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Daily energy fluxes, evapotranspiration and crop coefficient of soybean

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ABSTRACT

Evapotranspiration represents the main consumptive use of water in agricultural production and its magnitude is important for irrigation water management. Since water shortages are increasing in many areas, there is a pressing need to improve irrigation water management, for which farmers need reliable information and tools to make better irrigation decisions. There is a lack of knowledge about the water use and irrigation requirements of crops grown in different environments, especially of new crop hybrids. The overall objective of this study was to improve our understanding of the water requirements of soybean. Specific objectives were to: (1) measure and document the daily crop evapotranspiration (ETc) and other energy fluxes, (2) document the daily and seasonal behavior of crop coefficients (Kc), and (3) evaluate the impact of weather variables on alfalfa-reference (ETr) and grass-reference (ETo) evapotranspiration. Here we report results of direct ETc measurements using an eddy covariance system obtained from soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005. We found considerable differences in weather conditions among seasons that affected the accumulation of growing degree days, crop development pattern, crop ETc and Kc. We found that ETr values were on average 32.3% greater than ETo, which is important when choosing Kc values for calculating crop ETc. We also found that vapor pressure deficit (VPD) explained 90 and 92% of the variability in ETo and ETr, respectively. We presented daily measurements of energy fluxes and Kc values and found that measured Kc values were quite variable and often deviated considerably from the average Kc curves given in FAO-56 due to wetting events (rain and irrigation) and crop stress. Therefore, we recommend using the dual Kc method, rather than the single Kc method, for irrigation scheduling. In addition, we found considerable differences in crop maturity among years and suggested that acceleration in maturity could be due to crop stress, especially during the reproductive period. We raised the need for accurate methods to quantify the effect of stress on crop maturity and its impact on Kc.

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1. Introduction

Evapotranspiration is an important component of the hydrologic cycle, which affects the water balance of all vegetated and non-vegetated landscapes. For vegetated landscapes, crop evapotranspiration (ETc) represents the major consumptive use of water. For commercial cropping systems, ETc needs to be met by rainfall, in rainfed production systems, or by a combination of rainfall and irrigation, in irrigated production systems. Shortages of irrigation water are becoming common in many regions of the world, especially in arid and semi-arid regions due to factors like drought, more restrictive laws regulating the use of water in agricultural production and increased competition for water resources with non-agricultural uses, such us domestic, industry, and the environment. Because of these shortages, there is a pressing need to find new ways to conserve and use water more efficiently. Meeting crop ETc with irrigation also can be an expensive and energy-intensive operation, especially when water is pumped from deep wells. Knowing the daily ETc requirements of crops can be used to help producers decide when to apply irrigation and how much water to apply to increase crop yields and farm profits while reducing costs, energy use, and negative environmental impacts.

Accurate ETc information not only aids in irrigation water management, but since the flux of water vapor by crop transpiration and the flux of CO_2 needed for photosynthesis both take place thought leaf stomata, crop ETc is usually well correlated to crop biomass and yield production, which can be used to estimate crop yield if ETc is known (Hanks, 1974; Payero et al., 2005a, 2006a; Raes et al., 2009; Steduto et al., 2007, 2009). Estimating crop yield for crops subjected to different levels of water stress is important for

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making irrigation scheduling decisions in real time, for comparing alternative irrigation management options, and for evaluating the economic impact of alternative cropping systems under a variety of growing environments, including the potential impact of future climate change scenarios (Cammarano et al., 2012; Power et al., 2008, 2009, 2011).

There are several methods to directly measure the daily ET of crops and other land surfaces, such as lysimeters (Allen and Fisher, 1990; Howell et al., 1995; Payero and Irmak, 2008; Pruitt and Angus, 1960; Yang et al., 2003), Bowen ratio (Payero et al., 2003; Perez et al., 1999; Tanner et al., 1987; Todd et al., 2000; Tomlinson, 1996), eddy covariance (Billesbach, 2011; Burba and Anderson, 2007; Goltz et al., 1969), surface renewal (Anandakumar, 1999; Castellvi et al., 2006; Paw et al., 1995), remote sensing (Li et al., 2008; Samani et al., 2009; Tasumi et al., 2003), scintillometers (Allen et al., 2011; Anandakumar, 1999; Kite and Droogers, 2001), and closed chambers (Scott et al., 1999; Steduto et al., 2002). But, these methods are usually limited to research applications since they require a high level of expertise and specialized equipment that is usually expensive and difficult to install and operate. Also, some of these methods require large fetch areas, which can be a limitation even at some research sites. Therefore, most potential end users of ETc information, like farmers, have no practical means of directly measuring crop ETc.

There has been considerable research effort trying to develop accurate procedures to estimate ETc from weather data (Allen et al., 1998; Doorenbos and Pruitt, 1977) and to integrate this knowledge into empirical and mechanistic crop simulation models (Evett et al., 1995; Jones and Kiniry, 1986; Keating et al., 2003) and irrigation management tools (Chauhan et al., 2013; Evett and Lascano, 1993; Payero et al., 2011; Power et al., 2011; Rosa et al., 2012a,b). These models and tools need to be validated with field data, which is challenging because accurate field measurements of ETc are scarce and crop hybrids change rapidly, creating the need to collect more field data. For example, for the application of the FAO-56 methodology to estimate ETc (Allen et al., 1998), we rely on crop coefficient values that were derived primarily from field measurements recorded decades ago. Since then, the hybrids of major field crops like soybean, cotton, and maize have changed from conventional hybrids to genetically modified (GM) hybrids and there is some evidence that these new GM hybrids behave differently to water inputs and water stress compared to conventional hybrids (Yeates et al., 2006, 2009).

The overall objective of this study was to improve our understanding of the water requirements of soybean. Specific objectives were to: (1) measure and document the daily crop evapotranspiration (ETc) and other energy fluxes, (2) document the daily and seasonal behavior of crop coefficients (Kc), and (3) evaluate the impact of weather variables on alfalfa-reference (ETr) and grass-reference (ETo) evapotranspiration.

2. Methods

2.1. Site description and crop management

Field data for this study were collected from two soybean fields located at the University of Nebraska-Lincoln West Central Research and Extension Center, North Platte, Nebraska (41.1° N, 100.8° W, 861 m above mean sea level). Data were collected during 2002, 2003, and 2005 from fields that were under a ridge-tilled maize-soybean rotation and had a Cozad silt loam soil (*Fluventic Haplustolls*). In 2002, measurements were made in a 9.2 ha field (296 m × 311 m). In 2003 and 2005, measurements were made in an adjacent 11.5 ha field (265 m × 433 m) with similar soil and crop management practices. Surface irrigation with gated pipes was used in 2002 and 2003, and a lateral (linear)-move sprinkler irrigation system was used in 2005. Groundwater pumped from a deep well was used for irrigation. Since the fields were dedicated to commercial production, the farm manager made all crop management decisions, aiming at maximizing profits following local management guidelines and "*rules of thumb*." Each year, the crop was planted at 0.76-m row spacing and at a depth of approximately 2.5 cm with an east-west planting direction. Genetically modified roundup ready (RR) hybrids were planted each year. The hybrids were selected mainly for their high yield potential based on performance in local yield trials. In west central Nebraska soybean is usually planted in mid to late May and harvested in October. The hybrids, planting and harvest dates are shown in Table 1.

Table 1
Soybean hybrids, planting and harvest dates during 2002, 2003, and 2005 at North Platte, Nebraska.

Year	Hybrid	Planting date	Harvest date
2002	Asgrow AG2602 (RR)	25 May	20 October
2003	Renze 2600 (RR)	21 May	7 October
2005	LG Seeds C2820 (RR)	20 May	3 October

RR: roundup ready.

2.2. Field measurements

Each year, the energy fluxes and basic meteorological variables were measured using an eddy covariance system (ECS) (Campbell Scientific, Inc., Logan, Utah) installed on a tower at the center of the soybean field, which provided more than 130 m of fetch in all directions. At the study site, the predominant wind direction was from north-west to south-east. In 2002, measurements were made from January to October. In 2003, because of equipment problems measurements were made from 66 to 86 days after planting (DAP) and from 113 DAP until the end of the year. In 2005, measurements were made from May through October. This paper focuses on the data collected during the soybean growing season. The ECS was installed so that the sensors (except for those buried in the soil) were at least 1 m above the crop canopy. Sensors used in the study and the variables measured are listed in Table 2.

