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Evaluation of the impact of surface residue cover on single and dual crop coefficient for estimating soybean actual evapotranspiration

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Abstract

Single and dual crop coefficient methods are used in conjunction with grass reference evapotranspiration (ET_o) to estimate actual crop evapotranspiration (ET_c). However, the impact of soil surface residue cover on the accuracy of ET_c estimated with these methods is not well understood. The objective of this study is to evaluate and compare the accuracy of the FAO-56 single crop coefficient (single- K_c) and dual crop coefficient (dual- K_c) methods for estimating soybean [*Glycine max* (L.) Merr.] ET_c in a partially residue covered field. The study was conducted at the University of Nebraska–Lincoln, South Central Agricultural Laboratory (SCAL), Nebraska, during the 2007 and 2008 growing seasons. The field was under reduced-tillage (ridge till) on a silt loam soil and irrigated using a subsurface drip irrigation system. Evapotranspiration flux (ET_m) above the crop canopy was measured using a deluxe version of a Bowen ratio energy balance system (BREBS) and ET_o was calculated with the Penman–Monteith method. The single- K_c and dual- K_c -estimated ET_c values, both unadjusted for residue cover, were compared to ET_m . The unadjusted FAO-56 K_c values performed poorly as the single- K_c underestimated ET_m during the initial crop growth stage by 21% in 2007 and 33.6% in 2008 while the dual- K_c overestimated ET_m during the same growth stage by 16.8% in 2007 and 16.5% in 2008. Extended simulations were conducted to determine the magnitude by which ET_c is reduced for each 10% of soil surface covered with crop residue. Downward adjustments in soil water evaporation (E_s) for every 10% of the soil surface covered with crop residue improved the accuracy of ET_c estimated by the dual- K_c method. The largest changes in ET_c due to adjustments in E_s occur during the initial stage of the growing season. The best estimates for seasonal ET_c were obtained by reducing E_s by 5% for every 10% of surface covered with residue in 2007 ($R^2 = 0.77$, RMSD = 0.87 mm d⁻¹, $E = 0.94$) and 2008 ($R^2 = 0.83$, RMSD = 0.84 mm d⁻¹, $E = 0.95$). Greater improvements in the accuracy of estimated seasonal ET_c were obtained by reducing E_s by 2.5% for each 10% of surface covered with residue during the initial stage and by 5% during the rest of the crop growth stage. These results suggest that the more computationally-involved dual- K_c method with adjustments in E_s for each 10% of surface covered with residue improves the prediction of ET_c in fields with soil surface residue cover, especially during the initial growth stage. Inaccurate selection of percentage reduction in E_s can result in substantial overestimation or underestimation of seasonal ET_c by the dual- K_c method.

Keywords: Bowen ratio, Soil water stress coefficient, Soil evaporation coefficient, Crop coefficient, Residue cover

1. Introduction

Crop evapotranspiration (ET_c) from agricultural fields is the sum of crop transpiration (T), soil water evaporation (E_s), and direct evaporation of rainfall intercepted by plant canopy and crop residue (E_i). E_i normally occurs for a very small period following rainfall or sprinkler irrigation and is commonly considered insignificant in many ET_c estimation methods. Meteorological conditions determine the atmospheric evaporating power which is characterized by a grass-reference crop evapotranspiration (ET_o). In addition to many other factors, the rate of T is affected by crop growth stage and soil water content in the root zone, while the rate of E_s is influenced by different fac-

tors that affect soil surface conditions such as tillage practice, crop residue cover on the soil surface, and soil surface wetness. Crop residue left on the surface apart from intercepting rainfall also insulates the soil surface from radiant and advective energy (Steiner, 1989), and increases the diffusive resistance of water vapor transport from the soil to the atmosphere (Hammel, 1996; Flury et al., 2009). Several field studies have shown that surface crop residue can reduce E_s (Russel, 1939; Moody et al., 1963; Adams, 1966; Bond and Willis, 1970; Todd et al., 1991; Heilman et al., 1992; Klocke et al., 2009). Unger and Parker (1976) compared the effects of different types of residue on E_s and found residue thickness and surface coverage, rather than residue type, to be the main factors affecting E_s . Other studies

have also shown that crop residue that only partially covers soil surface has less effect on E_s because of greater surface temperature and larger drying gradients between bare soil and soil under residue covered areas (Willis, 1962; Chung and Horton, 1987; Steiner, 1989; Klocke et al., 2009).

Accurate estimation of ET_c in a soil-residue-crop system is of major interest for comparing crop water use between different tillage practices, determining regional irrigation water requirements, and in-season irrigation management. Direct field measurements of ET_c are possible by using micro-meteorological measurement methods such as lysimeters, Bowen ratio energy balance system, eddy correlation system, and flux profile techniques (Hatfield, 1990). However, these methods are expensive and difficult to deploy and maintain in both time and space. Hence, mathematical models are commonly used for estimating ET_c over the entire range of crop development stages. Many studies show that the Penman-Monteith equation is able to estimate ET_o from weather data under diverse climatic conditions with a reasonable accuracy (Amatya et al., 1995; Ventura et al., 1999; Irmak et al., 2008; Temesgen et al., 2005; Yoder et al., 2005; Lopez-Urrea et al., 2006). Several Penman-Monteith (Monteith, 1965)-type combination-based energy balance modeling approaches have been employed to estimate ET_c by separately taking into account soil surface and plant canopy conditions. These approaches include multi-layer Penman-Monteith-type methods (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990; Choudhury and Monteith, 1988; Norman et al., 1995; Kustas and Norman, 1999; Gardiol et al., 2003; Lagos et al., 2009; Guan and Wilson, 2009) and the dual crop coefficient (dual- K_c) method (Jensen et al., 1971; Wright and Jensen, 1978; Wright, 1981, 1982).

