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Submitted December 16, 2007; revised July 6, 2008; accepted September 22, 2008; published online November 5, 2008.

Evapotranspiration of irrigated and rainfed maize–soybean cropping systems

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Abstract

We have been making year-round measurements of mass and energy exchange in three cropping systems: (a) irrigated continuous maize, (b) irrigated maize–soybean rotation, and (c) rainfed maize–soybean rotation in eastern Nebraska since 2001. In this paper, we present results on evapotranspiration (ET) of these crops for the first 5 years of our study. Growing season ET in the irrigated and rainfed maize averaged 548 and 482 mm, respectively. In irrigated and rainfed soybean, the average growing season ET was 452 and 431 mm, respectively. On average, the maize ET was higher than the soybean ET by 18% for irrigated crops and by 11% for rainfed crops. The mid-season crop coefficient K_c ($=ET/ET_0$ and ET_0 is the reference ET) for irrigated maize was 1.03 ± 0.07 . For rainfed maize, significant dry-down conditions prevailed and mid-season K_c was 0.84 ± 0.20 . For irrigated soybean, the mid-season K_c was 0.98 ± 0.02 . The mid-season dry down in rainfed soybean years was not severe and the K_c (0.90 ± 0.13) was only slightly lower than the values for the irrigated fields. Non-growing season evaporation ranged from 100 to 172 mm and contributed about 16–28% of the annual ET in irrigated/rainfed maize and 24–26% in irrigated/rainfed soybean. The amount of surface mulch biomass explained 71% of the variability in non-growing season evaporation totals. Water use efficiency (or biomass transpiration efficiency), defined as the ratio of total plant biomass (Y_{DM}) to growing season transpiration (T) was 5.20 ± 0.34 and 5.22 ± 0.36 g kg⁻¹, respectively for irrigated and rainfed maize crops. Similarly, the biomass transpiration efficiency for irrigated and rainfed soybean crops was 3.21 ± 0.35 and 2.96 ± 0.30 g kg⁻¹. Thus, the respective biomass transpiration efficiency of these crops was nearly constant regardless of rainfall and irrigation.

Keywords: evapotranspiration, crop coefficient, water use efficiency, maize, corn, soybean, irrigation, rainfed

1. Introduction

Water and its movement through the soil–plant–atmosphere continuum is one of the most important factors affecting crop productivity (e.g., Boyer, 1982). For maize–soybean systems, extensive research has been conducted on the impact of water-related stress on crop development and yield (e.g., Denmead and Shaw, 1960; Musick and Dusek, 1980). The importance of evapotranspiration (ET) as a major com-

ponent of the agricultural water budget increases as water resources become limiting due to factors such as (a) potential climate change, (b) population growth, (c) competition from other water users, (d) drought, and (e) water quality degradation (e.g., Farahani et al., 2007). Furthermore, large evapotranspiration rates in agricultural regions can be an important factor which influences the regional climate (e.g., Shukla and Mintz, 1982). Future climatic conditions are likely to lead to an increase in evapotranspiration causing regional soil

moisture deficits in the Midwest (e.g., Easterling and Karl, 2001), thus affecting crop production in the region [<http://www.gcrio.org/CONSEQUENCES/summer95/agriculture.html>].

In recent years, widespread droughts have been reported in the Great Plains [<http://lwf.ncdc.noaa.gov/oa/reports/billionz.html#chron>]. During the past 7 years, Nebraska has been experiencing local and regional drought conditions [http://www.hprcc.unl.edu/nebraska/nebraska--JAN1999-AUG2006_drought.html]. In 2006, a severe spring/summer drought centered over the Great Plains region caused an estimated 6 billion dollars in damages. Such drought conditions put a great deal of stress on water resources in agricultural areas of the Midwest, especially irrigated regions through decreased water supply and greater pumping costs (e.g., Bowman and Collins, 1987).

In view of potential future shortages of water needed for agricultural production, more attention needs to be given to quantifying and improving water use efficiency (WUE). The WUE is generally defined (e.g., Steduto, 1996) as the ratio of biomass (or yield or photosynthesis) to water consumed in transpiration (or evapotranspiration). Because of the multiple ways WUE has been used in the literature, caution should be exercised in comparing results from different studies. Different soil/crop management practices are being assessed to improve water use efficiency in crop production (e.g., Hatfield et al., 2001). No-till management practices and better crop residue management can potentially reduce water lost through soil evaporation (e.g., Wilhelm et al., 2004; Ji and Unger, 2001; Sauer et al., 1998).