Data from the sensors were sampled, processed and stored in a SM16M data storage module using a CR23X datalogger that was housed in an environmental enclosure (Campbell Scientific, Inc., Logan, Utah). A deep-cycle marine battery (12 V, 75 A), recharged by a solar panel, was used to power the ECS. The data sampling frequency was 10 Hz (10 times a second) for the CSAT3, FW05, and KH20 sensors, and once per minute for all other sensors. Data were stored as 30-min averages and daily averages were calculated during post-processing.

The 30-min averages included solar radiation (R_s), net radiation (R_n), latent heat flux (LE), and sensible heat flux (H) (all in units of W m^{-2}). Soil heat flux (G) was calculated from the output of two HFT3 soil heat flux plates, one TCAV soil temperature sensor (which included four soil thermocouples), and one CS615 water content reflectometer (Campbell Scientific, Inc., Logan, Utah). The soil heat flux plates were installed at a depth of 0.08 m below the soil surface, 1 m apart. Two soil thermocouples were installed about 0.01 m to one side of each soil heat flux plate at depths of 0.02 and 0.06 m below the soil surface. The CS615 sensor was installed horizontally midway between the two soil heat flux plates at a depth of 0.025 m. Soil heat flux was calculated by combining the energy flux measured by the soil heat flux plates and the change in heat stored above the plates (Hanks and Ashcroft, 1980; Payero et al., 2005b).

The site was visited at least once a week and data were downloaded from the datalogger to a laptop for further processing. During each visit, sensors were inspected and maintained, and

Table 2
Sensors and variables measured at North Platte, Nebraska, during 2001.

Sensor model	Sensor type	Manufacturer	Variable measured
LI200X	Silicon Pyranometer	Licor, Inc., Lincoln, Nebraska	Solar radiation
Q7.1	Net Radiometer	Radiation and Energy Balance Systems, Inc., Bellevue, Washington	Net radiation
CS500	Temperature/RH sensor	Campbell Scientific, Inc., Logan, Utah	Air temperature/relative humidity
CSAT3	3-D sonic anemometer	Campbell Scientific, Inc., Logan, Utah	3-D wind speed/temperature, sensible heat
FW05	Fine-wire thermocouple	Campbell Scientific, Inc. Logan, Utah	Air temperature, sensible heat
KH20	Krypton Hygrometer	Campbell Scientific, Inc., Logan, Utah	Absolute air humidity, latent heat
CS615	Water content reflectometer	Campbell Scientific, Inc. Logan, Utah	Volumetric soil water content
HFT3	Soil heat flux plate	Radiation and Energy Balance Systems, Inc., Bellevue, Washington	Soil heat flux
TCAV	Soil thermocouple	Campbell Scientific, Inc., Logan, Utah	Soil temperature
03001	3-cup anemometer/wind vane	RM Young Co., Traverse City, Michigan	Horizontal wind speed and direction

the height of the crop canopy was measured (in 2002 and 2005). For each day, the 30-min energy fluxes were plotted and visually inspected to detect inconsistent data. One of the widely recognized problems of eddy covariance measurements is the presence of errors in energy balance closure. For example, Wilson et al. (2002) found an average closure error in eddy covariance measurements at 22 sites (50 site-years) around the world of around 20%. Twine et al. (2000) also found closure errors in the energy balance budget over grassland of 10–30% and indicated that one way of correcting eddy covariance LE data when closure was a problem (referred to as the "*residual-LE closure*") was to assume that H was accurately measured and solve for LE as a residual to the energy balance equation. We adopted this method in this study.

2.3. Computations of reference ET, ETc, and Kc

For comparison of alfalfa-reference and grass-reference evapotranspiration data and for establishing local weather patterns, we obtained long-term daily weather records from an electronic weather station located at the research site, which was part of the High Plains Regional Climate Center (HPRCC) weather network (http://www.hprcc.unl.edu). Data included maximum (T_{max}) and minimum (T_{min}) air temperature, relative humidity (RH), wind speed (measured at 3-m height), solar radiation, rainfall, and alfalfa-reference ET (*ET_N*). The HPRCC calculated *ET_N* using an equation developed by Kincaid and Heermann (1974) by modifying the Penman (1948) equation with an empirical wind function (Irmak et al., 2008a). In addition to obtaining *ET_N*, we calculated grass and alfalfa-reference ET using the standardized version (ASCE-EWRI, 2005) of the FAO-56 Penman–Monteith equation (Allen et al., 1998) for daily timesteps as:

$$\mathrm{ET_{ref}} = \frac{0.408\Delta(R_n - G) + \gamma(C_n/(T+273))U_2(e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)} \quad (1)$$

where Reference $\mathrm{ET_{ref}}$, grass-reference ET (ETo) or alfalfa-reference ET (ETr) (mm d^{-1}); Δ, slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}); R_n, calculated net radiation at the crop surface (MJ m^{-2} d^{-1}); G, heat flux at the soil surface (MJ m^{-2} d^{-1}); T, mean daily air temperature at 1.5–2.5 m height (°C); U_2, mean daily wind speed at 2 m height (m s^{-1}); e_s, saturation vapor pressure (kPa); e_a, actual vapor pressure (kPa); $e_s - e_a$, vapor pressure deficit (kPa); γ, psychrometric constant (kPa °C^{-1}); C_n, numerator constant (°C mm s^3 Mg^{-1} d^{-1}); C_d, denominator constant (s m^{-1}); 0.408, coefficient having units of m^2 mm MJ^{-1}. Parameters for grass and alfalfa for daily time steps are shown in Table 3.

Table 3
Parameters for daily time step calculation.

Parameter	Grass-reference	Alfalfa-reference
C_n	900 °C mm s^3 Mg^{-1} d^{-1}	1600 °C mm s^3 Mg^{-1} d^{-1}
C_d	0.34 s m^{-1}	0.38 s m^{-1}
Canopy height	0.12 m	0.50 m
Surface resistance (r_s)	70 s m^{-1}	70 s m^{-1}

Daily values for R_n, e_s, and e_a were calculated using equations (albedo, α = 0.23) given in FAO-56 and ASCE-EWRI (2005). Measured RH, T_{max}, and T_{min} values were used to calculate e_a and e_s for daily time steps. The Stefan–Boltzmann constant (σ) for the calculation of net outgoing longwave radiation (R_{nl}) was taken as 4.901×10^{-9} MJ K^{-4} m^{-2} d^{-1}. A value of 1.013×10^{-3} MJ kg^{-1} °C^{-1} that represents an average value of specific heat (c_p) at constant temperature was used in the calculations. The latent heat of vaporization (λ) was taken as 2.45 MJ kg^{-1} following FAO-56 and ASCE-EWRI (2005). This λ value was also used to convert the energy fluxes (R_s, R_n, LE, H, and G) measured with the eddy covariance system to daily water depths (mm d^{-1}). Therefore, the measured LE values when expressed as water depths are equivalent to crop evapotranspiration (ETc).

The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, c_p, and the ratio of molecular weight of water vapor to dry air (ε = 0.622). Atmospheric pressure (P) was calculated as a function of station elevation above sea level (z) [using Eq. 7 in FAO-56]. Daily soil heat flux (G) was assumed to be zero. Since wind speed was measured at a height of 3 m, it was converted to the standard 2-m height using Eq. 47 in FAO-56 (Allen et al., 1998).

Daily Kc values were derived from the measured ETc (derived from LE) and the calculated ETo as Kc = ETc/ETo. The derived daily Kc values were compared to the average Kc and basal (Kcb) curves for soybean given in FAO-56 for Central USA. The FAO-56 Kc and Kcb curves for each year was developed from values shown in Table 4. The time scale for the Kc and Kcb curves given in FAO-56 was also transformed from "days" to more meaningful cumulative growing

Table 4
Average grass-reference crop coefficients (Kc), basal crop coefficient (Kcb) and lengths of crop development stages (LS) for soybean given in FAO-56.

Growth stage	Definition	LS (days)[a]	Kc	Kcb
Initial	Planting to 10% ground cover	20	0.50	0.15
Crop development	10% ground cover to effective full cover	30/35	–	
Mid-season	Effective full cover to start of maturity	60	1.15	1.10
Late season	Start of maturity to harvest or full senescence	25	0.50	0.30
Total		140		

[a] LS, Kc, and Kcb values were taken from Tables 11, 12, and 17 in FAO-56, respectively. LS are values for Central USA.

