4

Daily Crop Evapotranspiration, Crop Coefficient and Energy Balance Components of a Surface-Irrigated Maize Field

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1. Introduction

Irrigation water shortage is affecting many areas of the world. This is the case in Nebraska and in other areas of the USA High Plains. In Nebraska, field maize (*Zea mays L.*) is the primary irrigated row crop and is one of the most important drivers of the state's economy. The most typical cropping rotations in Nebraska are continuous maize and maize following soybeans. With the development of ethanol and bio-fuel industries, continuous maize farming practices are increasing. Over-pumping of groundwater for irrigation, coupled with recent drought conditions, and increasing continuous maize production are causing serious concerns about the future availability and sustainability of water resources. Increasing fuel prices, which increases pumping costs should provide an economic incentive for farmers to match irrigation applications to crop water requirements. Accurate determination of actual crop evapotranspiration (ETc) can improve utilization of water resources through well-designed irrigation management programs. Reliable estimates of ETc are also vital for developing criteria for in-season irrigation management, water allocations, long-term estimates of water supply, water demand and use, design and management of water management infrastructures, and the effect of changes in land use and management on water balances (Irmak and Irmak, 2008).

Water shortage is creating a need for growers to produce crops using less water. An option is to use more efficient irrigation systems, which has already occurred to a large extend over the last four decades in the USA Midwestern states by converting from surface irrigation to overhead sprinkler systems. For example, water and labour shortages have already driven growers in Nebraska to switch from surface irrigation to more efficient overhead sprinkler irrigation systems (mainly center pivots). Currently, of the 3.5 million ha of irrigated land, 75% is irrigated using center pivots and 25% still uses surface irrigation, mainly furrow irrigation. Adoption of more efficient drip systems, like subsurface drip irrigation, to irrigate maize, however, has been limited due mainly to their high initial cost and maintenance requirements. Therefore, additional gains in irrigation efficiency will have to come from improved management of existing irrigation methods and by using sound irrigation scheduling techniques. A potentially useful irrigation scheduling technique can be implemented by developing and adopting computer tools to estimate daily soil water status. These tools normally use daily weather data as input to estimate crop evapotranspiration (ETc) and irrigation requirements from a daily soil water balance. For these tools to be accurate, they need to be validated with direct measurements of daily ETc from local crops and weather conditions.

Direct measurement of ETc can be performed using techniques such as weighing lysimeters, eddy covariance, Bowen ratio energy balance, surface renewal, and soil water balance. While each method has its own advantages and drawbacks, they have been successfully used to quantify ETc under different conditions. However, their practical and widespread application is limited, mainly due to their high cost and the need for skilled personnel to install and maintain equipment and to interpret the resulting data. Because of the lack of direct ETc measurements, ETc is usually estimated from weather data using a two-step approach (Doorenbos and Pruitt, 1975; 1977, FAO-56, 1998). In this approach, ETc is estimated by adjusting the calculated reference evapotranspiration (ETref), either grass- or alfalfa-reference ET (ETo or ETr, respectively), with a crop coefficient (Kc) value for the specific crop and growth stage (i.e., ETc = Kc x ETref). The Kc value takes into account the morphological and physiological characteristics of the crop and, to a limited degree, the effect of management practices (Wright, 1982; FAO-56, 1998).

Carefully developed Kc values, along with ETref values, can provide robust and accurate ETc estimates. This method relies heavily on published Kc values for different crops. While there are significant assumptions imbedded in the Kc values, which may not apply to many locations/conditions, the simplicity of this method has been one of the main reasons for its widespread adoption. However, accuracy for local conditions could be compromised by uncertainties in generalized Kc values. Kc values for the same crop can show significant variation between locations due to differences in crop variety, soil properties, irrigation method and frequency, climate, and perhaps more importantly, crop management practices. Consequently, the Kc values reported in the literature can vary significantly from actual values if crop growing conditions differ from those where they were experimentally derived. Thus, while it is a difficult and challenging task, locally-derived Kc values are preferable to produce more robust and accurate ETc estimates. The objectives of this study were to: (1) compare grass-reference and alfalfa-reference ET estimates under the conditions of West-Central Nebraska, (2) quantify the daily magnitude and seasonal trends of energy balance components and ETc for maize and, (3) derive daily maize Kc values under local conditions and compare these values with those reported in FAO-56.

2. Methods

2.1 Site description and crop management

Surface energy balance components were measured during 2001 at the University of Nebraska-Lincoln West Central Research and Extension Center, at North Platte, Nebraska (41.1˚ N, 100.8˚ W, 861 m above sea level). Measurements were made on a surface-irrigated maize field that was under a ridge-tilled maize-soybean rotation system (Fig. 1). The soil at this site is classified as Cozad silt loam (*Fluventic Haplustolls*), but profile sampling has shown that the soil in this field is predominantly loam to a depth of 1.2 m.

Maize was planted at 0.76-m row spacing on 8 May 2001 [Day of year (DOY) = 128], within the normal planting window for maize in the region. The planting density was 7.6 seeds per m^2 with a north-south row direction. The maize hybrid planted was DeKalb DKC63-22 (YG), which had a relative maturity of 113 days. The maize field was irrigated with gated pipes, every other furrow, using groundwater pumped from a deep well. The field was dedicated to commercial maize production; therefore, the crop was fully-irrigated to maximize yield by preventing water stress during the entire season. Only three irrigations were needed to supplement timely rainfall events, which were applied on 8 July, 8 August, and 25 August. Water application depths were not recorded, but neutron probe soil water measurements after the first irrigation event (data not shown) indicated that the applied irrigation water in each application was enough to refill the soil profile.

2.2 Energy balance measurements

Energy balance variables were measured using an eddy covariance system (Campbell Scientific, Inc., Logan, Utah) installed on a tower at the center of the experimental field (Fig. 1). The system had about 150 m of fetch in all directions. The field was surrounded by soybean to the north and east and by native grasses to the west and south. Predominant winds were in the north-west to south-east direction. The measurements were made during most of the year, from DOY 11 (11 January) to DOY 353 (19 December). There was a gap in data collection from DOY 38-85 (7 February–26 March) and several small gaps due to system malfunction. All system components, except the soil moisture, soil heat flux, and soil temperature sensors, were kept approximately 1 m above the crop canopy throughout the measurement period. Table 1 provides the list of instrumentation type and variables measured.

Data were sampled, processed and recorded with a CR23X datalogger (Campbell Scientific, Inc., Logan, Utah). The datalogger was housed in an environmental enclosure and had a SM16M data storage module. A 12-Volt (75-Amp) marine deep cycle battery, charged by a solar panel supplied power to the system. The sonic anemometer (CSAT3), fine wire thermocouple (FW05), and a krypton hygrometer (KH20) sensors were sampled at a frequency of 10 Hz (10 times per second). All other sensors were sampled once per minute. The 30-min averages were stored, and daily averages were calculated during post-processing.