The K_c method was originally developed and proposed by van Wijk and de Vries (1954). Jensen et al. (1971), Wright and Jensen (1978), and Wright (1981, 1982) have improved the K_c concept. These procedures, including dual- K_c , were also adopted by the Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56 (FAO-56, 1998). The dual- K_c method is simpler compared to the heavily-parameterized multi-layer models and may therefore be more suitable for operational applications where daily estimates of ET_c are needed. The dual- K_c method separately estimates daily crop transpiration (T) and soil evaporation (E_s) from reference grass evapotranspiration (ET_o) by applying two coefficients, namely, the basal crop coefficient K_{cb} and a soil water evaporation coefficient K_e (dual- $K_c = K_{cb} + K_e$). The basal crop coefficient (K_{cb}) is crop-specific and represents the ratio of ET_c to ET_o under conditions when the soil surface layer is dry, so that E_s is minimal, but the average soil water content in the root zone is adequate to sustain crop transpiration at a potential rate. The soil water evaporation coefficient (K_e) is the ratio of E_s to ET_o and represents the evaporation from wet soil, which occurs in addition to soil water evaporation included in K_{cb} . When using the dual- K_c method, K_{cb} values are adjusted for local climate and plant water stress conditions, and the K_e values are adjusted for surface soil wetness.

Although the dual- K_c method may provide a more precise approach of determining ET_c in a soil-residue-crop system, the single- K_c method is still widely used to estimate ET_c for irrigation scheduling on an operational basis. In the single crop coefficient (single- K_c) method (Jensen et al., 1970; Doorenbos and Pruitt, 1977), the effect of both T and E_s are integrated into a single crop-specific coefficient with no direct adjustment made for the effects of residue cover and surface soil wetness on E_s . However, adjustments can be made for the effects of limiting soil moisture on T using a plant water stress coefficient. The performance of both single- K_c and dual- K_c methods depends on accurate selection of representative coefficient values for each of the four crop growth stages (initial, crop development, mid-season, and late-season), identification of the locally ad-

justed lengths of the growth stages, and accurate estimation of ET_o from climatic parameters. While the FAO-56 (FAO-56, 1998) presents tables of crop coefficients and lengths of crop growth stages for various crops, these values are only "average" values and may not be valid for various conditions. Use of average FAO table values of crop coefficients and lengths of growth stages without local adjustment could introduce inaccuracies in the estimated ET_c . Because crop coefficients and lengths of growth stages are influenced by many factors including plant species (including hybrids/cultivars), soils, management practices (i.e., population density, row spacing, disease and weed control, irrigation, etc.), and climatic conditions, they should ideally be derived experimentally for each crop and region under various management practices for more accurate and representative estimation of ET_c . However, this is rarely done due to the complexity and costs involved.

Given the tremendous amount of variability in soil and crop management practices and climatic conditions that can influence the performance of the single- K_c and dual- K_c methods to estimate ET_c , very few studies have been conducted to quantify, evaluate, and compare the accuracy of the single- K_c and dual- K_c methods for estimation of ET_c in crop systems. Lui and Pereira (2000) evaluated the single- K_c and dual- K_c methods with measured crop evapotranspiration (ET_m) data and found the dual- K_c method to perform better than the single- K_c method. Tolk and Howell (2001) compared daily ET_m of limited and fully-irrigated grain sorghum to ET_c calculated using single- K_c and dual- K_c with ET_o . With the dual- K_c procedure, they found that the difference between cumulative ET_c and ET_m during the season varied substantially from 2 mm to around 70 mm, and by the end of the season the maximum difference between ET_c and ET_m was about 60 mm or 10%. The single- K_c procedure significantly underestimated final cumulative ET_m in the fully irrigated treatments by as much as 120 mm. ShiZhang et al. (2007) compared ET_m with ET_c estimated using single- K_c and dual- K_c for late rice crop. They found that the relative error between ET_m and ET_c estimated by the single- K_c and dual- K_c varied within 12.4–16.2%, and that the dual- K_c gave better estimates than the single- K_c . Majnooni-Heris et al. (2007) evaluated daily ET_c of maize crop for two crop seasons using single- K_c and dual- K_c methods. They found the seasonal total ET_c estimated by the dual- K_c method to be greater than those estimated by the single- K_c method by 78 and 68 mm during the two crop seasons.

The accuracy of ET_c estimated using the single- K_c and dual- K_c methods as impacted by crop residue left on the soil surface is unknown. The overall objective of this study is to determine whether the more computationally-involved dual- K_c method improves prediction of ET_c in conservation tillage cropping systems, which leaves substantial crop residue on the soil surface, as compared with the single- K_c method. The specific objectives were: (1) to evaluate and compare the accuracy and robustness of the single- K_c and dual- K_c methods for estimation of daily ET_c of soybean in a subsurface drip-irrigated field with partial surface residue cover, and (2) to determine the magnitude by which ET_c is reduced for each 10% of soil surface covered with crop residue.

2. Materials and methods

2.1. Description of study site and measurements

The datasets for this study were obtained from field research (Irmak and Mutibwa, 2009a, 2009b) conducted in a 13.5 ha subsurface drip-irrigated soybean field during the 2007 and 2008 growing seasons (May–October). The experimental field is located at the University of Nebraska–Lincoln, South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (latitude 40°34'N and longitude 98°8'W at an elevation

of 552 m above mean sea level). The climate at Clay Center is described as sub-humid with warm and dry summers and very cold and extremely windy winters with average temperatures below 0 °C. The warmest month of the year is usually July with an average maximum temperature of 30.9 °C, while the coldest month of the year is January with an average minimum temperature of -11.1 °C. The long-term (1982–2008) annual average precipitation at Clay Center is about 700 mm. Rainfall is not evenly distributed throughout the year. The wettest month of the year is May with an average rainfall of 120 mm. The soil in the field is classified as Hastings silt loam which is well drained soil with a 0.5% slope. The particle size distribution is 15% sand, 62.5% silt, 20% clay, and 2.5% organic matter content. The soil field capacity (θ_{fc}) is 0.34 m³ m⁻³, permanent wilting point (θ_{wp}) is 0.14 m³ m⁻³, and the saturation point (θ_{sat}) is 0.51 m³ m⁻³ (Irmak et al., 2008; Irmak and Mutiibwa, 2009a, 2009b; Irmak, 2010).