Recent studies have pointed out the important roles of the non-growing season or fallow periods in relation to the flow of energy, carbon and water in agricultural ecosystems (Kucharik and Twine, 2007). Such analyses are crucial in view of the globally expanding biofuel industry. For example, the USDA ARS has initiated studies [http://www.ars.usda.gov/research/projects/projects.htm?ACCN_NO=410653&showpars=true&fy=2006] with key objectives of determining sustainable removal of residues that would otherwise be left in the field so as not to (a) degrade the productivity of the land, (b) decrease soil organic matter, (c) diminish water quality, or (d) result in net carbon emissions (Graham et al., 2007). Long-term, continuous field measurements of mass and energy exchange are needed in agricultural crops with contrasting management practices to enhance our knowledge of evapotranspiration to help address these issues of significant scientific and economic importance.

Here we discuss year-round eddy covariance flux measurements of water vapor in three cropping systems (irrigated continuous maize, irrigated maize-soybean rotation, and rainfed maize-soybean rotation) in eastern Nebraska over a 5-year period. The primary objective of this study is to quantify evapotranspiration in these key agroecosystems and evaluate the contributions of growing season and non-growing season periods to the annual ET totals. Growing season distributions of the crop coefficient (K_c) are quantified. The role of surface mulch biomass is considered in examining the interannual variability of non-growing season evaporation. Also, water use efficiency of these crops is quantified.

2. Materials and methods

2.1. Study sites

The three study sites are located within 1.6 km of each other 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 (ICM: 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 (IMS: 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 (RMS: 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 (ICM and IMS) had a 10-year history of maize-soybean rotation under no-till. The rainfed site (RMS) 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 the beginning of the study to homogenize the top 0.1 m of soil and incorporate P and K fertilizers, as well as previously accumulated surface residues. The soils are deep silty clay loams, typical of eastern Nebraska, consisting of four soil series at all three sites: 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).

Since initiation in 2001, all fields have been under no-till (except ICM in 2005). Crop management practices (i.e., plant populations, herbicide and pesticide applications, irrigation) have been employed in accordance with standard best management practices (BMPs) prescribed for production-scale maize-soybean systems. Results from the first 4 years documented declining yields with continuous irrigated maize (ICM) because of difficulties in achieving uniform and adequate plant populations due to the heavy litter layer that impeded the sowing operation, greater immobilization of fertilizer N reducing fertilizer N use efficiency, and increasing incidence and severity of insect and disease damage. The latter is a common problem in continuous maize that is worsened when large amounts of crop residue litter remains on the soil surface (e.g., Bockus and Shroyer, 1998; Steffey et al., 1999). To address these constraints in our continuous irrigated maize system (ICM), 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. The conservation-plow minimizes soil disturbance by vertically distributing about 2/3 of the crop residue within the surface 0.2–0.25 m depth, while 1/3 remains on the soil surface. A small dose of N fertilizer is applied to the maize residue before the post harvest conservation-plowing operation. Table 1 summarizes major crop management information (including the dates of planting and harvest, cultivars planted, mulch biomass, and crop yields) for the study period. Following best management practices, to account for differences in water-limited attainable yield, lower planting densities were used in rainfed crops (RMS) as compared to

the irrigated crops (ICM and IMS). Nitrogen (N) was applied in the irrigated maize in three applications and a single N fertilizer application was made to maize in the rainfed system. No additional N was applied in the soybean years in 2002 and 2004.

2.2. Eddy covariance flux measurements

Our measurements began just after planting time in 2001. Eddy covariance measurements (e.g., Baldocchi et al., 1988) of fluxes of latent heat (LE), sensible heat (H), and momentum were made using the following sensors at each site: an omnidirectional 3D sonic anemometer (Model R3: Gill Instruments Ltd., Lymington, UK), and an open-path infrared $\text{CO}_2/\text{H}_2\text{O}$ gas analyzing system (Model LI7500: Li-Cor Inc., Lincoln, NE). 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; 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 a previous paper (Suyker et al., 2003). Air temperature and humidity (3.0 and 6.0 m; Humitter50Y, Vaisala, Helsinki, FIN), net radiation at 5.5 m (CNR1, Kipp and Zonen Ltd., Delft, NLD), and soil heat flux (0.06 m depth; Radiation & Energy Balance Systems Inc., Seattle, WA) were also measured.