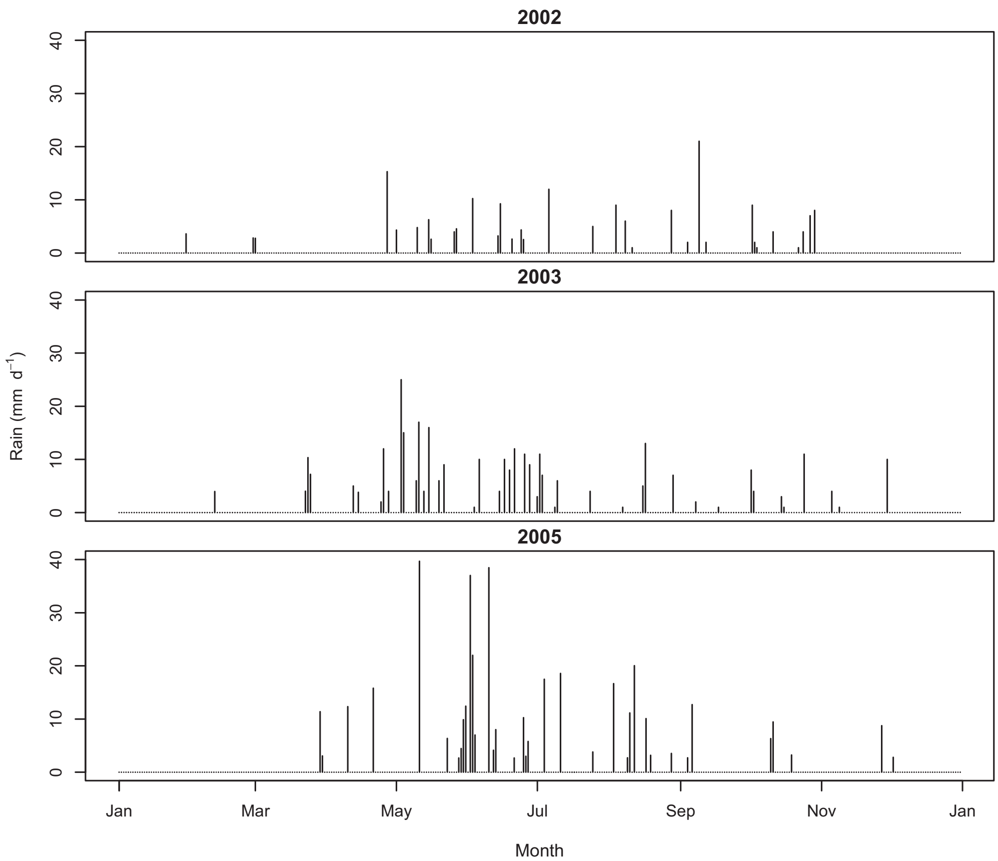


Fig. 1. Daily rain at North Platte, Nebraska, during 2002, 2003, and 2005.

degree days after emergence (CGDDe) based on observations of crop development stages during each year. Daily growing degree days (GDD) were calculated using lower and upper limits of 10 °C and 30 °C, respectively.

3. Results

3.1. Weather conditions

Average monthly weather conditions during the study years (2002, 2003, and 2005) and the long-term averages for the period of 1982–2006 for North Platte are shown in Table 5. At North Platte, precipitation is, on average, much lower than alfalfa-reference ET (*ET_N*). For the 1982–2006 period, precipitation averaged only 28% and 31% of *ET_N*, for the entire year and for the growing season (May–September), respectively. During the study, all years received less than normal precipitation (normal = 1982–2006 average). Year 2002 was especially dry, receiving less than half (44%) the normal precipitation. It was the driest year at North Platte since 1983, with precipitation accounting for only 11% of *ET_N*. Year 2003 received 75% and 63% of normal precipitation for the entire year and the growing season, respectively. Year 2005 was close to normal, receiving 97% of normal precipitation for the year. However, the 2005 growing season was wetter than normal, with 113% of normal rainfall from May to September. In addition to receiving much less precipitation than normal, year 2002 had the highest *ET_N* for both the entire year and for the growing season as compared with the long-term average and compared to 2003 and 2005. Year 2002 was unusually warm in June, with average air temperature of 3.8 °C above normal, 4.9 °C above 2003 and 3.2 °C above 2005. July is normally the month with the highest monthly *ET_N* at North Platte, but in 2002 the greatest *ET_N* occurred in June.

Fig. 1 shows the timing and magnitude of daily rainfall events during the three years of the experiment. Rainfall events during the 2005 soybean growing season were more frequent and of larger magnitude than during the other two seasons, with considerable rainfall occurring early in the growing season. Fig. 2 shows the impact of wetting events (rain and irrigation) on the daily surface soil water content.

Fig. 3 shows CGDDe (in units of °C day, McMaster and Wilhelm, 1997) as a function of days after emergence (DAE) for the 2002, 2003, and 2005 growing seasons, which followed third degree polynomial functions. Both 2002 and 2005 followed a similar pattern, while the 2002 season had a distinct pattern due to the warmer conditions, especially in June, as previously noted. Using Fig. 3 and the LS values in Table 4 we calculated the DAP, DAE, DOY, and the CGDDe needed to reach each development stage for each of the years of the study (Table 6). The difference in CGDDe between the years, with respect to 2002 was as high as 129 °C day by the start of the mid-season in 2003. This means that the crop should have developed faster and should have matured sooner in 2002, compared with 2003 and 2005. However, although not evaluated in this study, it is also known that in addition to temperature, soybean development (especially flowering) is very sensitive to photoperiod (Wang et al., 1998), which may help explain our findings.

3.2. Crop development

In 2002, the crop emerged on 30 May, started blooming on 16 July, and started maturing by 13 September. By 30 September, about 80% of the leaves had already dropped due to senescence.

Table 5
Average weather conditions for each month during the study period (2002, 2003, 2005), and long-term (1982–2006) average at North Platte, Nebraska. The growing season data represent values from May to September.