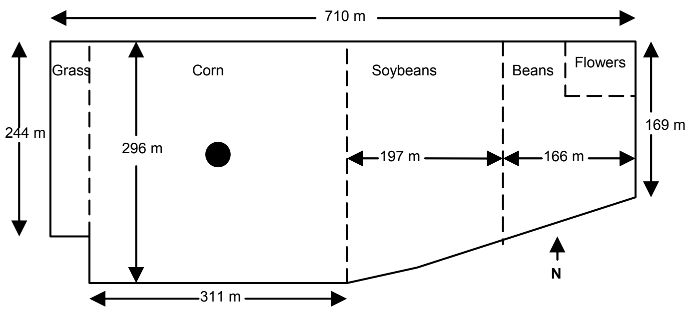

Fig. 1. Layout of the experimental field at North Platte, Nebraska, during the 2001 study. The black dot shows the location of the eddy covariance system used to measure the energy balance variables.

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
FW05	Fine-wire thermocouple	Campbell Scientific, Inc. Logan, Utah	Air temperature
KH20	Krypton hygrometer	Campbell Scientific, Inc. Logan, Utah	Absolute air humidity
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 Company Traverse City, Michigan	Horizontal wind speed and direction

Table 1. Sensors used and variables measured at North Platte, Nebraska, during 2001.

The 30-min averages included all of the energy balance components (in units of W m^{-2}), such as incoming shortwave solar radiation (Rs), net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G). G was calculated from the output of the two soil heat flux plates, the soil temperature sensor (which included four thermocouples), the soil water content reflectometer, and soil physical properties (Hanks and Ashcroft, 1980) as:

$$G = SHF + S \tag{1}$$

$$S = (T_i - T_{i-1}) \times D \times C_s / t \tag{2}$$

$$Cs = BD \times (C_{sd} + W \times C_w) \tag{3}$$

where, SHF = flux measured by the soil heat flux plates (W m^{-2}), S = change in heat stored above the soil heat flux plates (W m^{-2}), T_i = soil temperature during current time interval (°C), T_{i-1} = soil temperature during previous time interval (°C), D = depth to soil heat flux plates (m), C_s = heat capacity of soil (J m^{-3} °C^{-1}), t = time interval (s), BD = soil bulk density (kg m^{-3}), C_{sd} = specific heat of mineral soil (840 J kg^{-1} °C^{-1}), W = soil water content on a mass basis (kg kg^{-1}), and C_w = specific heat of water (4,190 J kg^{-1} °C^{-1}). The two soil heat flux plates were installed 1 m apart at a depth of 0.08 m from the soil surface. The two soil thermocouples were installed next to each soil heat flux plate at depths of 0.02 and 0.06 m.

The soil water content reflectometer was installed horizontally midway the two soil heat flux plates at a depth of 0.025 m.
The experimental site was visited at least weekly to download data, provide regular sensor maintenance, and measure crop canopy height. Crop canopy height was measured 17 times throughout the season. The 30-min energy fluxes for each day were plotted and visually inspected to detect inconsistent data. The LE values calculated from the KH20 sensor were rejected since they were unreasonably low, and daily LE values were instead calculated as a residual from the one dimensional energy balance equation (LE = Rn- G - H). As part of data validation, data were also excluded if the daily LE or Rn were greater than Rs, or if the daily average Rn was negative.

2.3 Weather data

In addition to the eddy covariance measurements, weather data for calculating daily reference ET were measured with an electronic weather station located at the research station, which was part of the High Plains Regional Climate Center (HPRCC) network. The data were downloaded from the HPRCC (http://www.hprcc.unl.edu/home.html), including daily maximum (Tmax) and minimum (Tmin) air temperature, relative humidity (RH), wind speed (measured at 3-m height), solar radiation, rainfall, and alfalfa-reference ET (ETr-Neb). The HPRCC calculated ETr-Neb using an equation developed by Kincaid and Heermann (1974) by modifying the Penman (1948) equation with an empirical wind function for Mitchell, Nebraska. Kincaid and Heermann (1974), however, suggested that the coefficients used in the new equation were nearly the same as those reported by Jensen (1969) for Twin Falls, Idaho (Irmak et al., 2008).

2.4 Reference ET, ETc and Kc

Daily grass- and alfalfa-reference ET were calculated using the standardized FAO-56 Penman-Monteith method (FAO-56, 1998) as:

$$\text{ETref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} U_2 \ (e_s - e_a)}{\left[\Delta + \gamma \ (1 + C_d U_2) \ \right]} \tag{4}$$

where, ETref = reference evapotranspiration, either grass-reference (ETo) or alfalfa-reference (ETr) evapotranspiration (mm d^{-1}), Δ = slope of the saturation vapour pressure versus air temperature curve (kPa $°C^{-1}$), Rn = 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 to 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 = vapour 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}. Daily Rn, e_s, and e_a were calculated using the equations given by FAO-56 (1998) and ASCE-EWRI (2005) using measured RH, Tmax, and Tmin, and constant albedo (α = 0.23). Values for the Stefan-Boltzmann constant ($\sigma = 4.901 \times 10^{-9}$ MJ K^{-4} m^{-2} d^{-1}) (for calculating net outgoing long-wave radiation (R_{nl})), specific heat at constant temperature ($c_p = 1.013 \times 10^{-3}$ MJ kg^{-1} $°C^{-1}$), and latent heat of vaporization (λ = 2.45 MJ kg^{-1}) followed FAO-56 and ASCE-EWRI (2005). The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, c_p, and the ratio of molecular weight of water vapour to dry air (ε = 0.622). P was calculated as a function of station elevation (z), and daily G = 0 MJ m^{-2} d^{-1} was assumed. Wind speed measured at a height of 3 m was converted to the standard height of 2 m using equation 47 in FAO-56 (1998). Parameters for calculating daily ETo and ETr are shown in Table 2.

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}

Table 2. Parameters used in the FAO-56 Penman-Monteith method for daily calculations of grass-reference and alfalfa-reference evapotranspiration (ETo and ETr).

In addition to the measured LE values, daily maize ET (ETc) for a well-watered maize crop was estimated using the reference ET and dual crop coefficient (Kc) approach [i.e., ETc = ETo x (dual Kc)] described in FAO-56. The basal Kc (K_{cb}) curve developed from values given in Table 11 and 17 of FAO-56, using the length of growth stages in Table 3 was used in the calculations. From the calculated ETo and measured ETc (LE) values, daily Kc values for maize were also derived (Kc = ETc/ETo), both as a function of days from emergence (DFE) and as a function of cumulative growing degree days from crop emergence (C-GDD). Measured Rn values over the maize canopy were also compared with those estimated using the FAO-56 Rn calculation method for a reference grass surface.

Growth Stage (GS)	Definition	Length (Days)	K_{cb}
Initial	Planting to 10% ground cover	30	0.15 (K_{cb} ini)
Crop Development	10% ground cover to effective full cover	40	-
Mid-Season	Effective full cover to start of maturity	50	1.15 (K_{cb} mid)
Late Season	Start of maturity to harvest or full senescence	50	0.15 (K_{cb} end)

Table 3. Lengths of crop growth stages and basal crop coefficient (K_{cb}) values for field maize given in FAO-56 (1998). Growth stage lengths are for Kimberly, Idaho.