In 2007, the field was planted with soybean (variety Pioneer 93M11) seeds on May 21 at a rate of 156,000 plants per hectare with a planting depth of 0.025 m and row spacing of 0.76 m with an east–west planting direction. Plants emerged on May 26 and were harvested on October 24, 2007. In 2008, the field was again planted with the same soybean variety on May 19, at the same planting density, planting depth, and row spacing as in 2007. Plants emerged on May 24 and were harvested on October 1, 2008. The subsurface drip irrigation (SDI) laterals were placed in the middle of every other row (1.52 m) and at a depth of approximately 0.40 m. Irrigation was applied seven times during the 2007 crop season and four times during the 2008 growing seasons. The available soil water in the effective root zone was maintained at maximum allowable depletion of approximately 45% of plant-available soil water during the mid-season growth stage to avoid crop water stress. Leaf area index (*LAI*) was measured using a model LAI-2000 plant canopy analyzer (LI-COR Biosciences, Lincoln, Nebraska, USA). On average, a total of 60 *LAI* measurements were taken on each measurement day and averaged for the day with measurements starting when *LAI* was approximately 1.10 (32 DAP). On each *LAI* measurement day, plant height (*h*) measurements were taken by measuring from the soil surface to the tip of the tallest leaf from approximately 15 randomly-selected plants and the values were averaged for that day (Mutiibwa and Irmak, 2011).

The evaporative flux (ET_m) above the crop canopy was measured by the Bowen ratio energy balance system (BREBS). The Bowen ratio formula (Bowen, 1926) for evaporative flux measurement is derived from the energy balance of the canopy surface and expressed as:

$$R_n - G = H + \lambda ET_c \quad (1)$$

where R_n = net radiation above crop canopy, G = soil heat flux, H = sensible heat flux, and λET_c = latent heat flux (all units in W m⁻²). Equation (1) can be rewritten in the following form:

$$ET_c = \frac{(R_n - G)}{\lambda(1 + \beta)} \quad (2)$$

where β = Bowen ratio $H/\lambda ET_c$ (dimensionless) and is calculated from measurements of air temperature and vapor pressure gradients taken at two heights above the crop canopy and within the boundary layer of the surface. Assuming that the transfer coefficients of heat and water vapor are equal, it can be shown that (Bowen, 1926; Tanner, 1960):

$$\beta = \frac{H}{\lambda ET_c} = \frac{\gamma \partial T_a / \partial e}{\partial e} \quad (3)$$

where γ = psychrometric constant (kPa °C), and $\partial T_a / \partial e$ is the gradient of the air temperature (T_a) and vapor pressures (e) for heights of 0.3–3.0 m. Measurements of H , G , R_n , T_a and e were made using a deluxe version of a BREBS (Radiation and En-

ergy Balance Systems, REBS, Inc., Bellevue, WA, USA) that was installed in the middle of the experimental field. The fetch distances were 520 m in the north–south direction and 280 m in the east–west direction. T_a and relative humidity (*RH*) were measured using two platinum resistance thermometers and monolithic capacitive humidity sensors (REBS Models THP04015 and THP04016, respectively). The BREBS used an automatic exchange mechanism that physically exchanged the T_a and *RH* sensors between two heights above the canopy. The lower exchanger sensors level was maintained at an average height of 1 m above the canopy as the crop grew, and the distance between the upper and lower exchanger sensors was kept at a constant distance of 1 m. Incoming and outgoing shortwave radiation were measured simultaneously using REBS model THRDS7.1 double sided total hemispherical radiometer. R_n was measured using a REBS Q*7.1 net radiometer. Both radiometers were installed at 4.5 m above the ground surface. G was measured using three REBS HFT-3.1 heat flux plates and three REBS STP-1 soil thermocouple probes. Each pair of soil heat flux plate and soil thermocouple was placed at a depth of 0.08 m below the soil surface in close proximity to each other. Measured G was adjusted for soil temperature and soil moisture content (Irmak, 2010). The BREBS and other datasets used in this study are part of the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) (Irmak, 2010) that operates ten deluxe versions of BREBS and one eddy covariance system over various vegetation surfaces. Detailed description of the microclimate measurements, including λET_c , H , G , R_n , and other microclimatic variables (actual vapor pressure, T_a , *RH*, wind speed and direction, incoming and outgoing shortwave radiation, albedo, and soil temperature) are presented in Irmak (2010).

The daily weather data (incoming shortwave radiation, air temperature, relative humidity, wind speed, and precipitation) used for the calculation of ET_o was obtained from an automated weather station (AWS) located approximately 1 km from the experimental field and operated by the High Plains Regional Climate Center (HPRCC): <http://hprcc1.unl.edu/cgi-hpcc/home.cgi>. The HPRCC-AWS consisted of standard instruments used for measuring climatic variables and was maintained on a natural grass. The fetch condition was adequate in all directions of the weather station. No corrections or adjustments were applied to the weather data as the HPRCC applies vigorous quality and integrity of the collected microclimatic data on a real-time basis.

2.2. Calculation of grass-reference evapotranspiration (ET_o)

Grass-reference evapotranspiration (ET_o) was calculated using the ASCE form of the Penman–Monteith (ASCE-EWRI PM) equation (ASCE-EWRI, 2005), which is essentially the original Penman–Monteith equation with an assumed fixed canopy resistance for a hypothetical grass-reference surface. The Penman–Monteith grass-reference equation for a daily time step is expressed as:

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma (C_n / (T + 273)) u_2 (e_s - e_a)}{[\Delta + \gamma (1 + C_d u_2)]} \quad (4)$$

where ET_o = grass-reference evapotranspiration (mm d⁻¹), Δ = slope of saturation vapor pressure versus air temperature curve (kPa °C⁻¹), R_n = net radiation (MJ m⁻² d⁻¹), G = soil heat flux (MJ m⁻² d⁻¹), T = mean daily air temperature (°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, *VPD*), γ = psychrometric constant (kPa °C), C_n = numerator constant that changes with reference surface (900 °C mm s³ Mg⁻¹ d⁻¹ for grass), C_d = denominator constant that changes with reference surface (0.34 s m⁻¹ for grass). Procedures for calculating the various parameters

of Equation (4) from measured weather data [solar radiation (R_s), RH , wind speed measured at 2 m (u_2), and air temperature (T_a)] are outlined in ASCE-EWRI (2005).