Year	Month	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	SoilT (°C)	RH (%)	u (m s^{-1})	R_s (MJ/m^2/d)	R_s (mm d^{-1})	Prec (mm d^{-1})	ET_NE (mm d^{-1})	Prec(mm)	ET_NE (mm)	Prec/ET_NE
2002	Jan	7.58	−9.30	−0.86	−1.19	50.25	2.03	7.46	3.05	0.12	2.04	3.61	63.25	0.06
	Feb	10.90	−8.88	1.01	0.57	42.68	2.55	11.62	4.74	0.10	3.15	2.82	88.09	0.03
	Mar	7.56	−8.39	−0.41	2.21	58.06	3.23	14.47	5.91	0.09	3.21	2.77	99.57	0.03
	Apr	18.44	1.31	9.87	11.72	49.18	3.54	18.64	7.61	0.51	5.95	15.29	178.61	0.09
	May	21.76	6.29	14.02	15.68	54.83	3.56	21.82	8.91	0.85	6.56	26.49	203.38	0.13
	Jun	32.29	15.91	24.10	24.07	49.31	3.72	24.95	10.18	1.07	9.10	32.21	273.02	0.12
	Jul	33.94	17.96	25.95	27.78	50.14	3.15	25.65	10.47	0.55	8.80	16.99	272.67	0.06
	Aug	30.91	15.15	23.03	25.25	58.38	3.17	20.87	8.52	0.77	7.36	23.98	228.22	0.11
	Sep	25.70	9.43	17.57	19.54	59.27	3.07	16.82	6.86	0.83	5.77	25.02	173.00	0.14
	Oct	12.61	0.02	6.32	9.90	75.30	2.64	10.10	4.12	1.16	2.30	35.97	71.20	0.51
	Nov	11.95	−4.31	3.82	4.46	62.21	1.84	8.88	3.63	0.00	1.88	0.00	56.54	0.00
	Dec	8.98	−8.45	0.26	0.62	58.35	1.61	7.13	2.91	0.00	1.53	0.00	47.35	0.00
2002 Total		18.58	2.28	10.43	11.77	55.78	2.84	15.72	6.42	0.50	4.80	**185**	**1755**	0.11
Growing season		28.92	12.95	20.93	22.46	54.39	3.33	22.02	8.99	0.82	7.52	**125**	**1150**	0.11
2003	Jan	6.71	−9.81	−1.55	−0.28	65.47	2.06	7.15	2.92	0.00	1.47	0.00	45.57	0.00
	Feb	3.99	−10.15	−3.08	0.50	72.20	2.47	11.07	4.52	0.14	1.55	3.96	43.38	0.09
	Mar	13.79	−3.76	5.01	4.57	60.56	3.19	14.18	5.79	0.69	3.64	21.54	112.88	0.19
	Apr	17.30	2.93	10.11	10.31	66.01	3.39	15.80	6.45	2.99	4.54	89.79	136.25	0.66
	May	21.69	7.70	14.70	16.68	69.52	2.86	21.55	8.80	1.48	5.22	45.97	161.90	0.28
	Jun	26.53	11.95	19.24	21.61	71.53	2.53	22.72	9.27	2.73	5.78	81.97	173.33	0.47
	Jul	33.61	16.33	24.97	28.70	59.29	2.76	24.20	9.88	0.74	7.78	22.99	241.33	0.10
	Aug	31.88	15.68	23.78	27.53	59.06	2.72	22.37	9.13	0.32	7.20	10.01	223.11	0.04
	Sep	25.36	6.53	15.95	19.54	55.47	2.57	18.79	7.67	0.90	5.69	26.97	170.64	0.16
	Oct	22.33	2.76	12.54	13.19	55.36	2.65	13.64	5.57	0.16	4.43	4.98	137.39	0.04
	Nov	9.29	−5.13	2.08	3.08	64.11	2.45	8.00	3.26	0.33	1.87	10.01	56.16	0.18
	Dec	7.09	0.23	3.66	2.18	34.24	2.69	5.12	2.09	0.00	0.09	0.00	2.69	0.00
2003 Total		19.41	3.28	11.35	13.30	63.33	2.70	16.33	6.66	0.88	4.11	**318**	**1505**	0.21
Growing season		27.82	11.64	19.73	22.81	62.97	2.69	21.93	8.95	1.24	6.33	**188**	**970**	0.21
2005	Jan	1.35	−10.14	−4.39	−0.27	79.16	2.92	6.29	2.57	0.00	1.10	0.00	33.96	0.00
	Feb	9.52	−5.91	1.81	1.85	62.65	2.53	9.93	4.05	0.00	2.34	0.00	65.51	0.00
	Mar	12.52	−3.69	4.42	5.56	56.70	3.17	12.69	5.18	0.47	3.59	14.45	111.38	0.13
	Apr	16.41	1.73	9.07	11.59	63.47	4.30	16.32	6.66	0.94	4.59	28.14	137.67	0.20
	May	22.31	6.30	14.31	17.62	61.85	3.77	21.01	8.58	2.43	6.32	75.41	195.94	0.38
	Jun	27.56	14.25	20.90	23.04	69.48	3.48	22.48	9.18	4.61	6.63	138.28	198.98	0.69
	Jul	32.79	16.27	24.53	27.90	56.67	3.47	24.46	9.98	1.29	9.11	39.88	282.42	0.14
	Aug	29.84	15.23	22.53	25.33	68.29	2.75	19.81	8.08	2.17	5.93	67.31	183.97	0.37
	Sep	28.49	11.14	19.81	22.59	59.36	3.48	17.47	7.13	0.51	6.49	15.39	194.69	0.08
	Oct	19.15	1.82	10.49	12.82	63.18	2.87	12.19	4.97	0.61	3.65	19.02	113.26	0.17
	Nov	13.87	−3.97	4.95	6.11	57.03	3.51	8.16	3.33	0.29	2.96	8.74	88.90	0.10
	Dec	3.68	−9.51	−2.91	−0.66	71.28	2.69	6.52	2.66	0.09	1.32	2.79	40.92	0.07
2005 Total		18.24	2.91	10.57	12.93	64.08	3.25	14.85	6.06	1.12	4.50	**409**	**1648**	0.25
Growing season		28.20	12.64	20.42	23.30	63.13	3.39	21.05	8.59	2.20	6.90	**336**	**1056**	0.33

Table 5 (*Continued*)

Year	Month	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	SoilT (°C)	RH (%)	u (m s^{-1})	R_s (MJ/m^2/d)	R_s (mm d^{-1})	Prec (mm d^{-1})	ET_NE (mm d^{-1})	Prec(mm)	ET_NE (mm)	Prec/ET_NE
1982–2006	Jan	4.30	−10.01	−2.85	−1.25	68.93	2.45	7.73	3.16	0.18	1.39	5.71	43.11	0.13
	Feb	6.65	−8.15	−0.75	0.01	66.16	2.72	10.65	4.35	0.29	2.09	8.17	58.60	0.14
	Mar	11.23	−4.09	3.57	3.67	61.67	3.33	14.30	5.84	0.51	3.48	15.69	108.03	0.15
	Apr	16.73	1.00	8.87	9.41	57.67	3.61	18.18	7.42	1.57	5.16	47.09	154.94	0.30
	May	22.25	7.34	14.79	15.72	63.72	3.42	20.81	8.49	2.20	5.90	68.28	182.89	0.37
	Jun	27.94	12.68	20.31	21.06	64.86	3.16	23.72	9.68	2.68	7.00	80.51	209.93	0.38
	Jul	31.19	15.55	23.37	24.58	64.99	2.93	23.81	9.72	1.82	7.28	56.35	225.77	0.25
	Aug	30.04	14.47	22.25	23.42	67.40	2.74	20.59	8.41	1.75	6.24	54.13	193.51	0.28
	Sep	25.14	8.40	16.77	17.71	62.97	2.87	16.43	6.71	1.29	5.19	38.71	155.71	0.25
	Oct	18.21	1.42	9.81	10.10	63.24	2.63	11.76	4.80	1.00	3.34	30.98	103.56	0.30
	Nov	9.96	−5.08	2.44	3.45	66.34	2.58	7.91	3.23	0.38	1.92	11.29	57.61	0.20
	Dec	4.72	−9.71	−2.50	−0.64	67.40	2.35	6.74	2.75	0.20	1.30	6.09	40.31	0.15
1982–2006 Total		17.46	2.08	9.77	10.70	64.61	2.90	15.27	6.23	1.16	4.21	**423**	**1534**	0.28
Growing season		27.31	11.69	19.50	20.50	64.79	3.03	21.07	8.60	1.95	6.32	**298**	**968**	0.31

T_{max}, T_{min}, and T_{mean}: maximum, minimum and mean air temperatures; SoilT: soil temperature at 10-cm depth; RH: relative humidity; u: wind speed, R_s: solar radiation; Prec: monthly precipitation; ET_NE: monthly alfalfa-reference evapotranspiration obtained from the High Plains Regional Climate Center. Numbers in bold are yearly totals, while all others are averages.

In 2005, the crop emerged on May 26 and started blooming on 18 July. By 14 September, about 90% of leaves were yellow and were starting to drop. No detailed records of crop development were kept during the 2003 season.

The plant canopy height as a function of DAE and CGDDe are presented in Fig. 4. In 2002 and 2005, the crop grew following approximately the same rates, when data are presented as a function of DAE. However, a different growth pattern was exhibited early in the season when canopy height was plotted against CGDDe, which could be due to the differences in the CGDDe pattern between the two seasons (Fig. 3). It is noticeable that in 2005 the crop grew very slowly during the period of about 40–50 DAE.

At full canopy cover, however, the maximum canopy height was similar during both seasons. During 2002, soybean canopy height increased at two distinct growth rates. The first growth rate period occurred from emergence to about 50 DAE. During this period, the canopy height increased linearly (R^2 = 0.99) at an average rate of 0.78 cm d^{-1}. From 50 to 80 DAE, the canopy also grew linearly (R^2 = 0.99) at an average rate of 1.32 cm d^{-1}. On average, from emergence to full canopy height, which occurred at about 80 DAE, the crop grew at an average rate of 0.94 cm d^{-1}, assuming a linear increase (R^2 = 0.97).

3.3. Relationship between ETo and ETr

Since ETc is commonly calculated using either ETo or ETr, it is important to understand how values for the two reference surfaces relate to each other. The relationship between daily ETo and ETr at North Platte is shown in Fig. 5. Daily ETo and ETr at this site were linearly related (R^2 = 0.98), although a second-degree polynomial provided a better fit for very high ETo values (e.g., ETo > 8 mm d^{-1}). However, the slope of the line (1.323), which deviates from the 1:1 line, indicates that ETr values were on average 32.3% greater than ETo. These results have important implications when choosing Kc values to be used with either ETo or ETr. Practitioners need to make sure that Kc values properly match the reference surface for which they were originally derived.