3. Results and discussion

3.1 Weather conditions

Table 4 shows the monthly averages of weather variables during 2001 at North Platte, Nebraska. Freezing temperatures occurred from January to March and during November and December. July had the highest monthly temperatures (Tmax, Tmin, and T) and ETr, although the highest average solar radiation (Rs) occurred in June. Annual rainfall during 2001 was 564 mm, which was 33% (141 mm) above the long-term average (normal) of 423 mm for North Platte for the period of 1982-2006 (Fig. 2). Above-normal rainfall occurred mainly in April and August, with rainfalls of more than twice the long-term average (Fig. 3). Rainfall in April refilled the soil profile prior to planting in early May. Rainfall was about normal in May and July, just above normal in September, and about half of normal in June and October. Rainfall in October had no effect on crop development, since by that time the crop had already reached physiological maturity. There were 30 rainfall events during the growing season, with several events occurring between 18 and 32 days after crop emergence when the crop was small and the soil surface was still exposed to solar energy (Fig. 4).

Month	**ETr (mm month⁻¹)**	**Tmax (°C)**	**Tmin (°C)**	**T (°C)**	**U_2 (m s^{-1})**	**Rs (MJ m^{-2} d^{-1})**	**RH (%)**
Jan	43.8	6.0	-7.8	-0.9	2.1	7.6	67.3
Feb	35.9	1.8	-9.4	-3.8	2.8	9.0	77.1
Mar	78.9	10.3	-2.8	3.8	2.5	13.3	71.2
Apr	147.8	18.0	3.1	10.6	3.1	18.6	62.2
May	170.8	22.0	8.8	15.4	2.6	20.4	61.9
Jun	227.3	28.8	12.6	20.7	2.8	24.9	61.0
Jul	233.4	33.7	18.0	25.9	2.7	24.0	67.7
Aug	200.9	30.7	14.9	22.8	2.3	21.5	65.5
Sep	142.6	25.2	9.8	17.5	2.4	16.1	68.6
Oct	112.6	19.5	1.4	10.4	2.1	12.5	57.2
Nov	62.7	14.1	-3.2	5.4	2.2	8.0	66.8
Dec	47.0	7.0	-8.4	-0.7	1.9	7.1	59.5
Avg	125.3	18.1	3.1	10.6	2.5	15.2	65.5
Min	35.9	1.8	-9.4	-3.8	1.9	7.1	57.2
Max	233.4	33.7	18.0	25.9	3.1	24.9	77.1

ETr = alfafa-reference evapotranspiration, Tmax = maximum air temperature, Tmin = minimum air temperature, T = average air temperature, U_2 = wind speed at 2 m height, Rs = solar radiation, RH = relative humidity.

Table 4. Average weather variables for each month during 2001 at North Platte, Nebraska

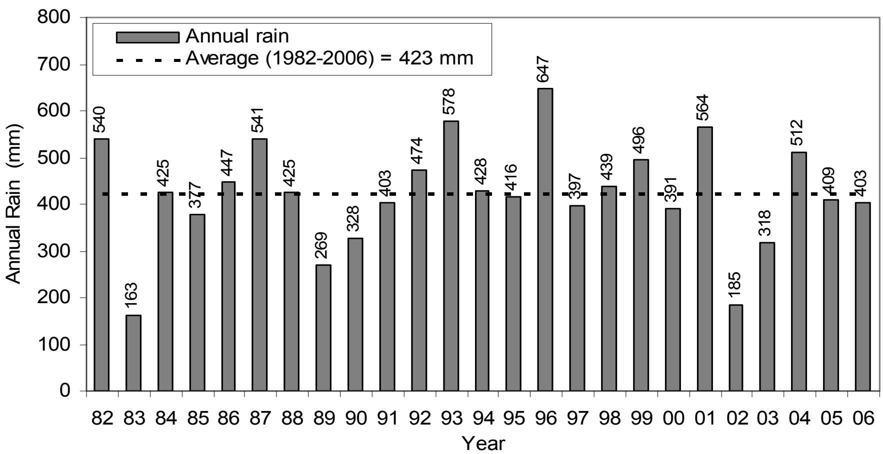

Fig. 2. Annual rainfall and long-term average (1982-2006) at North Platte, Nebraska

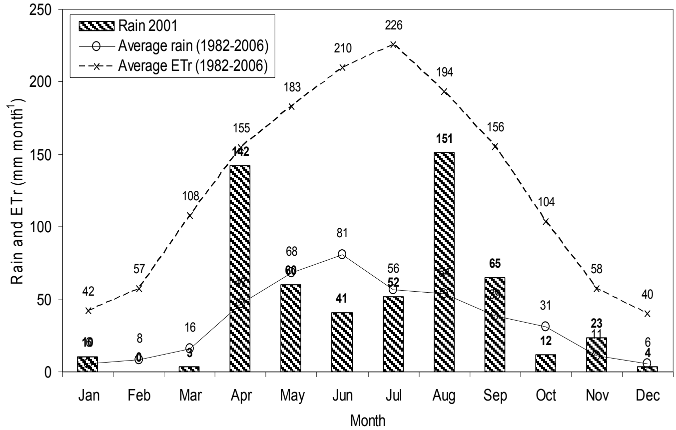

Fig. 3. Monthly rainfall at North Platte for 2001, and the long-term averages (1982-2006) for rainfall and alfalfa-reference evapotranspiration (ETr)

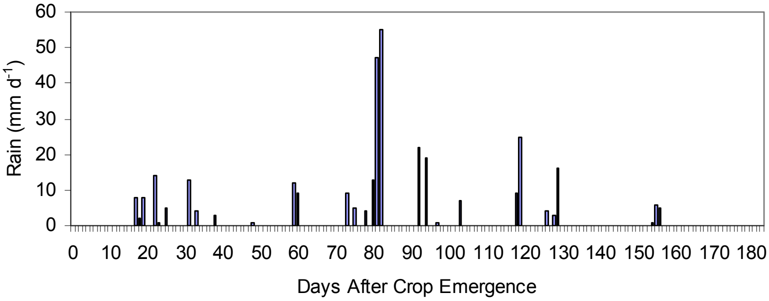

Fig. 4. Daily rainfall during the 2001 growing season at North Platte, Nebraska

3.2 Crop development

The crop emerged on 12 May (DOY 132), started tasseling on 13 July and about 90% of plants had tasseled by 16 July. The crop was at the silking stage by 19 July, matured at the end of September (about 25 September), and was harvested on 10 November. Figure 5 shows the progression in crop canopy height as a function of day of the year, day from emergence (DFE), and cumulative growing degree days from emergence (C-GDD). The crop grew slowly early in the season, but the growth rate increased as the season progressed until the crop reached maximum canopy height (2.7 m) at about 68 DFE (DOY 200, July 19, C-GDD = 723 ^{o}C-days). The crop had three periods with distinct growth rates (Fig. 6). The slopes of the three regression lines in Fig. 6 indicate that for DFE = 0 to 25 days, the crop grew at a rate of 0.008 m d^{-1}. The growth rate increased to 0.030 m d^{-1} during the period of DFE = 25 to 54 days. The highest growth rate was 0.114 m d^{-1} during DFE = 54 to 68 days.

