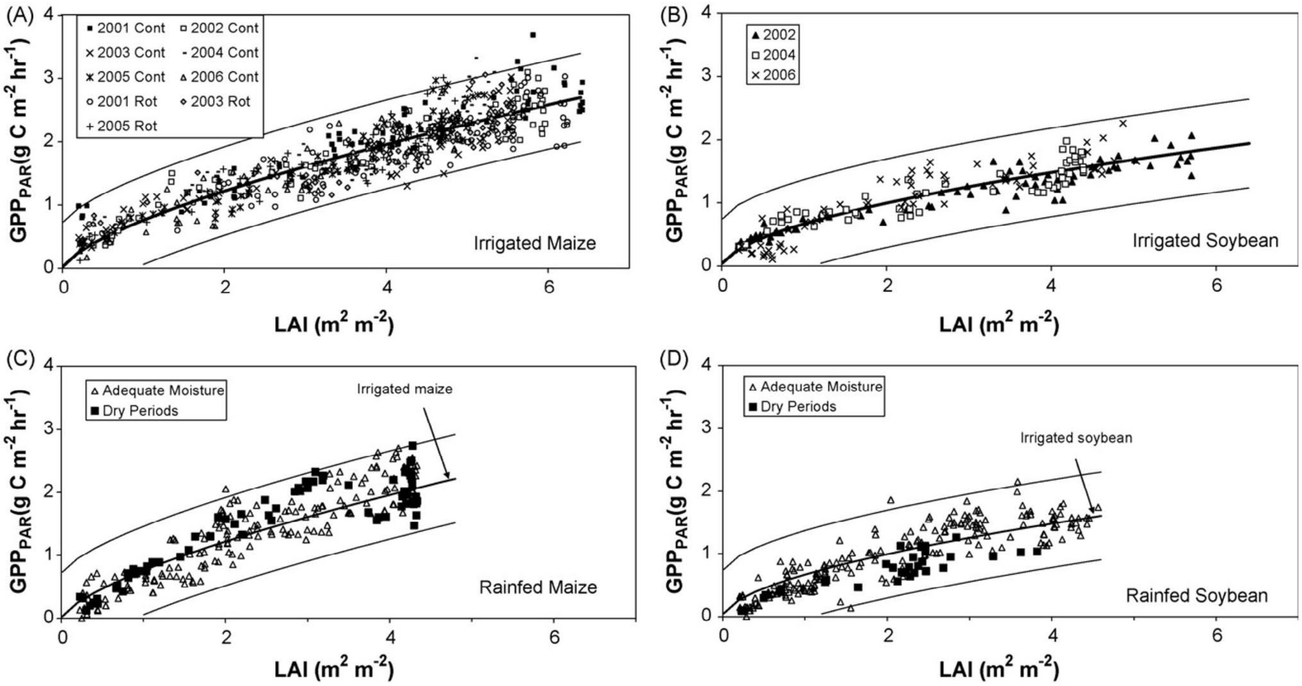

Figure 6. Gross primary production measured over a narrow range of incident PAR (1400–1500 μmol m^{-2} s^{-1}; GPP_{PAR}) plotted against green leaf area index (LAI) for **(A)** irrigated maize (6 years continuous and 3 years rotation from 2001 to 2006), **(B)** irrigated soybean (2002, 2004 and 2006), **(C)** rainfed maize (2001, 2003 and 2005), and **(D)** rainfed soybean (2002, 2004, and 2006). For rainfed crops, dry periods (see text for details) and periods of adequate soil moisture are denoted. Regression relationships for irrigated crops with 95% confidence bands are included.