Despite the strong linear relationship between ETo and ETr, the relationship still had some scatter. We further explored the nature and reasons for the scatter. A plot of the daily ETr/ETo ratio with time for the period of 2001–2005 (Fig. 6) reveals considerable seasonal variations of this ratio, ranging in magnitude between approximately 1.1 and 1.7. The slope of the line in Fig. 5 represents an average value of ETr/ETo = 1.323. However, the temporal behavior of the ETr/ETo ratio followed a sine wave pattern, reaching its minimum during the middle of the summer and its maximum during the middle of winter. This pattern is very similar to the yearly variation of albedo (α) for full-cover alfalfa, which can be calculated from day of the year (DOY) as (Wright, 1982):

$$\alpha = 0.29 + 0.06 \sin \left[\frac{\text{DOY} + 96}{57.3} \right] \quad (2)$$

Although with some scatter, the daily ETr/ETo ratio at North Platte during the period of 2001–2005 followed a similar sine wave function as (Fig. 6):

$$\frac{\text{ETr}}{\text{ETo}} = 1.35 + 0.20 \sin \left[\frac{\text{DOY} + 96}{57.3} \right] \quad (3)$$

These results suggest that the observed behavior of the ETr/ETo ratio could be due to the use of a fixed albedo for alfalfa, instead of using the variable values suggested by Wright (1982). In fact, the value for albedo has seasonal and diurnal variations since it is a function of solar altitude angle (zenith angle), and is different for grass and alfalfa (Payero et al., 2006b). The differences between the calculated ETr and ETo and the temporal variations of ETr/ETo then result from the weight given to the aerodynamic component

Table 6
Days after planting (DAP), days after emergence (DAE), day of the year (DOY), cumulative growing degree days after emergence (CGDDe, °C day) for soybean, observed at North Platte, Nebraska, during 2002, 2003, and 2005.

Growth stage	DAP	DAE	DOY			CGDDe			Difference CGDDe[a]	
			2002	2003	2005	2002	2003	2005	2003	2005
Start "Initial stage"	1		145	141	140	0	0	0	0	0
Start "Crop development"	20	16	164	160	159	173	121	104	−52	−69
Start "Mid-season"	55	51	199	195	194	646	517	520	−129	−126
End "Mid-season"	115	111	259	255	254	1366	1251	1246	−115	−120
Late season	140	136	284	280	279	1495	1418	1446	−77	−49

[a] Difference in CGDDe with respect to 2002.

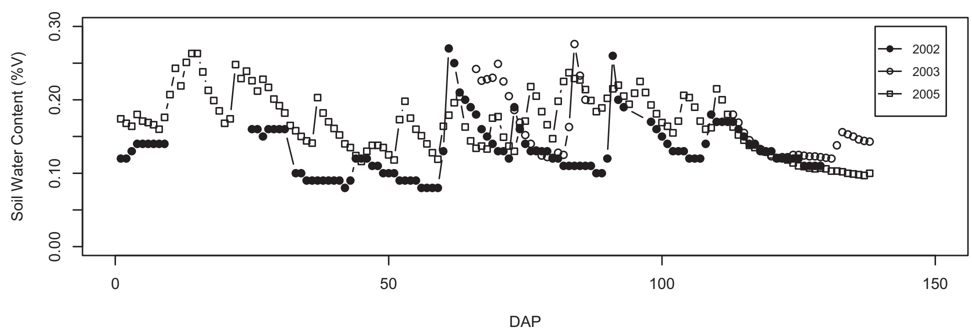


Fig. 2. Surface soil water content as a function of days after planting (DAP) measured at North Platte, Nebraska during 2002, 2003, and 2005.

with respect to the radiation component in Eq. (4), which is mainly determined by the "C_n" multiplier. This multiplier is much larger for alfalfa as compared with grass (Table 3).

The magnitude of ETr is always larger than ETo because the taller alfalfa reference crop (assumed to be 0.5 m tall) has a higher roughness, creating more turbulence and therefore, a lower aerodynamic resistance as compared with a shorter reference grass surface (assumed to be 0.12 m tall). The lower aerodynamic resistance of alfalfa then translates into a higher ETr compared with ETo. During the winter, ETr/ETo increases because the magnitude of the radiation component is low with respect to the aerodynamic component. The opposite occurs during the summer, when the magnitude of the radiation component increases and becomes larger relative to the aerodynamic component. Because of the different weight given to the aerodynamic component when calculating ETr or ETo, it is expected that the relationship between ETr and ETo would vary with location, which could have implications when transferring Kc values derived in one environment to other locations with significantly different environmental conditions.

Irmak et al. (2008b) reported that the ETr/ETo ratios determined by the same and different ETo or ETr methods exhibited substantial variations among locations. In general, variations in ETr/ETo ratios were less for the growing season than for the calendar year. Average standard deviation in ETr/ETo ratios between years reached a maximum of 0.13 for the calendar year and 0.10 for the growing season. They also reported that some of the methods for calculating ETo and ETr, including the ASCE-PM method, produced potentially unrealistically high ETr/ETo ratios (e.g., 1.78, 1.80) during the non-growing season. They speculated that these high values could be due to instabilities and uncertainties in estimating ETr and ETo during the dormant season since the theoretical reference conditions were usually not met during this period in most locations.

3.4. Effect of weather variables on ETo, ETr, and ETo/ETr

Table 7 shows correlation matrixes between daily weather variables and the calculated ETo, ETr, and ETr/ETo during the period 2001–2005 at North Platte, during the soybean growing season (May–September). ETo and ETr were highly correlated with mean air temperature (T_a), relative humidity (RH), vapor pressure deficit (VPD), solar radiation (R_s), and net radiation (R_n). The highest correlation, however, was with VPD, which integrated the effect of both, T_a and RH and explained 90 and 92% of the variability of ETo and ETr, respectively. Wind speed (U_2) had low correlation with ETo and ETr. For the growing season, ETr/ETo was best correlated with U_2, RH, and VPD.

3.5. Measured energy fluxes, ETo and Kc

Measured daily energy fluxes and the calculated ETo, expressed in units of water depth (mm), for 2002, 2003, and 2005, are shown in Figs. 7 and 8. As expected, all variables showed high variability for day to day mainly due to changes in weather conditions, canopy cover, and available soil water. The R_n energy reaching

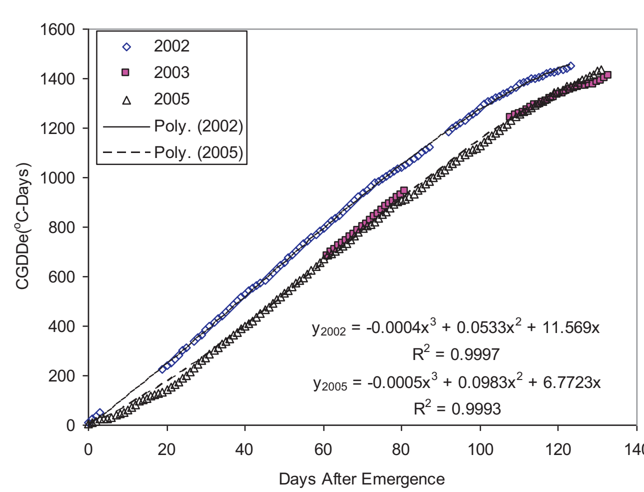


Fig. 3. Cumulative growing degree days from emergence (CGDDe) as a function of days after emergence for soybean, measured at North Platte, Nebraska, during 2002, 2003, and 2005 growing seasons. Daily growing degree days were calculated using lower and upper limits of 10 °C and 30 °C, respectively. Plot only includes days when energy balance data were available.

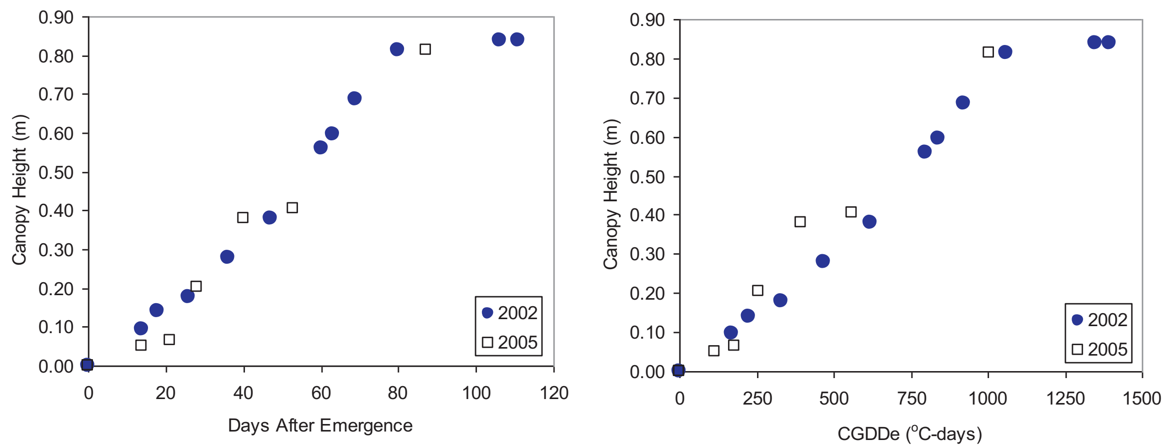


Fig. 4. Soybean canopy height as a function of days after emergence (DAE) and cumulative growing degree days from emergence (CGDDe) measured at North Platte, Nebraska, in 2002 and 2005. Daily growing degree days were calculated using lower and upper limits of 10 °C and 30 °C, respectively.