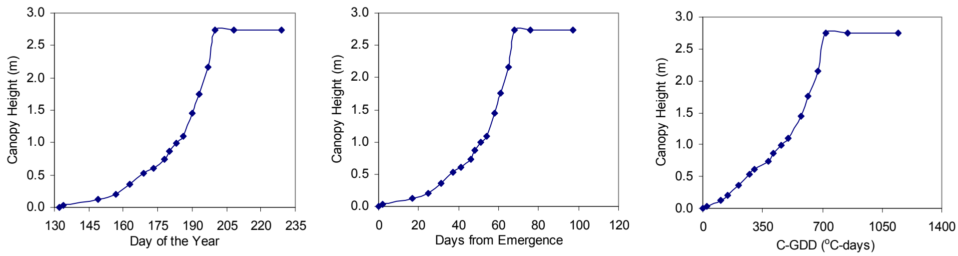

Fig. 5. Maize canopy height as a function of day of the year, days from emergence, and cumulative growing degree days from emergence (C-GDD) measured at North Platte, Nebraska, during the 2001 growing season. Daily growing degree days were calculated using a lower limit (base temperature) of 10 °C (50 °F), with no upper limit imposed.

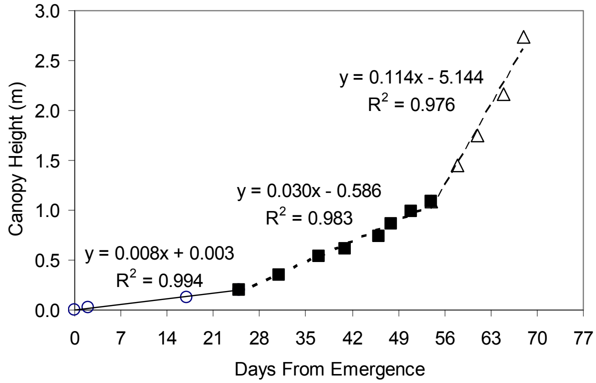

Fig. 6. Maize canopy height as a function of days from emergence measured in 2001 at North Platte, Nebraska. The lines are regression lines fitted for three different growing periods.

3.3 Reference ET

Calculated daily grass-reference ET for the whole year (ETo) (Fig. 7) varied from less than 0.5 mm d^{-1} during the winter to a maximum of about 10 mm d^{-1} during the summer. There were considerable day-to-day variations in ETo due to variations in climatic factors. Although linearly-related, there were considerable differences between the calculated grass-reference (ETo) and alfalfa-reference ET (ETr and ETr_Neb) values. Figure 8 shows good correlation of ETr and ETr_Neb[1] with ETo (R^2 of 0.97 and 0.98, respectively). The slopes of the lines, however, indicate that on average, ETr and ETr_Neb were 29% and 37% higher than ETo, respectively.

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[1] ETr_Neb is alfalfa-reference evapotranspiration as reported by the High Plains Regional Climate Center (HPRCC). The HPRCC calculates ETr_Neb using a modified Penman method with an empirical wind function. The ETr values, on the other hand, were calculated using Equation 4.

Our results are in agreement with those observed by Irmak and Irmak (2008) who found an average ratio of standardized ASCE-PM ETr to ETr_Neb of 1.29 for the conditions of south central Nebraska. Figure 9 also shows that the magnitude of the ETr/ETo ratio varied throughout the year from 1.03 to 1.68, reaching a minimum value in the middle of the summer and a maximum during the winter. Understanding the magnitude of the differences between the ETo and ETr are important when selecting crop coefficients for a local region. Practitioners need to make sure that Kc values are matched with the appropriate reference surface for which they were developed. Under the conditions of this study, failure to do so could potentially result in errors in ETc estimation as high as 37%.

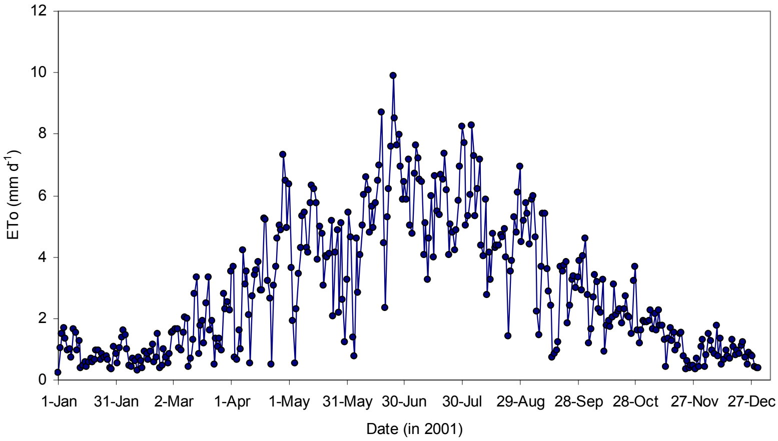


Fig. 7. Daily Grass-reference evapotranspiration (ETo) for 2001 at North Platte, Nebraska (n = 365).

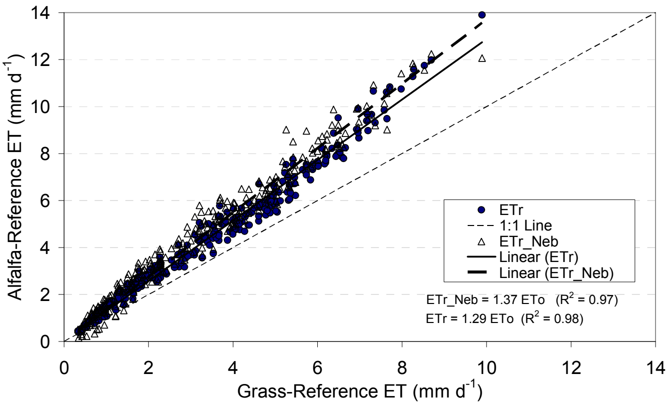


Fig. 8. Relationship between daily grass-reference and alfalfa-reference evapotranspiration values calculated for 2001 at North Platte, Nebraska. ETo and ETr are the grass- and alfalfa-reference evapotranspiration calculated using the FAO-56 procedure, and ETr_Neb are the alfalfa-reference evapotranspiration values obtained from the High Plains Regional Climate Center (n = 278).

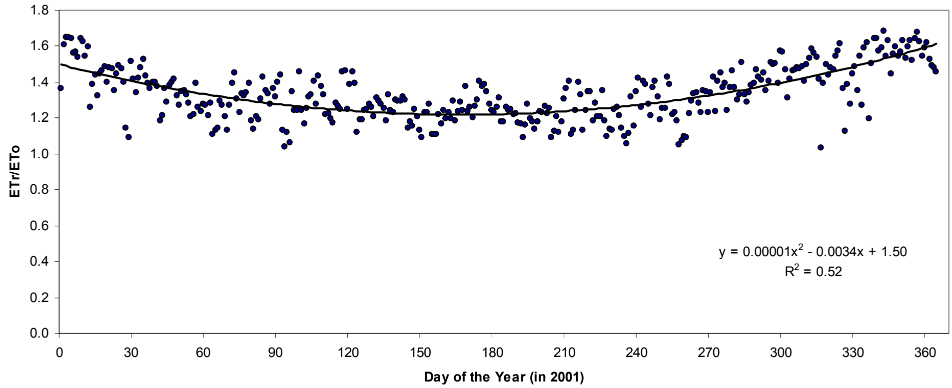


Fig. 9. Distribution of the ETr/ETo ratio as a function of day of the year during 2001 at North Platte, Nebraska. ETr and ETo are the estimated alfalfa-reference and grass-reference evapotranspiration, respectively, calculated with the standardized FAO-56 Penman-Monteith method (n = 365).