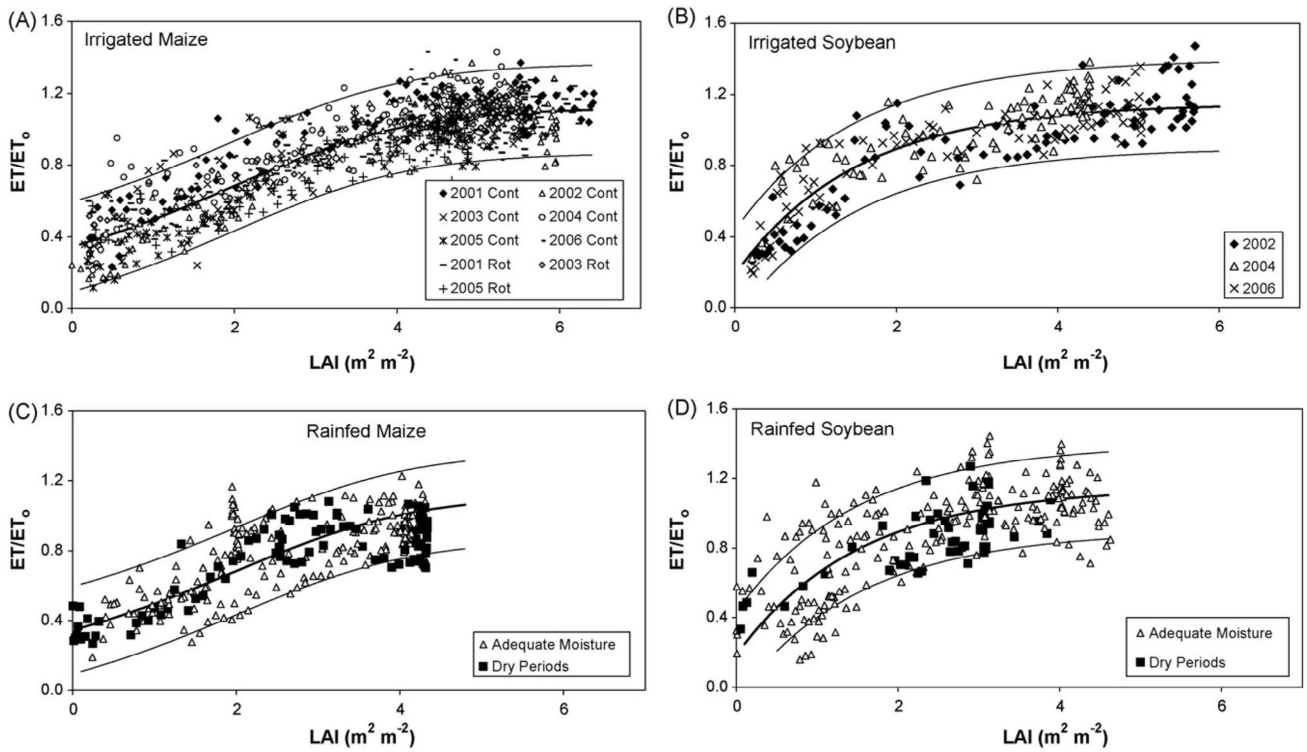

Figure 7. Daily ratios of evapotranspiration to a reference evapotranspiration (ET/ET_o) plotted against green leaf area index (LAI) for **(A)** irrigated maize (6 years continuous and 3 years rotation from 2001 to 2006), **(B)** irrigated soybean (2002, 2004 and 2006), **(C)** rainfed maize (2001, 2003 and 2005), and **(D)** rainfed soybean (2002, 2004, and 2006). For rainfed crops, dry periods (see text for details) and periods of adequate soil moisture are denoted. Regression relationships (quadratic) for irrigated crops with 95% confidence bands are included.

3.5.2. Biomass water productivity

For irrigated and rainfed maize, mean biomass WPETo was 28.0 ± 2.4 and 25.8 ± 1.1 g DM m^{-2}, respectively. Overall, the maize biomass water productivity was 27.5 ± 2.3 g DM m^{-2} with no significant difference among years and management practices studied here (two factor ANOVA; $\alpha = 0.025$). Similarly for soybeans, irrigated and rainfed values were 15.8 ± 4.3 and 12.3 ± 1.8 g DM m^{-2}, respectively. Mean irrigated/rainfed soybean

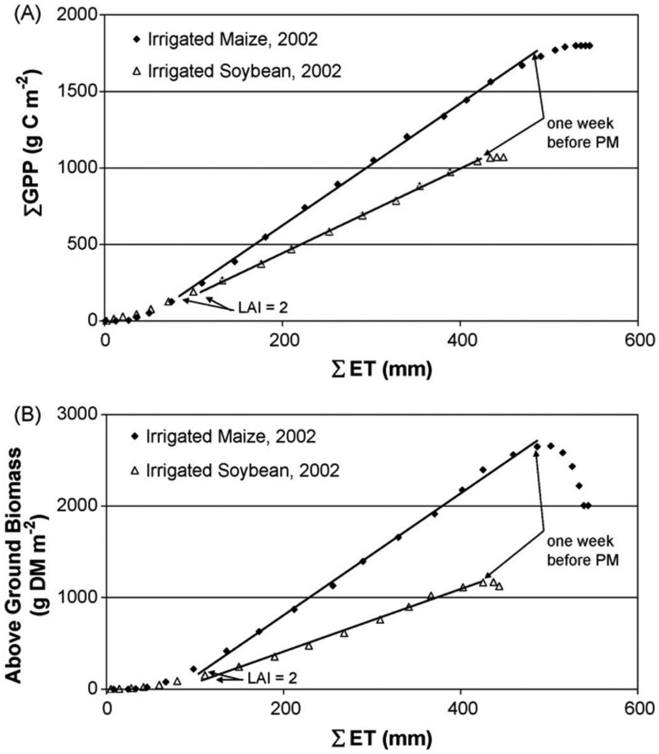

Figure 8. Typical examples of **(A)** cumulative gross primary production (GPP) vs cumulative evapotranspiration (ET) and **(B)** above-ground biomass vs cumulative ET for maize and soybean from emergence to harvest. A linear regression was fit for the period from LAI > 2 m^2 m^{-2} to a week before physiological maturity (PM).