Table 7
Correlation matrix between daily weather variables and ETo, ETr, and ETr/ETo obtained at North Platte, Nebraska, during 2001–2005, during the soybean growing season.

Variable	U_2	T_a	RH	VPD	R_s	R_n	ETo	ETr	ETr/ETo
U_2	1.00								
T_a	0.17	1.00							
RH	−0.16	−0.32	1.00						
VPD	0.22	0.74	−0.82	1.00					
R_s	−0.01	0.40	−0.63	0.55	1.00				
R_n	−0.01	0.48	−0.46	0.49	0.96	1.00			
ETo	0.36	0.75	−0.75	0.90	0.76	0.74	1.00		
ETr	0.46	0.71	−0.78	0.92	0.67	0.63	0.99	1.00	
ETr/ETo	0.69	0.20	−0.68	0.57	0.09	−0.05	0.50	0.63	1.00

U_2: wind speed at 2-m height; T_a: average air temperature; VPD: vapor pressure deficit; RH: relative humidity; R_s: solar radiation; R_n: calculated net radiation; ETo: grass-reference evapotranspiration; ETr: alfalfa-reference evapotranspiration.

the canopy represented between 0.2 and 8.2 mm d^{-1}, with an average of 5.3 mm d^{-1}. *G* represented the smallest energy component, ranging between −1.0 and 1.4 mm d^{-1}, with an overall average of 0.05 mm d^{-1}. *H* was the second smallest component, ranging from −3.7 to 4.0 mm d^{-1}, with an average of 0.4 mm d^{-1}. *H* was mostly positive early in the season before full canopy cover,

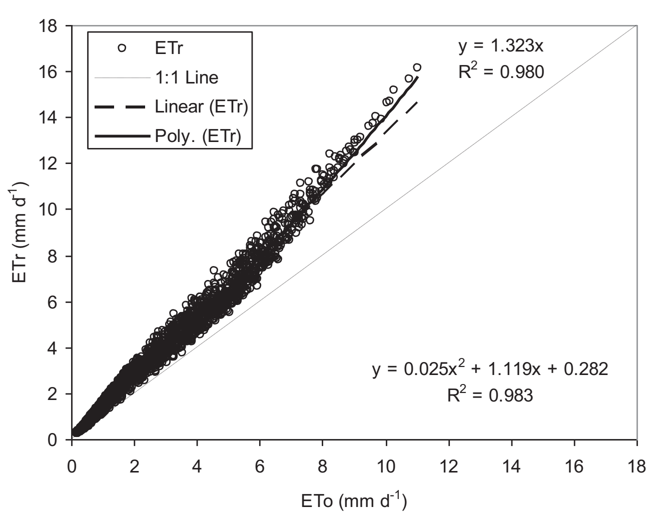


Fig. 5. Relationship between daily grass-reference and alfalfa-reference evapotranspiration (ETo and ETr) values calculated for the period of 2001–2005 at North Platte, Nebraska.

and late in the season after crop senescence started. *H* was predominantly negative during the mid-season crop development stage, when the energy available to the cropped surface is mostly used to evaporate water via crop evapotranspiration and predominantly for crop transpiration. During the times when *H* was negative, LE consequently exceeded R_n, which suggests the presence of advective energy transported from areas surrounding the soybean field by horizontally-moving wind. LE represented between 0.4 and 9.7 mm d^{-1}, averaging 4.6 mm d^{-1}. During the same period, ETo ranged from 0.9 to 11.1 mm d^{-1} with an average of 5.2 mm d^{-1}. Therefore, on average for the entire measurement period, LE was 0.6 mm d^{-1} and 0.7 mm d^{-1} smaller than ETo and R_n, respectively. Monthly averages of R_s, R_n, *H*, LE, *G*, ETo and Kc during the measurement periods are summarized in Table 8.

Table 8
Monthly average of ETo, energy fluxes (mm d^{-1}) and Kc measured in soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005.

Month	*n*	R_s	R_n	LE	*H*	*G*	ETo	Kc
Year 2002								
May	7	9.7	5.3	2.6	2.5	0.2	4.9	0.54
Jun	14	10.5	5.8	4.2	1.6	0.0	7.9	0.54
Jul	31	10.4	6.3	5.3	0.7	0.2	7.0	0.78
Aug	27	8.6	5.3	6.3	−1.0	0.0	5.6	1.14
Sep	30	6.8	4.0	4.5	−0.3	−0.2	4.0	1.11
Year 2003								
Jul	6	8.2	5.2	5.8	−0.5	0.0	4.7	1.22
Aug	15	9.7	6.3	7.4	−1.1	0.0	5.6	1.33
Sep	20	7.4	4.2	3.5	0.9	−0.2	3.5	1.04
Oct	6	5.4	2.4	1.7	0.9	−0.1	2.8	0.80
Year 2005								
May	11	10.6	5.0	2.5	2.3	0.3	4.2	0.70
Jun	30	11.1	6.0	4.5	1.1	0.4	4.9	0.96
Jul	31	11.9	6.4	5.6	0.6	0.2	6.4	0.89
Aug	31	10.0	4.6	4.9	−0.2	0.0	4.5	1.07
Sep	30	8.2	3.6	3.1	0.5	0.1	4.4	0.68
Oct	5	5.8	1.8	1.1	0.9	−0.2	2.3	0.41
All years								
May	18	10.2	5.2	2.6	2.4	0.3	4.6	0.62
Jun	44	10.8	5.9	4.4	1.4	0.2	6.4	0.75
Jul	68	10.2	6.0	5.6	0.3	0.1	6.0	0.96
Aug	73	9.4	5.4	6.2	−0.8	0.0	5.2	1.18
Sep	80	7.5	3.9	3.7	0.4	−0.1	4.0	0.94
Oct	11	3.7	1.4	0.9	0.6	−0.1	1.7	0.40

n: number of observations; R_s: solar radiation; LE: latent heat of flux; *H*: sensible heat flux; *G*: soil heat flux; R_n: net radiation; ETo: calculated grass-reference evapotranspiration; Kc: average measured crop coefficient.

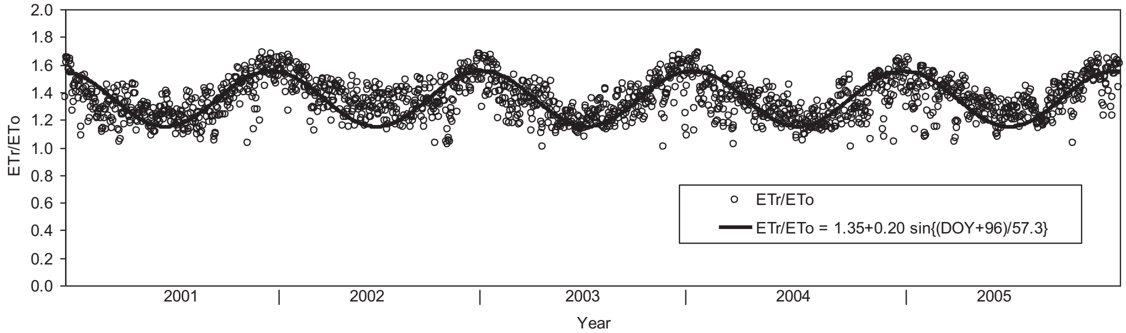


Fig. 6. Distribution of the daily ETr/ETo ratio as a function of time during the period of 2001–2005 at North Platte, Nebraska. ETr and ETo are the calculated grass-reference and alfalfa-reference evapotranspiration, respectively, calculated using the FAO-56 procedure. DOY: day of the year.

Daily grass-reference Kc values as a function of DAP and CGDDe are shown in Figs. 9 and 10, respectively. For comparison, the average Kc and basal Kc (Kcb) curves given in FAO-56 are also shown. Boxplot and average measured Kc values as a function of weeks after planting (WAP) are shown in Fig. 11. The highest average Kc for all years occurred in August. The measured daily Kc values were characterized by rapid increase when wetting events (rain or irrigation) occurred, followed by a steady decreased as the soil dried up. This pattern is most evident in the 2005 data, resulting from frequent rain and irrigation events. During that year, frequent irrigations were applied with a lateral move sprinkler system. Sudden increases in the measured Kc are especially noticeable during the initial growth period, due to large soil evaporation resulting from a wet soil surface that was nearly bare and exposed to solar radiation. Because of the frequent wetting events during the initial growth period of 2005, the measured Kc values were considerably larger than both the FAO-56 average Kc and Kcb.