To fill in missing data due to sensor malfunction, power outages, unfavorable weather, etc. (approximately 15–20% per year), 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 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 sliding 3-day intervals, and used to fill in missing flux values.

It is customary to compare the sum of latent and sensible heat fluxes ($\text{LE} + H$) measured by eddy covariance against the sum of R_n (net radiation) + storage terms, measured by other methods. As Meyers and Hollinger (2004) point out, the combination of soil and canopy heat storage and the energy used in photosynthesis of maize and soybean need to be considered for an accurate estimation of the energy balance closure. We calculated linear regressions between the hourly values of $H + \text{LE}$ and $R_n + G$ at our study sites (excluding winter months and 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 roughly estimated using procedures similar to those outlined in Meyers and Hollinger (2004). The regression slopes at the three sites averaged 0.89 ± 0.08 , implying a fairly good closure of the energy balance at our study sites.

2.3. Leaf area and mulch biomass

Leaf area was measured destructively at six different locations for 1 m linear row sections approximately on a bi-monthly basis. The cubic spline method was used to interpolate daily values. To estimate the surface mulch biomass, we used information developed in a concurrent study (A. Kochsiek, University of Nebraska, personal communication; Verma et al., 2005) in which biomass, left as stover following harvest, was measured each year and exponential decay rates for all components (stalks, stems, husks, seed pods, etc.) were estimated. Following the 2005 post-harvest conservation plowing, we assumed 30% of the accumulated harvested biomass was still present on the surface [<http://www.ncsu.edu/sustainable/tillage/tillage.html>].

Table 1. Crop management details, mulch biomass, and grain yield for the three sites during 2001–2005 (M – maize; S – soybean). Grain yield was adjusted to 0% moisture content.

Site/year	Crop/cultivar	Plant population (plants ha ⁻¹)	Planting date	Harvest date	Mulch biomass (Mg ha ⁻¹)	Grain yield (Mg ha ⁻¹)
Irrigated maize-soybean rotation (IMS)						
2001	M/Pioneer 33P67	82,000	May 10	October 18	0.91	11.41
2002	M/Pioneer 33P67	82,000	May 9	November 4	1.35	10.96
2003	M/Pioneer 33B51	77,000	May 15	October 27	1.60	10.24
2004	M/Pioneer 33B51	79,800	May 3	October 15	1.61	10.34
2005	M/Dekalb 63-75 CRW	70,800	May 4	October 13	0.52	10.16
Irrigated maize-soybean rotation (IMS)						
2001	M/Pioneer 33P67	80,900	May 11	October 22	0.86	11.33
2002	S/Asgrow 2703	333,100	May 20	October 7	0.95	3.47
2003	M/Pioneer 33B51	78,000	May 14	October 23	1.34	11.83
2004	S/Pioneer 93B09	296,100	June 2	October 18	1.02	3.23
2005	M/Pioneer 33B51	81,000	May 2	October 17	1.32	11.19
Rainfed maize-soybean rotation (RMS)						
2001	M/Pioneer 33B51	52,600	May 14	October 29	0.69	7.37
2002	S/Asgrow 2703	304,500	May 20	October 9	0.61	2.89
2003	M/Pioneer 33B51	57,600	May 13	October 13	0.80	6.53
2004	S/Pioneer 93B09	264,700	June 2	October 11	0.60	2.97
2005	M/Pioneer 33G68	56,300	April 26	October 17	0.99	7.69

3. Results and discussion

3.1. Weather conditions and leaf area

During the growing season (May–September), mean monthly air temperatures (Figure 1A) were generally within 1 °C of the 30-year climate normal (measured at a nearby weather station near Mead, NE; 1971–2000 *Climate Normals*; HPRCC, 2006), but typically tended to be warmer. The winter months were generally warmer (1–5 °C) than normal.