biomass WPETo was 14.1 ± 3.1 g DM m^{-2} with no significant differences among years and management practices (two factor ANOVA; α = 0.025). For irrigated and rainfed maize, biomass WP_D was 6.9 ± 0.7 g DM kPa m^{-2} mm^{-1}. For irrigated and rainfed soybean, mean biomass WP_D was 2.8 ± 0.4 g DM kPa m^{-2} mm^{-1}. Tanner and Sinclair (1983) reported values of biomass WP_D (k_d in their terminology). In their analysis, daytime average D was calculated from daily maximum and minimum temperatures and a seasonally averaged value was used. They also used total biomass, where the below-ground biomass was estimated as 20% of the above-ground biomass. When we recalculated our values following their procedures, our maize k_d was 9.9 ± 1.0 Pa, compared to their value of 9.5 ± 1.1 Pa obtained using data from Arizona, California, Colorado, and Nebraska. For soybean, our value was 4.3 ± 0.2 Pa, compared to their value of 4.0 Pa obtained using data from Kansas.

The above analysis indicates a conservative nature of water productivity based on photosynthesis or biomass, as was also suggested by Tanner and Sinclair (1983), Hsiao (1993), Steduto (1996), and Steduto et al. (2007). It is also worthwhile to consider the WP values of C_3 and C_4 crops reported in the literature. For example, Steduto and Albrizio (2005) reported biomass WP_{ETo} values of 25 and 33 g DM m^{-2} (with and without N fertilization, respectively) for an irrigated sorghum crop (C_4) which are comparable to the results for maize (27.5 ± 2.3 g DM m^{-2}) in our study. They also reported a value of 13 g DM m^{-2} for three C_3 crops (chickpea, fertilized wheat, and fertilized, pre-anthesis sunflower), which is close to our soybean results (14.1 ± 3.1 g DM m^{-2}). These comparisons seem to support Steduto et al. (2007) suggestion that WP should not differ much for crops of similar composition although its value should decrease from cereals, to legume, to oil crops. Obviously, more detailed studies on a variety of vegetations are needed for a thorough analysis of this matter.

4. Summary and conclusions

Carbon dioxide and water vapor exchanges were quantified in three maize-based cropping systems (irrigated continuous maize, irrigated maize–soybean rotation, and rainfed maize–soybean rotation) at Mead, Nebraska from 2001 to 2006. Mean peak gross primary production (GPP) was 24.9 and 22.9 g C m^{-2} d^{-1} in irrigated and rainfed maize, respectively. For soybean, irrigated and rainfed mean peak GPP was substantially lower at 15.4 and 14.4 g C m^{-2} d^{-1}, respectively. Mean peak evapotranspiration (ET) was 6.4 and 5.9 mm d^{-1} in irrigated and rainfed maize, respectively and 6.2 and 5.2 mm d^{-1} in irrigated and rainfed soybean, respectively. The seasonal distribution of daily GPP and ET had very congruent patterns for each crop and the peak values were consistent among the six growing seasons.

The proximity of the study sites with rainfed and irrigated crops allowed an examination of the impact of dry periods. For example, an extended dry period in 2003 reduced cumulative GPP of maize by 24% and cumulative ET by 22% of the irrigated growing season total. The relative impact of dry periods on GPP and ET of both crops in all years was of similar order and was reasonably correlated with the duration of the dry periods.

The GPP over a narrow range of incident PAR (GPP_{PAR}) was examined as a function of green leaf area index (LAI). Similarly, the daily ET, normalized by reference evapotranspiration (ET_o), was examined as a function of LAI. There was no statistical difference in the GPP_{PAR}–LAI and the ET/ET_o–LAI relationships among years for irrigated maize or soybean. Also, for a given LAI, the GPP_{PAR} or ET/ET_o values of rainfed crops were similar in relation to those for irrigated conditions (generally within the 95% confidence bands).

Water productivity (WP) was calculated as a ratio of cumulative GPP (or above-ground biomass) and ET. To facilitate comparison of results from different locations/years, we normalized WP (ET divided by reference evapotranspiration, ET_o, or daytime average vapor pressure deficit, D). For example, when normalized using D, the overall biomass water productivity was 6.9 ± 0.7 g DM kPa m^{-2} mm^{-1} for maize and 2.8 ± 0.4 g DM kPa m^{-2} mm^{-1} for soybean. No

Table 4. Water productivity using either gross primary production (photosynthetic WP) or above-ground biomass (biomass WP) normalized by reference evapotranspiration (WP_{ETo}) or daytime averaged vapor pressure deficit (WP_D).