3.4 Energy fluxes

Figure 10 shows the trend in 30-min average energy fluxes for three cloud-free days during the maize growing season. In addition to clear-sky conditions, these days were presented because they represent a range of canopy cover conditions. Measurements on DOY 120 were taken prior to planting (with a bare soil surface), DOY 161 represents a maize canopy height of about 0.30 m, and DOY 216 represents a maize crop at full cover. The contribution of H and G with respect to the other energy fluxes tended to decrease as canopy cover increased. Also, worth noticing is that positive LE values were recorded in this environment during the night, which would result from advection of heat. During DOY 216, LE exceeded Rn during the afternoon hours (i.e., LE/Rn > 1.0), which is another indication of advection of heat.

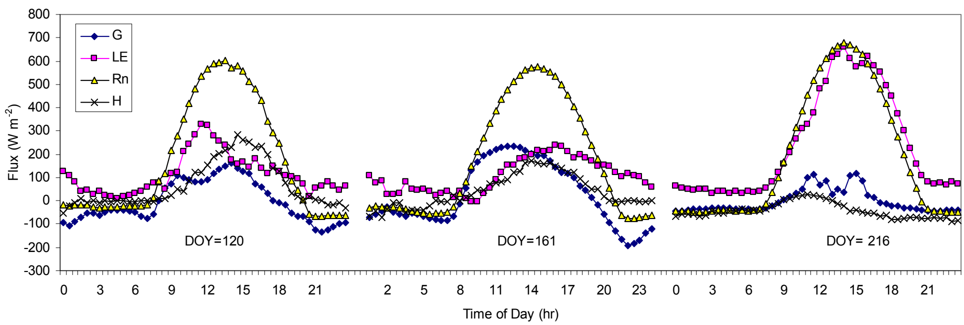
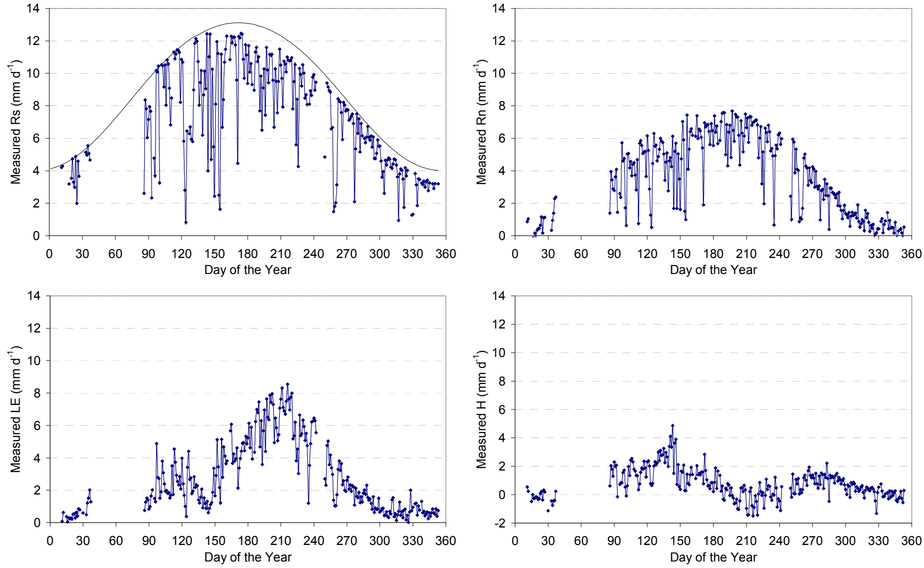
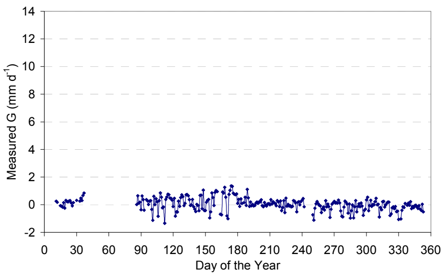


Fig. 10. Values of energy balance components measured during three clear-sky days on a surface-irrigated maize field at North Platte, Nebraska, during 2001. LE = latent heat flux (ETc), H = sensible heat flux, G = soil heat flux, Rn = net radiation. Each data point represents the 30-min average flux. DOY =day of the year. Maize was planted on DOY 128.

Daily values of energy fluxes (Fig. 11) show that all variables had considerable day-to-day fluctuation due to daily changes in weather and surface soil water conditions. Measurement of Rs during cloud-free days conformed to the theoretical bell-shaped clear-sky solar radiation (Rso) "envelope". As expected, significant reduction in daily Rs with respect to Rso resulted from the presence of clouds. The maximum energy input from solar radiation measured during this study was equivalent to a water loss of 12.5 mm d^{-1}. Advection can also supply additional energy to the environment for evapotranspiration. However, its magnitude would be expected to be minor compared with that supplied directly by Rs. Therefore, the maximum measured value of 12.5 mm d^{-1} of Rs would place an approximate upper limit on the ET that can effectively occur at this site, considering that a portion of Rs would be reflected and would not be entirely available for LE.





Month	G/Rs	LE/Rs	Rn/Rs	H/Rs	G/Rn	LE/Rn	H/Rn
Jan	0.05	0.13	0.17	-0.01	0.45	0.94	-0.39
Feb	0.10	0.26	0.29	-0.07	0.44	1.06	-0.50
Mar	0.02	0.20	0.46	0.25	0.03	0.42	0.55
Apr	0.02	0.30	0.49	0.17	0.04	0.60	0.35
May	-0.02	0.26	0.55	0.31	-0.04	0.46	0.58
Jun	0.01	0.44	0.57	0.12	0.02	0.77	0.21
Jul	0.01	0.65	0.66	0.00	0.02	0.97	0.01
Aug	0.01	0.63	0.63	-0.01	0.01	1.02	-0.02
Sep	-0.04	0.45	0.54	0.13	-0.08	0.82	0.25
Oct	-0.03	0.24	0.39	0.17	-0.08	0.63	0.44
Nov	-0.10	0.24	0.25	0.11	-0.45	0.99	0.46
Dec	-0.04	0.21	0.18	0.01	-0.33	1.30	0.03
Total	**0.00**	**0.33**	**0.43**	**0.10**	**0.00**	**0.83**	**0.16**

Fig. 11. Daily energy balance components measured on a surface-irrigated maize field at North Platte, Nebraska, during 2001. Rs = solar radiation, LE = latent heat flux (ETc), H = sensible heat flux, G = soil heat flux, Rn = Net radiation. The table shows the average monthly values of each variable as a fraction of Rs and Rn calculated from the daily measurements. The fractions for February and March are based on very few measurements. The solid line in the Rs graph is the calculated clear-sky solar radiation (Rso) or Rs envelope (n = 258).