Precipitation (290–350 mm) received at the three sites during the growing seasons of 2002, 2003, and 2005 (Table 2; Figure 1B) was significantly below the 450 mm normal (1971–2000 *Climate Normals*; HPRCC, 2006). In 2001 and 2004, the precipitation amounts (about 400–426 mm) were only slightly below normal. Irrigation totals ranged from 230 to 350 mm in maize years and from 185 to 210 mm in soybean years.

Seasonal distributions of green leaf area index (LAI) are presented in Figure 2. The peak LAI of irrigated maize (ICM and IMS) ranged from 4.9 to 6.4 m² m⁻². The peak LAI for rainfed was about 4.3 m² m⁻². For irrigated soybean, the peak LAI was between 4.4 and 5.7 m² m⁻². Rainfed soybean had peak LAI between 3.1 and 4.4 m² m⁻².

3.2. Growing season evapotranspiration

3.2.1. ET totals

Measured evapotranspiration, integrated over the growing season during the 5 years of our study, is given in Figure 3A. For irrigated maize (ICM and IMS), the average growing season ET total was 548 mm (range: 502–586 mm). For rainfed maize, the average growing season ET was 482 mm (range: 449–505 mm). For irrigated and rainfed soybean (2 years of data in each case), the average ET values were 452 mm (range: 430–474 mm) and 431 mm (range: 420–441

Figure 1. (A) Mean monthly air temperatures (measured at the irrigated continuous maize site, ICM) and 30-year climate normals (1971–2000 *Climate Normals*; HPRCC, 2006), (B) growing season precipitation and irrigation at the three sites. ICM = irrigated continuous maize; IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation.

mm), respectively. On average, the maize ET was higher than the soybean ET by 96 mm (18%) for irrigated crops and by 52 mm (11%) for rainfed crops (Figure 3B). The ET from irrigated maize was higher than that of the rainfed maize by 66 mm (12%). The ET for irrigated soybean was higher by 21 mm (5%) as compared to the rainfed soybean. Variability in growing season ET totals is influenced by several atmospheric and biological factors. For example, R_n explained

Table 2. Growing season (GS: planting to harvest) and annual (Ann: planting to planting) totals of net radiation (R_n), evapotranspiration (ET), and combined precipitation and irrigation (Precip + Irrig) for all sites and years. Also included are the values of annual ET as a percentage of Precip + Irrig, annual ET as a percentage of net radiation, and growing season potential evapotranspiration (ET_0). In 2001, values of R_n , ET, and precipitation were estimated during the period between planting and the initiation of measurements using data from a nearby weather station.

Year	Site, crop (M – maize; S – soybean)	R_n		ET			Precip + Irrig		ET as % of R_n Ann (%)	ET as % of Precip + Irrig Ann (%)	ET_0 GS (mm)
		GS (MJ)	Ann (MJ)	GS (mm)	Ann (mm)	Ann (MJ)	GS (mm)	Ann (mm)			
2001–2002	ICM, M	2005	2738	586	714	1714	525	684	63	104	681
2002–2003	ICM, M	2078	2828	565	679	1661	644	840	59	81	777
2003–2004	ICM, M	1948	2532	540	640	1567	558	733	62	87	676
2004–2005	ICM, M	1923	2645	502	618	1514	523	682	57	91	652
2005–2006	ICM, M	1994	2776	526	687	1682	593	813	61	85	791
2001–2002	IMS, M	1996	2899	535	691	1663	597	798	57	87	685
2002–2003	IMS, S	1802	2732	474	638	1561	576	795	57	80	687
2003–2004	IMS, M	2008	3042	578	746	1825	636	934	60	80	675
2004–2005	IMS, S	1548	2287	430	566	1388	443	707	61	80	527
2005–2006	IMS, M	2077	2869	550	690	1689	629	912	59	76	785
2001–2002	RMS, M	1894	2768	505	656	1582	318	512	57	128	686
2002–2003	RMS, S	1725	2576	441	599	1466	373	601	57	100	692
2003–2004	RMS, M	1845	2894	449	621	1520	290	622	53	100	654
2004–2005	RMS, S	1461	2105	420	553	1357	311	575	64	96	511
2005–2006	RMS, M	2014	2741	493	616	1506	364	653	55	94	777

Figure 3. Growing season evapotranspiration (ET): (A) for each year and site, (B) average and range for each crop (irrigated and rainfed), and (C) growing season ET vs. the number of days with $\text{LAI} > 2.5 \text{ m}^2 \text{ m}^{-2}$. ICM = irrigated continuous maize; IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation. In (A), M = maize and S = soybean.