Site	Photosynthetic WP_{ETo}		Photosynthetic WP_D		Biomass WP_{ETo}		Biomass WP_D	
	Mean g C m^{-2}	Std dev	Mean g C m^{-2} mm^{-1} kPa	Std dev	Mean g DM m^{-2}	Std dev	Mean g DM m^{-2} mm^{-1} kPa	Std dev
Irrigated maize	17.9	1.2	4.6	0.5	28.0	2.4	6.9	0.7
Rainfed maize	20.0	1.3	5.9	0.9	25.8	1.1	6.9	0.5
All maize	18.4	1.5	5.0	0.8	27.5	2.3	6.9	0.7
Irrigated soybean	12.1	1.3	2.5	0.3	15.8	4.3	3.0	0.5
Rainfed soybean	11.8	0.7	2.8	0.4	12.3	1.8	2.6	0.2
All soybean	12.0	1.0	2.6	0.4	14.1	3.5	2.8	0.4

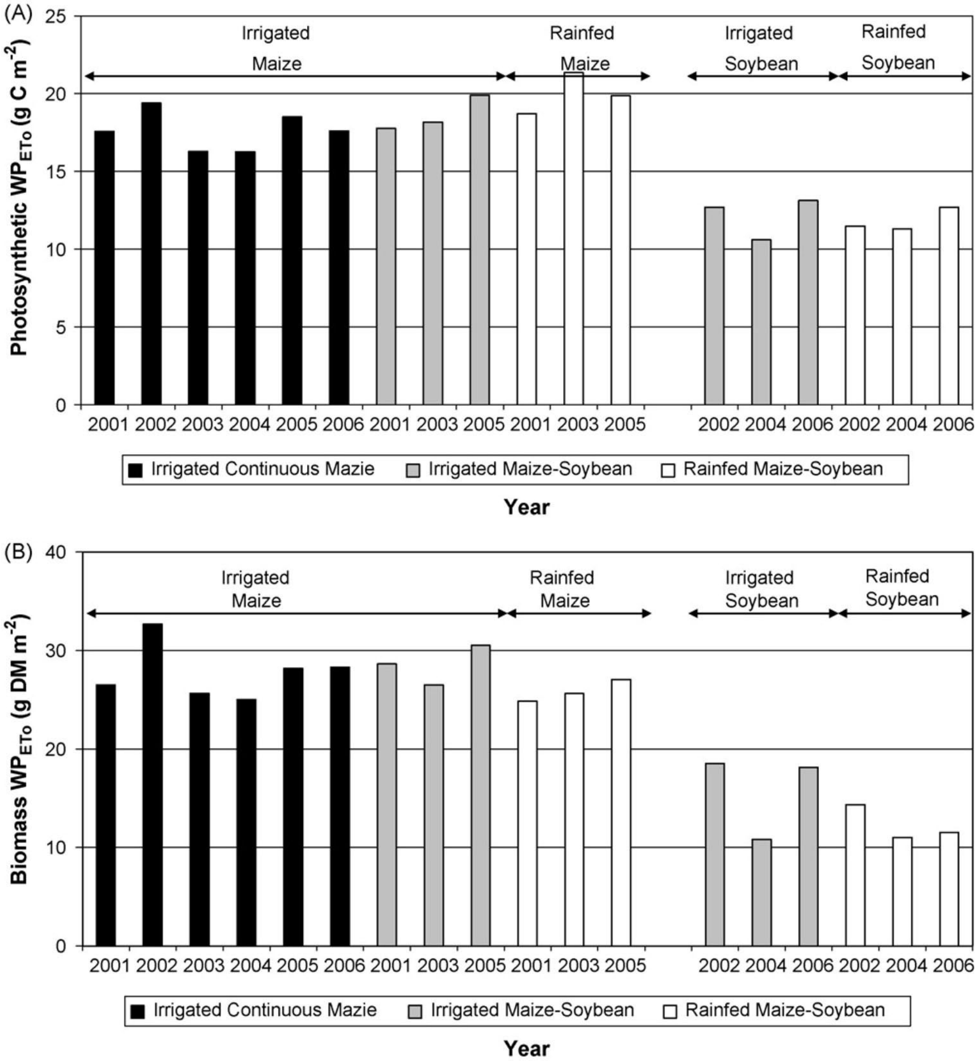

Figure 9. (A) Photosynthetic water productivity normalized by reference evapotranspiration ET_o (photosynthetic WP_{ETo}) and **(B)** biomass water productivity normalized by ET_o (biomass WP_{ETo}) for the cropping systems studied here.

significant difference was found among years and management practices (continuous vs rotation cropping, irrigated vs rainfed). Our results were also quite comparable with those from other locations, indicating a robustness in the value of WP, when normalized appropriately.

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