Net radiation (Rn) measured over the maize canopy followed a similar trend as Rs during the year, but, as expected, it was always lower than Rs. The maximum measured Rn was equivalent to a water depth of 7.7 mm d^{-1}. Figure 12 shows that the Rn measured over the maize canopy was well-correlated to the values calculated for grass using the FAO-56 procedure (R^2 =0.92). Although there were some differences in measured daily Rn over the maize canopy and Rn calculated for grass, on average, the relationship followed the 1:1 line almost perfectly. Similar results between non-stressed maize and grass surface in south central Nebraska were reported by Irmak et al. (2010). Irmak et al. (2010) stated that the Rn values measured over maize canopy vs. grass canopy would be expected to be similar due to the fact that both plant species have similar biophysical attributes and that the albedo values for grass and non-stressed maize canopy were similar enough to only cause minor differences in Rn.

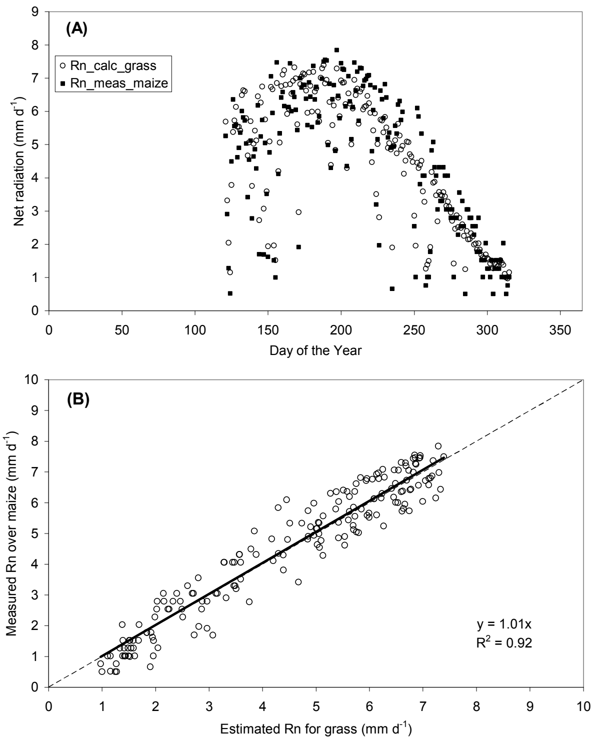


Fig. 12. (A) Comparison of daily net radiation (Rn) measured over maize (Rn_meas_ maize) with Rn calculated for grass (Rn_calc_grass) using the procedure described in FAO-56 (1998), and (B) regression analysis of measured and estimated Rn data in (A) (— Linear regression line, ----1:1 line, n = 185).

The measured daily LE values (the same as ETc when converted to a water equivalent, such as mm d^{-1}) followed a similar trend throughout the year as the energy available from Rs and Rn (Figure 11). However, it is important to note that the LE curve peaked much later than the Rs and Rn curve. Rs peaked at about DOY 170, Rn at about DOY 190, and LE at about

DOY 210. The delay on the peak of LE with respect to that of Rs and Rn is, in part, a reflection of the marked impact of the properties of the crop and soil surface on LE.

The maximum LE measured during the study was 8.5 mm d^{-1}, which was 0.8 mm d^{-1} higher than the maximum Rn value. LE values of 5 mm d^{-1} or higher were observed in April (DOY 191-120) from bare soil. These relatively high LE values were due to the presence of a wet soil surface resulting from spring rain. Relatively high values of ET early in the season in a maize field were also measured by Howell et al. (1998). Li et al. (2003), using lysimeter ET measurements in a semi-arid region, found that maize approached a peak ET rate of 48.45 mm per week (6.92 mm d^{-1}) at the 12^{th} week after sowing (94 days). These values are much lower than the values obtained in this study, and the fact that the crop took much longer to reach the peak ETc in the Li et al. (2003) study, and points to a cooler environment, compared with the conditions of this study. However, Howell et al. (1998) reported daily ET values (measured with weighing lysimeters) for maize at Bushland, Texas, of close to 14 mm d^{-1} (see Fig. 4 of Howell et al., 1998), which were much higher than the maximum ET values measured in this study.

The magnitude of sensible heat flux (H) was comparable to that of LE early in the growing season, but tended to decrease as the crop cover increased. Usually, an opposite trend between LE and H was observed. When LE was low, H was high, and when LE was high during the mid and late season, H was at its lower values. H fluctuated from approximately -2 mm d^{-1} on DOY 210 to as high as 5 mm d^{-1} on DOY 140. H usually had negative values during the winter and during the growing season when the crop was at full canopy cover.

Although G can be a significant component of the energy balance of a crop canopy when measured in short time steps, such as hourly, the daily average is usually close to zero. This is because positive values obtained in the middle of the day will cancel out negative values obtained during the rest of the day, and especially at night (Payero et al., 2001; Payero et al., 2005). Figure 11 shows that daily G averages usually fluctuated between small negative and positive values (about -1 mm $d^{-1} \leq G \leq +1$ mm d^{-1}), but the average was 0.0 mm d^{-1}.

Figure 11 also shows the ratios of the different energy-balance fluxes with respect to Rs and Rn for each month. For each of the variables, the magnitude of the ratios varied considerably from month to month. Overall, the G/Rs and G/Rn ratios were very close to zero. For the entire year, about 43% of Rs was available to the surface as Rn. A higher percentage of Rs was available as Rn during the summer months, and a lower percentage was available during the winter moths due to higher albedo. Furthermore, 33% of Rs was partitioned into LE and 10% into H. That means that, on average, about 57% of daily Rs was reflected and/or diffused. Also, on average for the entire year, 83% of the available daily Rn energy was used for LE and 16% for H.

Figure 13 shows the relationships between the daily values of Rs, Rn, and LE. Although the relationship had some scatter, there was a good linear relationship between daily Rs and the daily Rn values measured over the maize canopy ($R^2 = 0.87$). The relationship was offset from the origin reflecting the fact that Rn can be negative while Rs cannot. The R^2 value indicated that 87% of the variability in Rn could be explained by variability in Rs, while the remaining 13% of the variability is due to other factors. The main factors include the changes in the characteristics of the surface, and changes in the angle of incidence of the incoming Rs. Both of these factors suffer from daily and seasonal variations, which would affect albedo. Although there was a reasonable linear relationship between Rn and LE ($R^2 = 0.76$), the relationship was better explained by a curvilinear function that could be fitted to a second degree polynomial ($R^2 = 0.80$). These results suggest that Rn explained about 80% of the variability in LE.