75% of the variability in ET totals of both crops and all years studied. Similarly, leaf area plays an important role (e.g., Suyker and Verma, 2008). About 66% of the variability in the growing season ET total was explained by the number of days when the LAI was greater than $2.5 \text{ m}^2 \text{ m}^{-2}$ (Figure 3C).

These growing season ET totals are generally comparable to results from other studies in the region. For example, from their 2 years of study in central Kansas, Hattendorf et al. (1988) reported the average ET of irrigated and rainfed maize of 568 and 561 mm, respectively. Schneekloth et al. (1991) reported a 3-year average maize ET of 640, 557, and 389 mm

Figure 2. Green leaf area (LAI) at the three sites for (A) maize canopies in 2001 and 2002, (B) maize canopies in 2003 and 2004, (C) maize canopies in 2005, and (D) soybean canopies in 2002 and 2004. ICM = irrigated continuous maize; IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation.

for full, limited, and rainfed conditions in west central Nebraska. For soybean, average growing season ET in the three irrigation regimes was 520, 520, and 426 mm. In northwest Kansas, Lamm et al. (1995) measured a 3-year average maize ET of 586, 542, and 459 mm under full, half and no irrigation. In southwest Kansas, Norwood (1999) measured ET from 395 to 601 mm for rainfed maize in no-till management and 385–505 mm in conventional tillage over four growing seasons. For rainfed soybean, he reported ET ranging from 450 to 470 and from 408 to 476 mm, respectively for the two management practices.

3.2.2. Seasonal distributions of ET/ET_0

Seasonal distributions of daily ET, normalized by the reference evapotranspiration (ET_0 , calculated using the FAO Penman-Monteith equation: Allen et al., 1998), are given in Figure 5 and Figure 6. Normalizing ET by ET_0 is intended to account for the day-to-day variability in atmospheric conditions (also, the seasonal totals of ET_0 are given in Table 2).

Figure 4. Seasonal distributions of crop coefficient $K_c = ET/ET_0$ at the irrigated sites: (A) irrigated maize over 5 years at ICM, (B) irrigated maize for 3 years at IMS, and (C) irrigated soybean over 2 years at IMS. Days with precipitation have been removed. ICM = irrigated continuous maize; IMS = irrigated maize–soybean rotation; RMS = rainfed maize–soybean rotation.

The ET/ET_0 ratio is also commonly referred to as the crop coefficient (K_c ; e.g., Allen et al., 1998). For irrigated maize in both ICM and IMS fields, prior to emergence ($LAI < 0.5$), K_c was 0.27 ± 0.17 (95% confidence interval; Figure 4A and B; Table 3). During this period, evaporation from soil/residue is important and the variability in the magnitude of K_c is primarily affected by surface conditions (e.g., mulch cover, rain, heavy dew). With increasing LAI , K_c increased reaching a mid-season average of 1.03 ± 0.07 (Table 3). By the end of the growing season ($DAP = 135\text{--}140$), K_c was 0.33 ± 0.17 . The seasonal distribution of K_c in the irrigated maize fields appears to be quite consistent among the years. Also, our K_c values are generally within the range of the values recommended in the Food and Agricultural Organization of the United Nations (FAO) report (Table 3; Allen et al., 1998) for our region: 0.3 (initial part of the season), 1.16 ± 0.04 (mid-season, adjusted for climatic conditions at our sites based on their recommendations), and 0.35 (end of season).

The seasonal distribution of K_c in the irrigated soybean was also quite consistent between the two growing seasons

Figure 5. Seasonal distributions of crop coefficient $K_c = ET/ET_0$ in rainfed sites: (A) maize over 3 years at RMS, and (B) soybean for 2 years at RMS. Days with precipitation have been removed. RMS = rainfed maize–soybean rotation.