While wetting events tend to increase the evaporation component of ETc, crop stress on the other hand tends to decrease the transpiration component. Therefore, both of these processes will impact the measured Kc values. The impact of crop stress on Kc can be seen in both the 2002 and 2005 data. Although the soybean fields were irrigated targeting maximum yield, most farmers do not measure soil water content and, therefore, can unknowingly

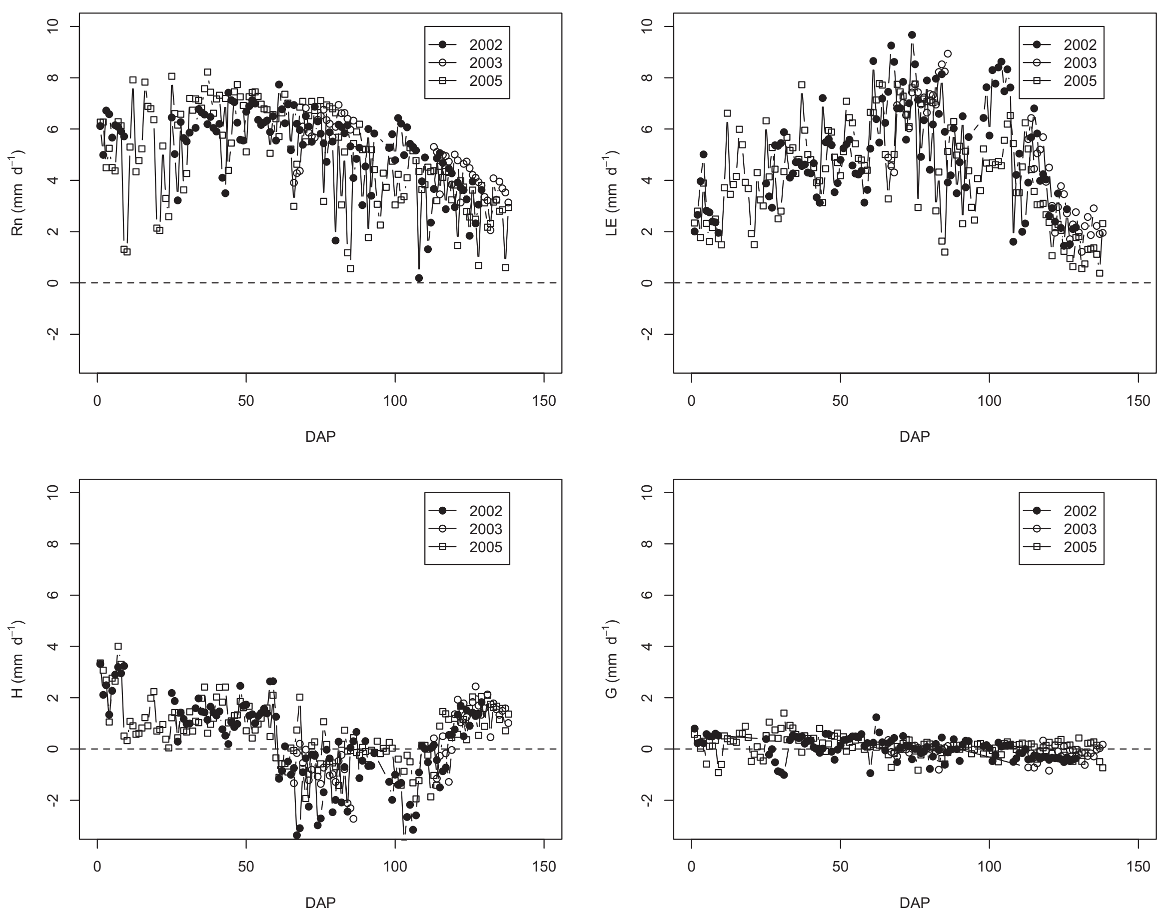


Fig. 7. Daily energy balance components as a function of days after planting (DAP) measured in a surface (gravity)-irrigated soybean field at North Platte, Nebraska, during the 2002, 2003, and 2005 growing seasons. R_n: net radiation; LE: latent heat flux; H: sensible heat flux; G: soil heat flux.

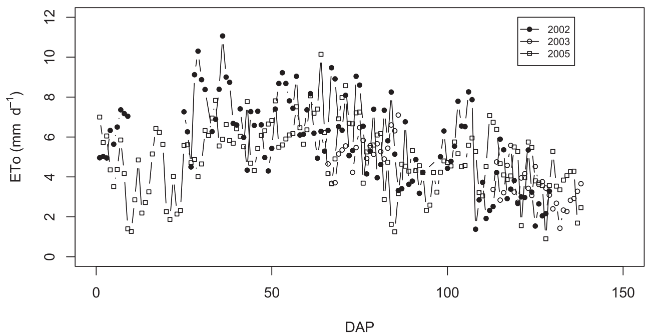


Fig. 8. Daily grass-reference evapotranspiration as a function of days after planting (DAP) calculated from weather data for North Platte, Nebraska, during the 2002, 2003, and 2005 growing seasons.

impose crop stress. For example, in 2002 the measured Kc values in the first 60 DAP were much lower than the FAO-56 values, which is indicative of crop stress. In 2005, the measured Kc values were also much lower that the FAO-56 Kc and Kcb values from about 40 DAP to 100 DAP, which covers the period from halfway through the development stage to the end of the mid-season stage. This resulted from irrigating with a low capacity sprinkler system that was not

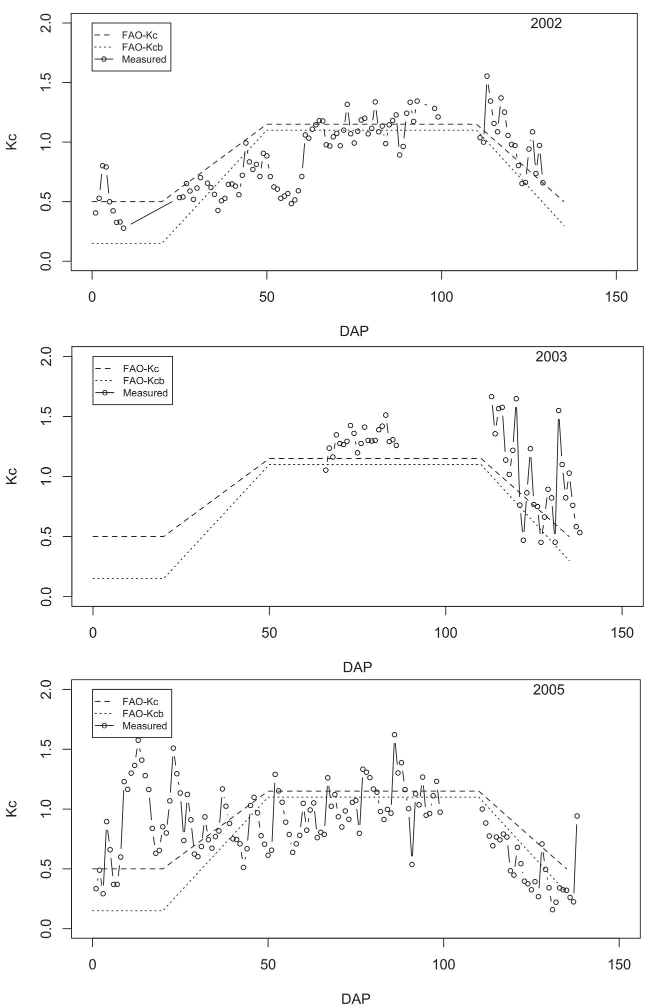


Fig. 9. Measured grass-reference crop coefficient (Kc) values measured in soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005, as a function of days after planting (DAP). The FAO–Kc and FAO–Kcb curves were constructed based on the average Kc and basal crop coefficients (Kcb) values given in FAO-56 for soybean for Central USA.