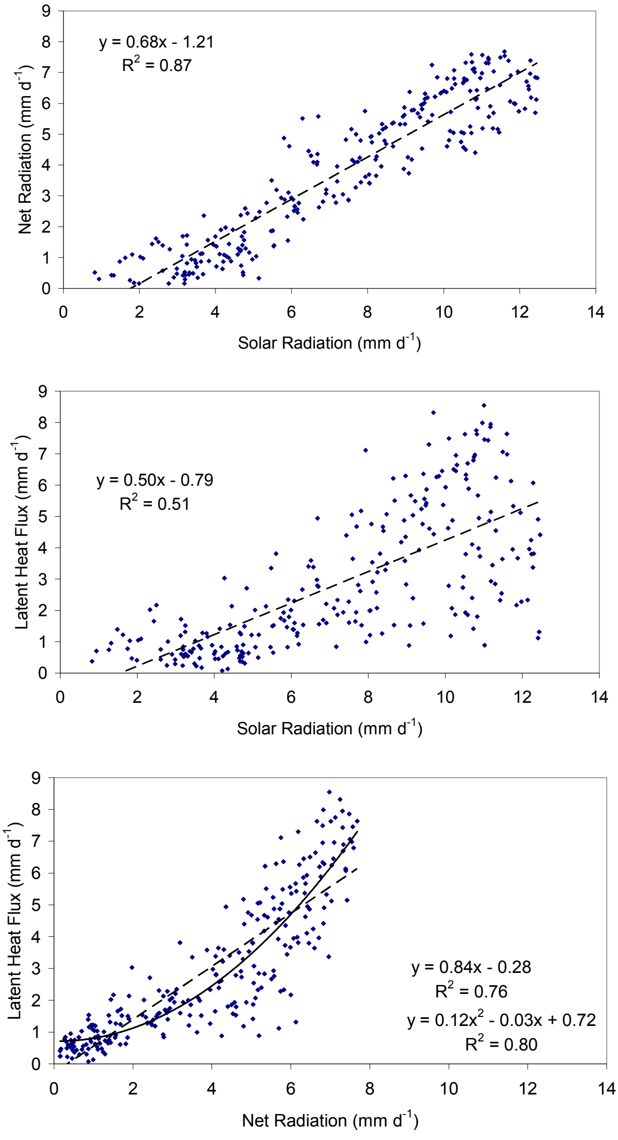


Fig. 13. Relationships between daily values of energy balance components measured in a surface-irrigated maize field at North Platte, Nebraska, during 2001 (— polynomial, ---- linear, n = 258).

In Figure 13, there were a considerable number of days when LE did not respond to increasing Rn, especially between the Rn range of 4 to 6 mm d^{-1} and the LE range of 1 to 2 mm d^{-1}. Similarly, there were days when an increase in LE was observed for this same range of Rn. This is because although Rn is one of the main drivers of LE in most cases, in dormant (non-growing) periods, as well as in conditions with extremely high atmospheric demand, vapour pressure deficit, wind speed, and air temperature can play crucial roles in the magnitude of LE. Thus, in these conditions, the variations in LE are more often due to variations in these other factors than to variations in Rn. Figure 13 also shows that the relationship between Rs and LE was relatively poor ($R^2 = 0.51$). The correlation between LE and Rs gets weaker with increases in both variables (i.e., when Rs > 6 mm d^{-1} and when LE > 2 mm d^{-1}). This is because, while Rs is the main source of available energy for LE, the amount of energy actually utilized (Rn-G) for LE is dictated or controlled by many factors that are dynamic in space and time. These factors include, but are not limited to, soil water status, soil and crop management practices, climatic and microclimatic factors.

3.5 Crop coefficient curve

Measured daily crop coefficients are presented in Figure 14 as a function of day from emergence (DFE) and cumulative growing degree days from emergence (C-GDD), along with the basal Kc curve for maize given in FAO-56 for Kimberly, Idaho. Although the time scale in FAO-56 was only given in days from planting, in this study, the C-GDD corresponding to the days from planting were calculated, and Kc curves were presented in both DFE and C-GDD "time" scales. The basal Kc curve for Kimberly, Idaho, was selected because Kimberly has a similar climate to North Platte and it is located at a similar latitude (North Platte = 41.1° N, Kimberly = 42.4° N).

There was significant variability in the daily Kc values, which made it challenging to fit an average Kc curve to the observed data. For instance, for the mid-season development stage, the daily Kc values ranged from 0.93 to 1.44. Also, early in the season, from emergence to about 40 days from emergence, frequent rain events wetted the soil surface, which resulted in high evaporation rates and high Kc values. This made it difficult to obtain a good estimate of the basal Kc early in the season without independent measurements of the evaporation and/or transpiration components of ET. Because of the daily variability in Kc, no attempt was made to fit a function to the data. However, Figure 14 shows that the basal Kc values given in FAO-56 for Kimberly fitted the general trend in Kc obtained in this study reasonably well, except for the periods when the soil surface was wet, as would be expected. However, in the mid-season stage, the Kimberly curve corresponded more to the average Kc values than to the basal Kc values, but early and late in the season, the Kimberly curve followed the apparent basal values reasonably well, especially when using the C-GDD "time" scale.

Parkes et al. (2005) using lysimeter and soil water measurements, found that the Penman-Monteith model provided the best model efficiency when used with a peak Kc of 1.25 for maize in China. Also, Li et al. (2003) found Kc values for maize to be used with the FAO-56 Penman-Monteith model of 0.5, 1.02, 1.26, and 0.68 during the initial, crop development, mid-season, and late-season stages, respectively. The 1.25 or 1.26 values for the mid-season are within the range of values obtained in this study. Jensen et al. (1990) suggested that grass-reference Kc values for a full-cover crop should not exceed 1.25 if this value is to represent large expanses of vegetation. Also, the "spikes" in the Kc curve following wetting events exceeded the maximum 1.20 value suggested by FAO-56 and Jensen et al. (1990).