2.3. Calculation of ET_c using single- K_c and dual- K_c methods

Detailed description of procedures for applying the single- K_c and dual- K_c methods to estimate ET_c is given in FAO-56. Single- K_c method estimates ET_c using the equation:

$$ET_c = K_s K_c ET_o \quad (5)$$

and the dual- K_c method estimates ET_c using:

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (6)$$

where ET_o = grass reference evapotranspiration, K_c = single crop coefficient, K_{cb} = basal crop coefficient, K_s = soil water stress coefficient, and K_e = soil water evaporation coefficient. Appropriate K_c and K_{cb} values for soybean were taken from FAO-56, which are derivatives of the values which were originally introduced and published by Doorenbos and Pruitt (1977) in FAO-24. The K_c table in FAO-24 had multiple entries for four wind and RH classes. These FAO-24 K_c -values have been condensed into one column of values in FAO-56 representing K_c -values for standard climatic conditions defined as a sub-humid climate having average daytime minimum relative humidity (RH_{min}) = 45% and having calm to moderate wind speeds (u_2) averaging 2 m s⁻¹. For climate with $RH_{min} \neq 45\%$ or u_2 at 2 m $\neq 2$ m s⁻¹, the coefficients are adjusted according to the following equation (Pereira et al., 1996) :

$$K_{adj} = K_{table} + [0.04 (u_2 - 2) - 0.004 (RH_{min} - 45)] (h/3)^{0.3} \quad (7)$$

where $K_{table} = K_c$ or K_{cb} values taken from the FAO-56 tables, and $K_{adj} = K_c$ or K_{cb} adjusted for the local climatic conditions. The K_s concept was first introduced by Jensen et al. (1971) to account for increased evaporation occurring when the soil surface is partially or completely wetted by irrigation or precipitation. The K_s was estimated as:

$$K_s = \frac{(TAW - D_r)}{(1 - p)TAW} \quad \text{for } D_r > RAW \quad (8)$$

and

$$TAW = 1000 (\theta_{Fc} - \theta_{WP}) Z_r \quad (9)$$

$$RAW = p TAW \quad (10)$$

where D_r = root zone depletion, defined as water shortage relative to field capacity (mm), RAW = readily available soil water in the root zone (mm), TAW = total available soil water in the root zone (mm), p = fraction of TAW that a crop can extract from the root zone without suffering water stress, θ_{Fc} = soil water content at field capacity ($\theta_{Fc} = 0.34$ m³ m⁻³), θ_{WP} = soil water content at permanent wilting point ($\theta_{WP} = 0.14$ m³ m⁻³), and Z_r = the effective rooting depth (m). The initial effective depth at planting ($Z_{rmin} = 0.1$ m) and the maximum effective depth occurring at mid-season ($Z_{rmax} = 1.2$ m) of soybean were used. The development of the root zone was assumed to increase in proportion to the increase in K_{cb} . The value of p varies with atmospheric evaporative demand, crop characteristics and soil type. Doorenbos et al. (1986) suggest p values for different crops ranging between 0.125 and 0.7 for an atmospheric evaporative demand varying from 2 mm to 10 mm d⁻¹. Several authors show that the p value for soybean is between 0.4 and 0.6 (Doorenbos et al., 1986; Rosadi et al., 2007; Raes et al., 2009). An average of $p = 0.5$ as suggested for the FAO AquaCrop model (Raes et al., 2009) was used in the study.

The calculation of root zone depletion (D_r) employs a daily water balance computation for the root zone expressed as:

$$D_{r,i} = D_{r,i-1} - (P_i - RO_i) - I_i - q_i + ET_{c,i} + DP_i \quad (11)$$

where $D_{r,i}$ = root zone depletion at the end of day i (mm), $D_{r,i-1}$ = depletion in the root zone at the end of the previous day, $i-1$ (mm), P_i = precipitation on day i (mm), RO_i = runoff from the soil surface on day i (mm), I_i = net irrigation depth on day i that adds to root zone water content (mm), q_i = capillary rise from groundwater table on day i (mm), $ET_{c,i}$ = actual crop evapotranspiration on day i (mm), and DP_i = deep percolation from the root zone on day i (mm). The study field was flat and groundwater table low, hence RO_i and q_i were assumed to be zero.

The sum of K_{cb} and K_e in Equation (6) cannot exceed some maximum value (K_{cmax}) which defines an upper limit on the evaporation and transpiration from any cropped surface based on the available latent energy. K_{cmax} was calculated for grass reference ET_o as:

$$K_{cmax} = \left\langle \max \left\{ 1.2 + \left(\frac{h}{3} \right)^{0.3} [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \right\} (K_{cb} + 0.05) \right\rangle \quad (12)$$

where h = mean maximum plant height (m) and $\max$ indicates the selection of the maximum value within the brackets $\{\}$. The K_e was adjusted for the soil surface wetness using the following equation:

$$K_e = K_r (K_{cmax} - K_{cb}) \leq f_{ew} K_{cmax} \quad (13)$$

where K_r = a dimensionless evaporation reduction coefficient and f_{ew} = the fraction of the soil that is both exposed to solar radiation and that is wetted. K_r was calculated as:

$$K_r = \frac{(TEW - D_{e,i-1})}{(TEW - REW)} \quad (14)$$

and

$$TEW = 1000 (\theta_{Fc} - 0.5 \theta_{WP}) Z_e \quad (15)$$

where TEW = total evaporable water defined as the maximum depth of water that can be evaporated from the soil when the top soil has been initially completely wetted (mm), $D_{e,i-1}$ = cumulative depth of evaporation from the soil surface layer at the end of day $i-1$ (mm), Z_e = depth of the surface soil layer that is drying by evaporation (m), and REW = readily evaporable water (mm). Average typical values of Z_e and REW for silt loam soil ($Z_e = 0.1$ m and $REW = 9.5$ mm) were used.

Because the study field was irrigated by a subsurface drip irrigation system with drip laterals buried at 0.4 m below the soil surface, soil surface wetting was only by precipitation which was assumed to be evenly distributed over the soil surface (crop canopy sometimes redistributes rainfall over the soil surface). The effective fraction of the soil surface covered by crop canopy was estimated as:

$$f_c = \left[\frac{(K_{cb} - K_{cmin})}{(K_{cmax} - K_{cmin})} \right]^{(1+0.5h)} \quad (16)$$

where f_c = effective fraction of the soil surface covered by crop canopy, K_{cmin} = minimum K_c for bare soil with no ground cover (≈ 0.15), and h = mean plant height. Therefore, the fraction of the soil that is exposed to solar radiation and air ventilation and from which the majority of E_s takes place is expressed as $(1 - f_c)$.