(Figure 4C) even though the 2004 crop was a different hybrid, was planted later, and had lower LAI (Table 1; Figure 2). Before significant leaf emergence, K_c values were about the same as those in irrigated maize (0.27 ± 0.17). Then, in 2 weeks ($DAP = 41\text{--}55$), K_c increased somewhat rapidly from about 0.3 to 0.9. Further increase in K_c was gradual, reaching a mid-season value of 0.98 ± 0.02 . In comparison to maize, the duration of mid-season plateau in K_c is shorter by about 30 days. With senescence, there was a rapid decrease in K_c over a period of about 3 weeks. At the end of the growing season, K_c was 0.32 ± 0.12 . These results are also generally within range of the values recommended in the FAO report for our region (Allen et al., 1998): 0.4 (initial part of the season), 1.14 ± 0.03 (mid-season, adjusted for climatic conditions at our sites), and 0.5 (end of season).

As expected, there was significantly larger year-to-year variability in the seasonal distributions of K_c for the rainfed crops (Figure 5). In Figure 6, these results are examined against the corresponding values for the irrigated crops in conjunction with the precipitation distributions. Dry-down periods (periods with extended gaps without any significant precipitation: >5 mm/event) occurred during different parts of the season in 2001, 2003, and 2005. Towards the end of dry-down periods (e.g., 70–93 DAP in 2001, 67–97 DAP in 2003, and 54–83 DAP in 2005), K_c tended to decrease below the corresponding value for the irrigated crop. Rise in K_c was observed following a significant rain (>20 mm/event). Average mid-season K_c of rainfed maize was 0.84 ± 0.20 over the 3 years of our measurements (Table 3). In soybean years, there seemed to be sufficient rainfall events throughout the growing season in 2004 and during mid- to late season in 2002. Dry-down early in the 2002 season helped temporarily

lower the rainfed K_c values. Without significant mid-season dry-down in rainfed soybean, mid-season K_c (0.90 ± 0.13 ; Table 3) was only slightly lower than those for irrigated fields (0.98 ± 0.02).

3.3. Non-growing season evaporation

For the non-growing season periods (harvest to subsequent planting), evaporation totals (E) ranged from 100 to 172 mm during the 5 years of our study (Figure 7A). Combining these values with the growing season ET, the average annual ET (from planting to planting) for irrigated maize was 683 mm (668 mm for ICM, 709 mm for IMS). The average annual ET for rainfed maize was 631 mm. For soybean, annual ET averaged 602 and 576 mm for irrigated and rainfed conditions, respectively. The non-growing season E total, as a percentage of annual ET, was 16–28% in irrigated/rainfed maize (16–23% in ICM, 20–23% in IMS, and 20–28% in RMS) and 24–26% in irrigated/rainfed soybean. On an annual basis (Table 2), ET accounted for about 53–64% of annual R_n at our study sites. In terms of the water input, the annual ET was generally 76–91% of precipitation + irrigation at the irrigated sites and about 94–100% of precipitation at the rainfed site.

Since soybeans are generally planted later and harvested earlier than maize, to facilitate a more accurate examination of interannual variability, we integrated evaporation over a common period: 1 November–1 May. The total evaporation over this common period ranged from 94 to 143 mm (Figure 7B). Some features of the non-growing season E become readily apparent (Figure 7B). The maize–soybean rotation had very similar non-growing season E through all 5 years, regardless of irrigation. Also, the non-growing season E in continuous maize during the first 4 years (2001–2002 to 2004–2005) was consistently lower than that from the maize–soybean rotations (average E in ICM was 100 mm compared

to 116 mm in IMS and RMS). In contrast, following the 2005 conservation plowing, the non-growing season E was the highest measured over 5 years (143 mm). The interannual variability in non-growing season E seems reasonable considering the different amounts of mulch left after harvest.

In Figure 8, we examine the non-growing season E/E_{eq} (where E_{eq} is the equilibrium evaporation—e.g., Slatyer and McIlroy, 1961) as a function of mulch biomass left after harvest (Table 1). Here E has been normalized by E_{eq} to help account for the variability in relevant atmospheric conditions. As seen in Figure 8, the amount of surface mulch biomass seemed to explain 71% of the interannual variability in non-growing season E . Considering that these measurements covered a wide range of mulch biomass in both no-till and conservation-plowed maize–soybean systems, results in Figure 8 indicated a dominant role of mulch biomass in controlling non-growing season evaporation.