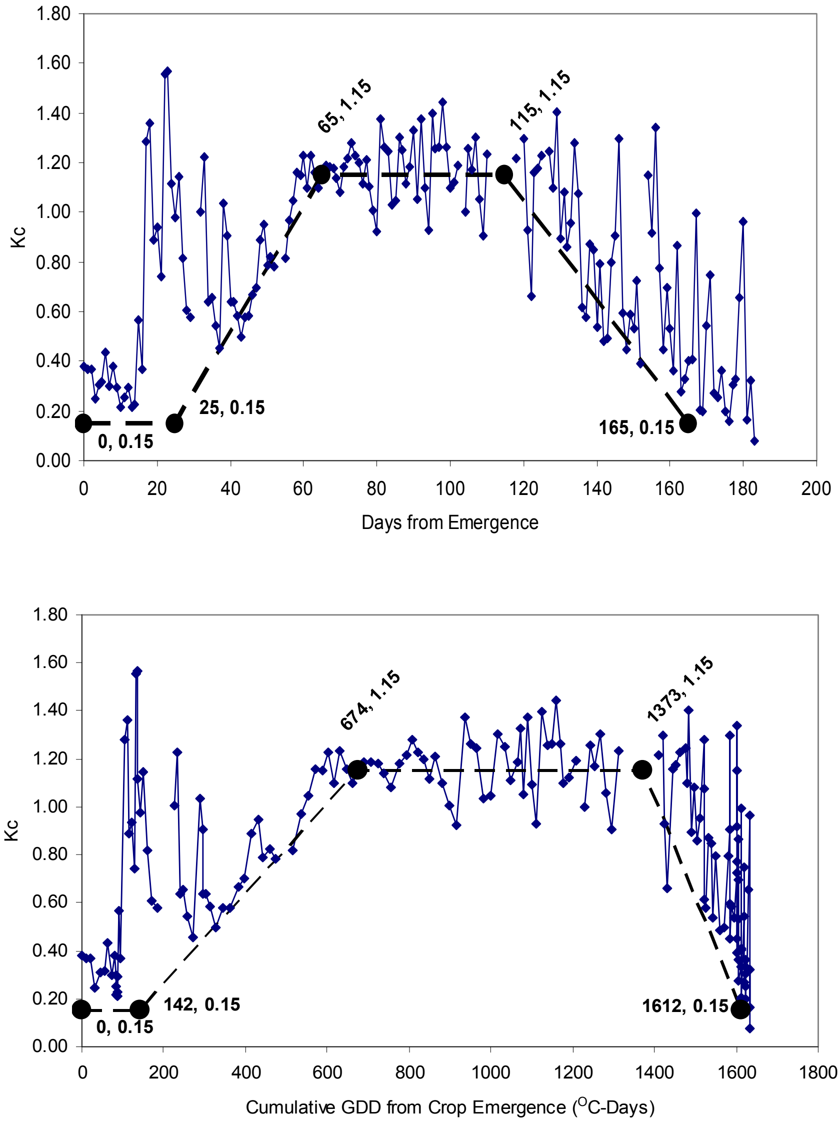


Fig. 14. Crop coefficient (Kc) curves for field maize measured at North Platte, Nebraska, during 2001, as a function of days from emergence and cumulative growing degree days (GDD) from crop emergence. The Kc values were calculated based on a grass reference (ETo), which was calculated with the FAO-56 method. The broken line represents the Kc function proposed in FAO-56 with growth stage lengths for Kimberly, Idaho. The number pairs on the graphs are the coordinates for each of the black dots for the Kimberly curves from FAO-56 (n =182).

3.6 Measured and estimated maize ETc

A comparison of the daily measured and calculated maize ETc values is presented in Figs. 15 and 16. The calculated daily ETc values correlated reasonably well with measured values throughout the season. Regression analysis showed a good linear relationship (R^2 = 0.86) between measured and estimated values, and the slope of the line (1.06) showed just a 6% departure from the 1:1 line. The departure seemed to be created by an overestimation of the calculated ETc values at high ETc rates. For instance, although measured values were limited to a maximum of 8.5 mm d^{-1}, estimated values were as high as 10.7 mm d^{-1}. Differences in the estimated and measured ETc could be due to potential errors in the water balance procedure used to estimate ETc and to potential measurement errors.

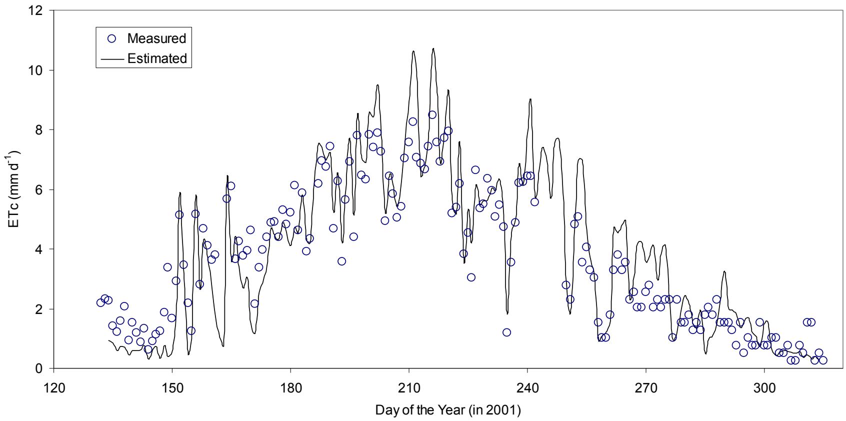


Fig. 15. Comparison of measured and estimated daily maize evapotranspiration (ETc) at North Platte, Nebraska, during 2001. ETc was estimated using the FAO-56 dual crop coefficient procedure (n = 182).

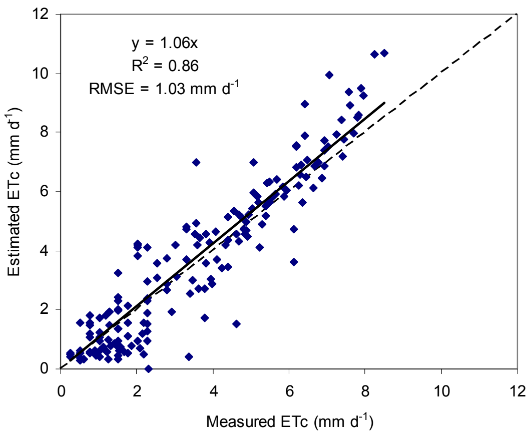


Fig. 16. Relationship between measured and estimated daily maize evapotranspiration (ETc) during 2001 at North Platte, Nebraska. The solid and dashed lines are the regression and 1:1 lines, respectively. RMSE = root mean squared error (n = 182).

4. Conclusions

Daily surface energy balance components, including crop evapotranspiration, for field maize were measured from a surface-irrigated field at North Platte, Nebraska, during 2001. Using these measurements and weather variables from a nearby weather station, other variables such as daily ETo, ETr, ETr/ETo, Kc, and maize ETc were calculated. We found that daily ETo in 2001 varied from less than 0.5 mm d^{-1} during winter to a maximum of about 10 mm d^{-1} during summer. ETr and ETr_Neb were linearly related with ETo, but ETr and ETr_Neb were 29% and 37% higher than ETo. The ETr/ETo ratio varied during the year from 1.03 to 1.68, with lowest values in summer and highest in winter.

All measured energy balance components had considerable day-to-day variability due to rapid changes/fluctuations in weather conditions, which is typical to west-central Nebraska. Although Kc values had considerable daily variations, the values given in FAO-56 for maize, using the lengths of growth stages from Kimberly, Idaho, fitted the measured data reasonably well, except early in the season when the soil surface was wet. The fit improved when we used cumulative growing degree days from crop emergence as the “time” scale.

Daily maize ETc calculated with FAO-56 [ETc = ETo x (dual Kc)] also fitted measured daily ETc values reasonably well (R^2 = 0.86, slope = 1.06). Locally-developed Kc curves can be vital for more accurate quantification of ETc for an effective irrigation management. Locally-derived Kc curves can minimize the errors associated with using curves developed for other climates and for other soils and crop management conditions.

5. Acknowledgements

The authors would like to acknowledge Don Davison for providing technical support for this project. Names of commercial products are solely provided as information to the reader and do not imply an endorsement or recommendation by the authors or their organizations.

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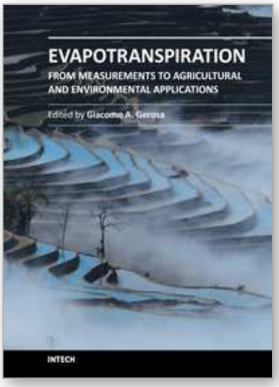

Evapotranspiration - From Measurements to Agricultural and Environmental Applications
Edited by Dr. Giacomo Gerosa

ISBN 978-953-307-512-9
Hard cover, 410 pages
Publisher InTech
Published online 09, November, 2011
Published in print edition November, 2011

This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

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