Lastly, adjustments were made on the estimated ET_c to account for the effects of residue cover on E_s . A general rule of thumb is to reduce E_s by about 5% for each 10% of the soil surface that is covered by crop residue. For example, when 60% of the soil surface is covered by crop residue, then soil evaporation is reduced by 30%. To apply this to the single- K_c method, single- K_c values during the initial crop growth stage (K_{cini}) are reduced by about 30%, and single- K_c values during the mid-season crop growth stage (K_{cmid}) are reduced by 30% of the difference be-

tween $K_{c\ mid}$ and $K_{c\ ini}$. If the same adjustment is applied to the dual- K_c method, the magnitude of E_s is reduced by 30%.

2.4. Estimation of surface residue cover

The study used the relationship between measured crop yield and crop residues produced (Wortmann et al., 2008) and tables of typical percent residue remaining after winter-weathering and various field operations (Shelton et al., 2000) to estimate the percent of residue from the previous crop season remaining on the field surface after planting. Wortmann et al. (2008) estimate that approximately 1 ton of residue (at 10% moisture) is produced with 1.02 ton of maize grain yield and 0.82 ton of soybean. In 2007, the residue remaining on the field was from a previous maize crop harvested on October 5–6, 2006. The yield of 2006 maize crop was 11.6 ton ha⁻¹ and the amount of residue produced at harvest was estimated at 11.4 ton ha⁻¹. Maize residues are less fragile and are little affected by over winter-weathering. About 90% of maize residue remains after winter weathering (Shelton et al., 2000). The maize residue stalks were shredded by a stalk chopper before planting soybean crop in 2007. The field was ridge-tilled and planted which left about 60% of residue remaining on the soil surface (Shelton et al., 2000). The final amount of surface residue remaining on the field surface at the beginning of the 2007 crop season was 6.2 ton ha⁻¹ estimated by multiplying the amount of residue after harvest by the percent residue remaining after winter-weathering and the percent residue remaining after planting operations. The 2007 soybean crop was harvested in October 2007, and the combine-measured yield and estimated amount of residue produced were 4.7 ton ha⁻¹ and 5.7 ton ha⁻¹, respectively. Soybean residues are fragile and are reduced by over winter-weathering to about 75% (Shelton et al., 2000). In 2008 the field was not tilled but ridge-planted with soybean in May 2008 which resulted in little or no change of surface residue remaining on the soil surface. The final amount of residue remaining at the beginning of the 2008 crop season was 4.3 ton ha⁻¹ estimated by multiplying the amount of residue after harvest by the percent residue remaining after winter weathering.

The amounts of residue remaining at the field surface was evenly distributed and continued to decrease during the growing season due to residue decomposition. Residue decomposition is controlled mainly by environmental factors, primarily temperature and moisture content of residue layer (Gregory et al., 1985; Roper, 1985), carbon/nitrogen (C/N) ratio of the residue (Meentemeyer, 1978; Parr and Papendick, 1978; Aber and Melillo, 1982; Reinertsen et al., 1984), solar radiation and humidity. The daily amount of residue remaining on the soil surface was estimated using a first order exponential decomposition function (Steiner et al., 1999):

$$M_t = M_o \exp^{-k_d (DCD)} \quad (17)$$

where M_t is total residue mass at time t (ton ha⁻¹), M_o is the initial mass at the beginning of the crop season (ton ha⁻¹), k_d is a crop-specific decomposition coefficient (ton ton⁻¹ d⁻¹), and DCD is decomposition days. The coefficient k_d accounts for the differences in C/N ratio and physical properties of the residues and reported values for legume residues are significantly higher than those of cereal residues. Steiner et al. (1999) and Quemada (2004) reported k_d values ranging from 0.015 to 0.042 for cereal residues while van Donk et al. (2008) reported k_d values ranging from 0.02 to 0.03 for legume residues and 0.013 to 0.015 for cereal residues. The values $k_d = 0.030$ for soybean residue and $k_d = 0.015$ for maize residue were used in this study. DCD is calculated as a function of daily air temperature and residue moisture coefficients. Daily temperature and moisture coefficients (TC and MC , respectively) are calculated and constrained from 0 to 1, with 1 indicating conditions for maximum decomposition and 0 indicating no decomposi-

tion. Based on the principle of most limiting factor, the DCD for a given day is equal to the minimum of TC or MC and expressed as:

$$DCD = \min(TC, MC) \quad (18)$$

The coefficient TC is calculated using the procedures proposed by Steiner et al. (1994):

$$TC = \frac{2T_a^2(T_{opt})^2 - T_a^4}{(T_{opt})^4} \quad (19)$$

where T_a is daily average air temperature (°C), and T_{opt} is the optimum air temperature for residue decomposition ($T_{opt} = 32$ °C). In calculating MC , it is assumed that 4 mm of precipitation is enough to fully wet a layer of residues (Steiner et al., 1994). If precipitation for a given day is more than 4 mm, the precipitation coefficient (PC) is set to 1, and for precipitation below 4 mm, PC is equal to precipitation divided by 4. MC was calculated (Steiner et al., 1994) as:

$$MC_t = 0.5MC_{t-1} + PC_t \quad (MC_t = 1.0 \text{ when } MC_{t-1} > 1.0) \quad (20)$$

$$PC_t = 1.0 \quad \text{when } P_t \geq 4.0 \text{ mm} \quad (21)$$

$$PC_t = P_t / 4 \quad \text{when } P_t < 4.0 \text{ mm} \quad (22)$$

where P_t is the current day precipitation (mm), PC_t is precipitation coefficient for the current day, and MC_t and MC_{t-1} are the moisture coefficients for the current and previous day, respectively. The fraction of soil surface covered with crop residue (C_r) was estimated as a function of the mass of residue (Gregory, 1982) which is expressed as:

$$C_r = 1 - \exp(-A_m M_t) \quad (23)$$

where A_m is an empirical parameter that converts mass to an equivalent area and varies with residue characteristics and randomness of distribution. Reported values of A_m for maize and soybean are 0.32 and 0.20, respectively (Gregory, 1982).