3.4. Energy partitioning

As noted in an earlier paper (Suyker and Verma, 2008), in irrigated fields, the Bowen ratio (β) was comparable ranging from 0.3 to -0.3 for maize and soybean when the canopy was fully developed (negative values are associated with conditions of sensible heat advection—see Rosenberg et al., 1983 for a discussion of the phenomenon). Here we compare β (midday average from 1200 to 1400 h, local time) for irrigated and rainfed maize during the growing season (Figure 9A). With the onset of a dry period in August, β in the rainfed maize field became larger ranging up to 1.8. Values of β in both fields were large (2.0–4.0) during senescence in September. In the non-growing season (Figure 9B), β varied widely. The value of β was fairly large when the surface was dry and was near zero on cool/cloudy days with wet surface conditions.

Table 3. K_c values and 95% confidence intervals for specified periods of the growing season (ICM = irrigated continuous maize; IMS = irrigated maize–soybean rotation; RMS = rainfed maize–soybean rotation). Integration periods for initial, middle and end of the growing season were related to crop growth stages as recommended by Allen et al. (1998). The mid-season K_c FAO-56 is from the FAO report (Allen et al., 1998) adjusted for climatic conditions and canopy height. Measurements at the RMS began after the initial growth period in 2001, so the initial K_c is missing.

Crop	Site/year	This study			Mid-season K_c FAO-56
		Initial K_c	Mid-season K_c	End K_c	
Irrigated maize	ICM/2001	0.25 ± 0.21	1.09 ± 0.18	0.44 ± 0.36	1.16
	ICM/2002	0.21 ± 0.12	1.00 ± 0.23	0.38 ± 0.03	1.18
	ICM/2003	0.33 ± 0.32	1.06 ± 0.20	0.37 ± 0.30	1.18
	ICM/2004	0.21 ± 0.20	1.04 ± 0.18	0.24 ± 0.15	1.17
	ICM/2005	0.21 ± 0.25	1.01 ± 0.20	0.23 ± 0.32	1.14
	IMS/2001	0.37 ± 0.12	0.98 ± 0.20	0.38 ± 0.26	1.18
	IMS/2003	0.43 ± 0.50	1.04 ± 0.16	0.40 ± 0.39	1.15
	IMS/2005	0.23 ± 0.25	1.00 ± 0.16	0.23 ± 0.15	1.12
Irrigated soybean	IMS/2002	0.22 ± 0.13	0.97 ± 0.25	0.38 ± 0.14	1.13
	IMS/2004	0.34 ± 0.32	0.99 ± 0.29	0.29 ± 0.27	1.15
Rainfed maize	RMS/2001	–	0.89 ± 0.19	0.29 ± 0.12	
	RMS/2003	0.37 ± 0.33	0.71 ± 0.40	0.30 ± 0.13	
	RMS/2005	0.23 ± 0.24	0.90 ± 0.20	0.27 ± 0.19	
Rainfed soybean	RMS/2002	0.22 ± 0.13	0.86 ± 0.37	0.47 ± 0.11	
	RMS/2004	0.34 ± 0.32	0.95 ± 0.41	0.26 ± 0.19

Figure 6. Seasonal distributions of crop coefficient $K_c = ET/ET_0$ and precipitation at the rainfed site (RMS) in (A) 2001, (B) 2003, (C) 2005, (D) 2002, and (E) 2004. The K_c for the corresponding irrigated crop (IMS) is also included for comparison. IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation.

3.5. Water use efficiency (WUE)

Here we present our results using two commonly used definitions of water use efficiency (WUE). First, WUE_{ET} or ET efficiency, defined as the ratio of grain yield (Y) to growing season evapotranspiration (ET), is plotted for all three sites in Figure 10A. For irrigated maize, the average value was $2.00 \pm 0.15 \text{ g kg}^{-1}$ (95% confidence interval) with little interannual variation. In the rainfed maize, average values were about 25% smaller ($1.49 \pm 0.12 \text{ g kg}^{-1}$), but as steady as the irrigated maize. Our results on WUE_{ET} are bracketed by the range of values observed in several studies on maize (generally 1.6 g kg^{-1} in arid regions and 2.7 g kg^{-1} in humid regions: Tanner and Sinclair, 1983). For soybean, our data indicated no significant difference between irrigated and rainfed WUE_{ET} with average values of 0.71 ± 0.03 and $0.68 \pm 0.07 \text{ g kg}^{-1}$, respectively.