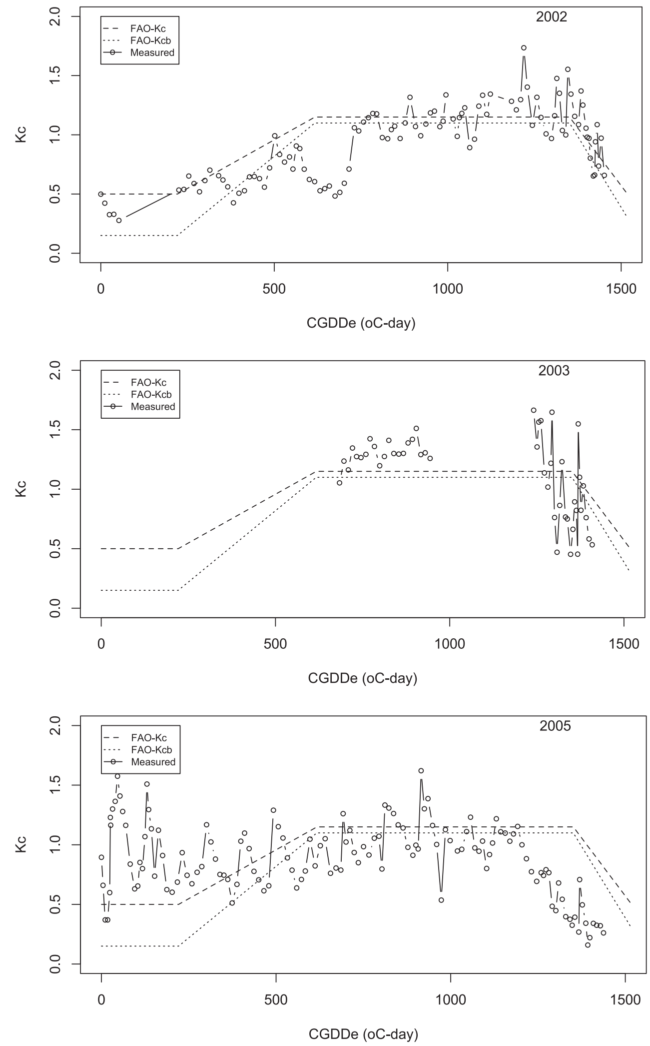


Fig. 10. Measured grass-reference crop coefficient (Kc) values measured in soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005, as a function of cumulative growing degree days from crop emergence (CGDDe). The FAO–Kc and FAO–Kcb curves were constructed based on the average Kc and basal crop coefficients (Kcb) values given in FAO-56 for soybean for Central USA.

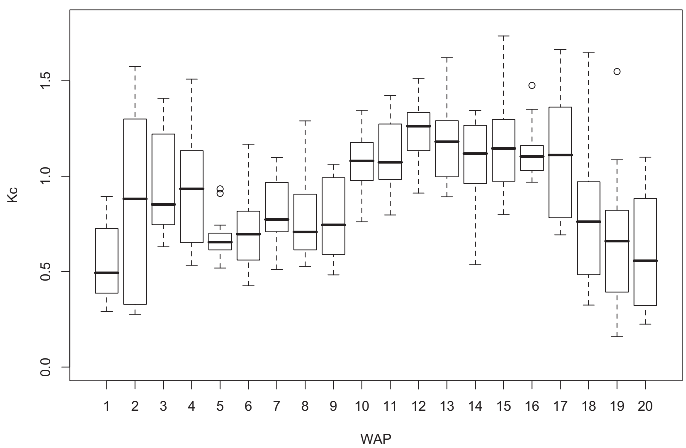
able to keep up with the water demands of the crop. Because of the effects of wetting events and crop stress on Kc, the dual Kc methodology proposed by Wright (1982) is preferable to the single Kc approach, especially for irrigation scheduling applications. The dual Kc approach accounts for crop stress and soil evaporation as:

$$\mathrm{ETc} = (K_s\,\mathrm{Kcb} + K_e)\mathrm{ET}_{ref} \tag{4}$$

$$T = (K_s\,\mathrm{Kcb})\mathrm{ET}_{ref} \tag{5}$$

$$E = (\mathrm{ETc} - T) = (K_e)\mathrm{ET}_{ref} \tag{6}$$

where ET_{ref}, reference ET (mm d^{-1}); T, transpiration (mm d^{-1}); E, evaporation (mm d^{-1}); K_s, transpiration stress coefficient, which is a factor describing the effect of water stress on crop transpiration (unitless); Kcb; basal crop coefficient (unitless), which is ETc/ET_{ref} when the soil surface is dry but transpiration is occurring at the potential rate such that water stress is not limiting transpiration, and K_e, soil evaporation coefficient (unitless). Therefore, the observed increase in Kc during wetting events was due to an increase in K_e and also due to evaporation coming directly off the wet crop canopy (Martin et al., 2012), while the decrease in Kc was due to a decrease in K_s caused by crop stress (Payero et al., 2009).



WAP	AverageKc
1	0.54
2	0.85
3	0.98
4	0.94
5	0.68
6	0.72
7	0.80
8	0.80
9	0.77
10	1.07
11	1.11
12	1.23
13	1.17
14	0.08
15	1.16
16	1.13
17	1.12
18	0.77
19	0.64
20	0.60

Fig. 11. Boxplot of measured grass-reference crop coefficient (Kc) from soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005, as a function of weeks after planting (WAP).

The FAO-56 average Kc curves fitted the measured Kc reasonably well for the non-stressed period occurring after 60 DAP in 2002. However, the fit was poor for 2003 and 2005. In 2005 the late-season stage started about 10 days or 150 °C day CGDDe sooner than predicted by FAO-56 (Figs. 9 and 10). The late-season stage started at about 105 DAP rather than 115 DAP and at 1200 °C day rather than at the expected 1350 °C day CGDDe. It is possible that crop stress contributed to accelerating crop maturity. As noted earlier, because of the warmer conditions, it was expected for the crop to have matured sooner in 2002 compared with 2003 and 2005. The opposite, however, was observed for 2005, which we attributed to crop stress. However, even though the crop was also stressed early in the season in 2002, that stress did not seem to have accelerated maturity. This suggests that stress during the reproductive stage seems to have more of an impact on accelerating maturity than stress during the vegetative stage. There is a need for methods to better quantify the impact of crop stress on accelerating crop maturity.

The results of this study show that because of wetting events and crop stress, actual Kc measurements can significantly deviate from the smooth Kc curves that are often used for calculating crop ETc. Recognizing the impact of wetting events on Kc values is especially important when using Kc values to estimate ETc in humid regions or when irrigation is applied frequently in places like Nebraska where frequent sprinkler irrigation with center pivots is a common practice. Although not tested in this study, it is also known that Kc values can also be significantly affected by planting density because it affects the fraction of soil that is covered by vegetation and leaf area index (Allen and Pereira, 2009). Therefore, the limitations of available Kc values need to be recognized when using them for calculating ETc to be used for water planning and irrigation scheduling.

4. Conclusions

In this study we measured and documented the daily ETc and other energy balance components of soybean, documented the daily and seasonal behavior of soybean crop coefficients (Kc) and evaluated the impact of weather variables on crop reference evapotranspiration. While doing these, we found considerable differences in weather conditions among seasons that affected the accumulation of growing degree days, crop development pattern, crop ETc and Kc. Comparing ETr and ETo we found that ETr values were on average 32.3% greater than ETo, which is important when choosing Kc values for calculating ETc. Exploring the variability of the ETr/ETo ratio we also found that the ratio followed a sine pattern with respect to day of the year, similar to the changes in alfalfa albedo. When evaluating the effect of weather variables on ETo and ETr we found that ETo and ETr were highly correlated with T_a, RH, VPD, R_s, and R_n. The highest correlation, however, was with VPD, which integrated the effect of both T_a and RH and explained 90 and 92% of the variability of ETo and ETr, respectively.

We presented daily measurements of energy fluxes, including R_n, LE, H, and G. We found that H was mostly positive during the early and late portion of the growing season, but became mostly negative during the mid-season stage. Because of the negative H, LE exceeded R_n during the mid-season period. We also presented daily measured Kc values and compared them to the average Kc and basal Kc curves given in FAO-56. We found that measured Kc often deviated considerably from the FAO-56 values due to wetting events (rain and irrigation) and crop stress. These deviations are, however, theoretically explained by the dual crop coefficient method used in FAO-56 and originally proposed by Wright (1982), although actual data showing these effects are not commonly available. Therefore, we recommend using the dual Kc method instead of the single Kc method for irrigation scheduling, especially when the soil surface is frequently wetted by rain or irrigation. This is particularly relevant early in the growing season when the soil surface is exposed. It is also important in humid regions with frequent rain events and in areas where sprinkler or surface drip irrigation systems that apply frequent irrigations that wet the soil surface are used.

In addition, we found considerable differences in crop maturity during 2002 and 2005 and we speculated that the acceleration in crop maturity in 2005 was due to crop stress, but raised the need for accurate methods to quantify the effect of stress on crop maturity and its impact on Kc.

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