2.5. Analyses and statistics

The predictive qualities of the single- K_c and dual- K_c methods were evaluated by comparing estimated evapotranspiration (ET_c) against BREBS-measured evapotranspiration (ET_m) using graphical presentations and statistical parameters. The goodness-of-fit between ET_m and ET_c was evaluated using the coefficient of determination (R^2), the modified coefficient of efficiency (E) proposed by Legates and McCabe (1999), and cumulative ET_m and ET_c . The R^2 describes the proportion of total variance in the measured data that is explained by the estimates. It ranges from 0.0 to 1.0, with higher values indicated better agreement. However, R^2 is insensitive to additive and proportional differences between datasets. Because of these limitations, E was used as an additional measure to verify the agreements between ET_m and ET_c . E is expressed as:

$$E = 1.0 - \frac{\sum_{i=1}^n (X_i - Y_i)^2}{\sum_{i=1}^n (X_i - \bar{X})^2} \quad (24)$$

where X = measured data, Y = estimated data, n = size of the sample data, i = number of order of variable in the sample, and $\bar{X}$ = mean of X . The statistic E examines whether the difference between measured and estimated data is as large as the variability in the measured data. The possible E values range from $-\infty$ to 1, with higher values indicating better agreement between the measured and estimated data. An E value of 0 indicates that the estimated data is only as good as the mean of the measured data, while a negative E value indicates that the mean of the measured data is better than the estimated data. E represents an improvement over R^2 in that it is sensitive to differences in measured and estimated means and vari-

Figure 1. Estimated fraction of soil surface covered with crop residue during the crop growing seasons in 2007 and 2008.

ances, and will always be lower than that value (Legates and McCabe, 1999).

For error analysis, the root mean square difference (*RMSD*) and mean bias error (*MBE*) were used. Both *RMSD* and *MBE* represent the average difference between measured and estimated datasets. The *RMSD* measures the non-systematic variation between datasets and the *MBE* measures the systematic variation between datasets. The *RMSD* and *MBE* are expressed as:

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - Y_i)^2} \quad (25)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (X_i - Y_i) \quad (26)$$

To ascertain statistical significant differences between the measured and estimated evapotranspiration and between single- K_c and dual- K_c estimated evapotranspiration, a two-sample *t*-test of significance for analyzing the difference between the means of two datasets was added in our analysis. A *t*-test was calculated at 5% critical value for rejection ($\alpha = 0.05$). Analysis of variance (ANOVA) at 5% critical value for rejection ($\alpha = 0.05$) was calculated to test the null hypothesis of equality in the means of estimated ET_c values obtained by different levels of E_s reduction in the dual- K_c method. Both *t*-test and ANOVA were performed by statistical functions in Excel 2010 (Microsoft 2010).

3. Results and discussions

3.1. Crop residue cover and canopy shading

Data are presented showing the fraction of soil surface covered by crop residue and shaded by the canopy in 2007 and 2008 growing seasons, which may have contributed to the differences observed in estimated ET_c . The experimental field was under reduced tillage with crop residue evenly spread on the soil surface. The estimated fraction of soil surface covered with crop residue during the growing season in 2007 and 2008 are presented in Figure 1. In 2007, the fraction of residue cover decreased from about 86% in early season to about 58% at the end of the season, whereas it was about 60% in early season and 27% in late season in 2008. The year 2007 had more residue cover on the soil surface and a slower residue decomposition rate than 2008, since residue cover in 2007 was predominantly from a previous year maize crop, and residue cover in 2008 was predominantly from the soybean harvested at the end of the 2007 crop season. Maize produces more mass of less fragile residue than soybean. After mid-season growth stage, soybean leaves gradually senesce and fall onto the ground increasing the amount of surface residue cover on the soil sur-

Figure 2. Crop coefficient curves and measured LAI in 2007 and 2008.

face. Crop residues on the soil surface reduce the amount of solar radiation reaching the soil surface resulting in decreased energy available for E_s . Surface residue further decreases E_s by increasing the diffusive resistance of water vapor transport from the soil to the atmosphere (Hammel, 1996; Flury et al., 2009). Todd et al. (1991) showed that the presence of a straw mulch in a maize field significantly reduced E_s to between 0 and 0.10 mm d⁻¹ under dryland conditions, 0.5 mm d⁻¹ under limited irrigation, and 0 to 1.1 mm d⁻¹ under full irrigation. Because of the differences in percent soil surface covered with crop residue in this study, the impact of residue on E_s between the two years (2007 and 2008) were different.

The fraction of soil surface shaded by soybean canopy is influenced by crop row spacing and seeding rates (Renner and Mickelson, 1997; Nice et al., 2001), the angle of solar radiation inclination, crop variety, and environmental factors that affect plant growth. Todd et al. (1991) showed that canopy shading

Figure 3. K_{cb} , single- K_c and dual- K_c crop curves showing the peaking of dual- K_c following rainfall events in (a) 2007 and (b) 2008.

Figure 4. BREBS-measured ET_m and ET_c estimated using the single- K_c and dual- K_c methods showing similar trends and responses to changes in daily meteorological conditions throughout the growing season (a) 2007 and (b) 2008.

played a more important role in reducing E_s than straw mulch under dryland conditions. Under limited and full irrigation, they found that crop canopy and straw mulch contributed equally to E_s reduction. Both 2007 and 2008 crops were planted with the same soybean variety, at the same seeding rates and row spacing. Soil and plant nutrient and water management practices were also similar. Thus, the only difference between the two years was in climatic factors. The results shown in Figure 2 indicate that the difference in canopy shading between the two years was minimal.