Figure 7. Integrated evaporation (E) during the non-growing season periods for each of the 5 years at all three sites during (A) harvest to planting and (B) the common integration period from 1 November to 1 May. ICM = irrigated continuous maize; IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation.

Water use efficiency, WUE_{DM} or biomass transpiration efficiency, is defined as the ratio of total plant biomass (Y_{DM} : above plus below ground) to growing season transpiration (T). Following Amos and Walters (2006), we assumed an 11% root to shoot ratio for maize and 20% for soybean at physiological maturity. We estimated soil evaporation (E) from measured atmospheric and biophysical variables following Ritchie (1972) and Tanner and Jury (1976). The WUE_{DM} values (Figure 10B) show virtually the same average for irrigated and rainfed maize with small interannual variability, 5.20 ± 0.34 and $5.22 \pm 0.36 \text{ g kg}^{-1}$, respectively. For soybean, WUE_{DM} for irrigated and rainfed sites is 3.21 ± 0.35 and $2.96 \pm 0.30 \text{ g kg}^{-1}$, respectively. For these two crops, there was no significant difference between the WUE_{DM} in irrigated and rainfed systems.

Figure 8. Non-growing season evaporation (E : integrated from 1 November to 1 May) normalized by equilibrium evaporation (E_{eq}) as a function of seasonal average surface mulch biomass.

Figure 9. Midday averaged (1200–1400 h, local time) Bowen ratio for irrigated continuous maize (ICM) and rainfed maize soybean (RMS) during (A) the 2003 growing season (maize in both fields) and (B) the 2002 growing season (maize in ICM and soybean in RMS) and the subsequent non-growing season period. Data during precipitation were not included.

4. Summary and conclusions

Evapotranspiration (ET) was measured in three fields of irrigated continuous maize, irrigated maize-soybean rotation, and a rainfed maize-soybean rotation at Mead, NE during 2001–2005. For irrigated and rainfed maize, growing season ET ranged from 502 to 586 and 449 to 505 mm, respectively. For irrigated and rainfed soybean, ET ranged from 430 to 474 and 420 to 441 mm, respectively. The ET for

irrigated maize was higher than rainfed maize by 12% and the ET for irrigated soybean was higher than rainfed soybean by 5%. During the growing season, the crop coefficient (K_c) for irrigated maize was approximately 0.27 ± 0.17 early in the season, 1.03 ± 0.07 during mid-season, and 0.33 ± 0.17 at the end of the season. Similarly, the corresponding K_c for irrigated soybean was 0.27 ± 0.17 , 0.98 ± 0.02 , and 0.32 ± 0.12 , respectively. Annual ET (planting to planting) averaged 683 and 631 mm for irrigated and rainfed maize, respectively. For soybean, average annual ET was 602 and 576 mm for irrigated and rainfed conditions, respectively. Non-growing season evaporation contributed 16–28% of annual ET totals in irrigated and rainfed maize and 24–26% in irrigated and rainfed soybean. Water use efficiency (evapotranspiration efficiency), based on the ratio of yield to growing season ET, was 2.00 g kg^{-1} in irrigated maize and about 25% lower in rainfed maize. The WUE in irrigated and rainfed soybean was comparable (0.71 and 0.68 g kg^{-1} , respectively).

Acknowledgments

The research discussed here was supported by the Office of Science (BER), U.S. Department of Energy Grant no. DE-FG02-03ER63639 and the University of Nebraska-Lincoln Program of Excellence. We gratefully acknowledge the technical assistance of Ed Cunningham, Todd Schimelfenig, Jim Hines, and Mark Schroeder. We thank Dr. Tim Arkebauer and Dave Scoby for providing data on leaf area. We thank Dr. Derrel Martin, Dr. Suat Irmak and Mr. Luis Octavio Lagos for their valuable assistance calculating reference ET.

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Figure 10. Water use efficiency calculated for each site/year defined as (A) the ratio of grain yield to growing season evapotranspiration (WUE_{ET}), and (B) the ratio of total plant biomass to growing season transpiration (WUE_{DM}). ICM = irrigated continuous maize; IMS = irrigated maize-soybean rotation; RMS = rainfed maize-soybean rotation. In (A), M = maize and S = soybean.

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