3.2. Basal crop coefficient, single- K_c and dual- K_c crop curves

The basal crop coefficient (K_{cb}) and single- K_c values for the four growth stages (initial, crop development, mid-season, and late-season) of soybean were adjusted for the local climate and soil water stress conditions. The average lengths of the growth stages of soybean for central USA were used. However, the lengths of these growth stages can be influenced by many factors, including planting date, soil temperature, soil and crop management practices, irrigation regime, and the local climatic conditions. Crop curves generated by plotting crop coefficient values versus the time of the season were graphed with measured LAI in Figure 2 to show the relationship of crop coefficients to actual leaf area development. Figure 2 shows that the

growth rate of LAI in both years (2007 and 2008) was slightly delayed as compared with the average growth rate for central USA. Assuming that full canopy cover for soybean is reached at $LAI = 3.0$, the beginning of the mid-season growth stage appears to start later than the times suggested in the crop curve by 2 d in 2007 and 5 d in 2008. Also assuming that the late-season stage begins with the start of decline in LAI , it appears that it started earlier by 12 d in 2007 and 8 d in 2008. These shifts in lengths of the growing stages may have affected the accuracy of estimated ET_c . The K_e value was selected for silt loam soil and adjusted for surface soil wetness.

Figure 3 shows that K_{cb} and single- K_c crop curves are time-averaged for the initial, development, mid-season and late season crop growth stages. In the initial stage, E_s is the predominant component of ET_c , and K_{cb} and single- K_c are constant representing average rate of E_s from a dry soil surface. In the crop development stage, K_{cb} and single- K_c are increasing. This is due to the development and expansion leaf surface. As the number and size of leaves increase, the number of stomata increases and so is the transpiration rate. The transpiration rate increase is directly related to ET_c . At mid-season stage, the full canopy cover is reached and transpiration rate is typically at a potential (maximum) rate. As the leaves mature and senescence set in, the number of leaves transpiring decreases and the crop curve decreases. The dual- K_c is responsive to the

Figure 5. Regression plots of seasonal ET_m and ET_c estimated by the single- K_c and dual- K_c methods.

surface wetness and increases whenever the soil surface was moist, following rainfall especially during the initial and late-season growth stages. Effects of surface wetness were minor after full cover was reached. For example, Figure 3 showed high peaks in dual- K_c during the initial and crop development stages following rainfall events, while the impact of rainfall on K_c value was less pronounced during mid-season stage.

3.3. Estimated ET_c with single- K_c and dual- K_c methods unadjusted for residue cover

BREBS-measured ET_m and ET_c estimated using the single- K_c and dual- K_c methods had similar trends and responses to changes in daily meteorological conditions throughout the growing season in both 2007 and 2008 as shown in Figure 4. However, large differences between ET_m and ET_c values are observed during the initial and at the end of the late-season growth stages. In both years, the single- K_c underestimated ET_m during the initial crop growth period while dual- K_c overestimated ET_m during the same growth stage. Cumulative ET_m during the initial growth stage was 55.4 mm in 2007 and 66.0 mm in 2008. The single- K_c method underestimated ET_m during the initial stage by 21.1 and 33.6% in 2007 and 2008, respectively. The RMSD and MBE between ET_m and ET_c estimated by single- K_c during the same stage were 1.56 mm d⁻¹ and 0.60 mm, respectively, in 2007; and 1.84 mm d⁻¹ and 1.1 mm, respectively, in 2008. The dual- K_c method overestimated ET_m during the initial growth stage by 16.8 and 16.5%

in 2007 and 2008, respectively. The RMSD and MBE between ET_m and ET_c estimated by dual- K_c during the same stage were 1.1 mm d⁻¹ and -0.5 mm, respectively, in 2007; and 1.2 mm d⁻¹ and -0.5 mm, respectively, in 2008. The coefficient of efficiency (E) between ET_m and the estimated ET_c during the same stage was 0.40 for single- K_c and 0.80 for dual- K_c in 2007, and 0.60 for single- K_c and 0.89 for dual- K_c in 2008.

During the crop development growth stage, both single- K_c and dual- K_c methods overestimated ET_m . Cumulative ET_m during the development growth stage was 109 mm in 2007 and 123 mm in 2008. The single- K_c method overestimated ET_m during the development stage by 16.1 and 11.0% in 2007 and 2008, respectively. The RMSD and MBE between ET_m and the single- K_c estimated ET_c during the same stage were 1.3 mm d⁻¹ and -0.6 mm, respectively, in 2007; and 1.0 mm d⁻¹ and -0.4 mm, respectively, in 2008. The dual- K_c method overestimated ET_m during the development stage by 18.1 and 13.8% in 2007 and 2008, respectively. The RMSD and MBE between ET_m and dual- K_c estimated ET_c during the same stage were 1.3 mm d⁻¹ and -0.7 mm, respectively, in 2007; and 1.0 mm d⁻¹ and -0.6 mm, respectively, in 2008. Cumulative ET_c estimated by single- K_c and dual- K_c methods during the development growth stage were 43.7 mm and 64.7 mm, respectively, in 2007 and 43.9 mm and 76.9 mm, respectively, in 2008. The agreement between ET_m and ET_c was very good ($E > 0.98$) for both the single- K_c and dual- K_c methods during the mid-season growth stage. At the mid-season stage, the plant canopy attains effective full ground cover and ET_c is predom-

inantly plant transpiration (T). Cumulative ET_m during the mid-season growth stage was 313 mm in 2007 and 289 mm in 2008. The single- K_c and dual- K_c methods underestimated ET_m during the mid-season growth stage by 4.2 and 4.4% in 2007, respectively, but in 2008 both methods overestimated ET_m by 3%. The $RMSD$ during the mid-season growth stage was low (0.4 mm d^{-1}) for both single- K_c and dual- K_c methods in 2007 and 2008 crop growing seasons.

The agreement between ET_m and ET_c during the late-season growth stage was poor for both K_c methods. Both single- K_c and dual- K_c overestimated ET_m towards the end of the late-season stage. The late-season growing stage of soybean is usually marked by senescence of leaves, beginning with the lowest leaves of the plant. High temperatures may accelerate senescence and shorten the late season stage. Cumulative ET_m during the late season growing stage was 58.4 mm in 2007 and 41.8 mm in 2008. The single- K_c method overestimated ET_m during the late season stage by 12.8 and 60.2% in 2007 and 2008, respectively. The $RMSD$ and MBE between ET_m and the single- K_c estimated ET_c during the same stage were 0.9 mm d^{-1} and -0.3 mm , respectively, in 2007; and 1.3 mm d^{-1} and -1.1 mm , respectively, in 2008. The dual- K_c method overestimated ET_m during the development stage by 51 and 75% in 2007 and 2008, respectively. The $RMSD$ and MBE between ET_m and dual- K_c estimated ET_c during the same stage were 1.8 mm d^{-1} and -1.3 mm , respectively, in 2007; and 1.6 mm d^{-1} and -1.3 mm , respectively, in 2008.

Figure 5 shows the regression plots of ET_m and ET_c estimated by the both K_c methods for the whole crop season counted from planting to the end of the late season stage. The R^2 for the single- K_c and dual- K_c methods was 0.72 and 0.64, respectively, for the 2007 crop season and 0.63 and 0.75, respectively, for the 2008 crop season. These results show that in 2007, the ET_c estimated by the single- K_c method was in closer agreement to ET_m than the ET_c estimated by the dual- K_c method. But in 2008, the reverse was true with the ET_c estimated by the dual- K_c method being in closer agreement to ET_m , indicating inconsistency of the K_c method in estimating ET_c . Figure 6 shows the seasonal cumulative ET_m and ET_c in 2007 and 2008 crop seasons. The seasonal cumulative ET_m was 535 mm in 2007 and 520 mm in 2008. The seasonal cumulative ET_c estimated by the single- K_c method was equal to the seasonal cumulative ET_m in 2007 and it overestimated the seasonal cumulative ET_m by 27.3 mm (5.3%) in 2008. The dual- K_c method overestimated the seasonal cumulative ET_m by 45.6 mm (8.5%) in 2007 and by 67.9 mm (13.1%). The $RMSD$ and E between ET_m and single- K_c estimated ET_c for the entire crop season were 1.0 mm d^{-1} and 0.92, respectively, for 2007; and 1.1 mm d^{-1} and 0.90, respectively, for 2008. Similarly, the $RMSD$ and E between ET_m and dual- K_c estimated ET_c for the entire crop season were 1.1 mm d^{-1} and 0.91, respectively, for 2007; and 1.0 mm d^{-1} and 0.92, respectively, for 2008. A two-sample t -test of significance analysis of the difference between the means of BREBS measured- ET_m and ET_c obtained by the crop coefficient methods is given in Table 1. The results showed no statistical significance difference between the seasonal mean of BREBS-measured ET_m and seasonal mean of single- K_c estimated ET_c for both 2007 and 2008. The seasonal mean of dual- K_c estimated ET_c was significantly different from BREBS-measured ET_m in 2008 but not in 2007. Comparison between the seasonal means of ET_c estimated by the single- K_c and dual- K_c methods also showed statistical significance difference in 2008 but not in 2007.

3.4. Adjustment of estimated ET_c for surface residue cover

In the studies cited above, E_s is shown to be reduced by surface residue cover and the proportion by which it is reduced is influenced by several factors, including residue thickness and the fraction of the soil surface covered. The FAO-56

Figure 6. Cumulative ET measured by BREBS and estimated by the single- K_c and dual- K_c methods.

recommends a reduction of 5% in E_s for each 10% of the soil surface covered with crop residue. However, the recommended values are only approximate and a more accurate assessment of the impact of residue is needed for precise estimation of ET_c in cropping systems with soil surface residue cover. From the results presented in Figure 4, it was observed that single- K_c method substantially underestimated ET_c during the initial growing stage when ET_c is predominantly E_s and largely influenced by soil surface conditions. Hence, the single- K_c method-estimated ET_c did not need a downward adjustment on E_s due to the impact of surface residue cover. The dual- K_c method, on the other hand, substantially overestimated ET_c during the initial and crop development stages and therefore needed a downward adjustment on E_s due to the impact of surface residue cover. The E_s component of ET_c estimated using the dual- K_c method was test-adjusted at four levels to determine the optimum percentage of reduction in E_s to account for soil surface covered with crop residue. The testing levels were set at 0, 2.5, 5, and 7.5% reduction in E_s for each 10% of surface covered by residue. The estimated surface residue cover showed that in 2007 the fraction of residue cover decreased from about 86% in the early season to about 58% at the end of the season, whereas in 2008 it decreased from about 60% in the early season to 27% at the end of the season.

The regression analysis between ET_m and the adjusted ET_c are shown in Figures 7 & 8 for 2007 and 2008. Table 2 presents a summary of statistical analysis used to compare the dual- K_c estimated seasonal ET_c at various levels of E_s adjustment with the single- K_c estimated ET_c and ET_m . The best estimates of seasonal ET_c were obtained by reducing E_s by 5% in 2007 ($R^2 = 0.77$, $RMSD = 0.87 \text{ mm d}^{-1}$, $E = 0.94$) and 2008 ($R^2 = 0.83$,

Figure 7. Regression plots of seasonal ET_m and ET_c estimated by the dual- K_c methods at various levels of E_s reduction in 2007 crop season (a) 0%, (b) 2.5%, (c) 5%, and (d) 7.5%.

$RMSD = 0.84 \text{ mm d}^{-1}$, $E = 0.95$). Figure 9 shows the cumulative ET_c by various E_s reduction levels compared to ET_m , and Table 3 shows the percent change in cumulative ET_c for each growth stage at various levels of E_s reduction per 10% of the soil sur-

face covered with crop residue. The most notable changes in ET_c due to adjustments in E_s occur during the initial and crop development stages. During the mid-season growth stage, adjustment of E_s due to percent of soil surface covered with

Table 1. A two-sample t -test of significance analysis of the difference between the means of BREBS measured- ET_m and ET_c obtained by crop coefficient methods.

Data sets tested for significance difference	Observations per dataset	Pooled variance	Degrees of freedom	Computed t -value	Critical t -value ($\alpha = 0.05$)
2007 Total crop season					
ET_m and ET_c (single- K_c)	133	3.40	264	0.01	1.97
ET_m and ET_c (dual- K_c)	133	3.30	264	1.54	1.97
ET_c (single- K_c) and ET_c (dual- K_c)	133	3.27	264	1.56	1.97
2007 Initial growth stage					
ET_m and ET_c (single- K_c)	21	1.02	40	1.55	2.02
ET_m and ET_c (dual- K_c)	21	1.68	40	1.02	2.02
ET_c (single- K_c) and ET_c (dual- K_c)	21	1.41	40	2.44	2.02
2008 Total crop season					
ET_m and ET_c (single- K_c)	135	3.13	268	0.94	1.97
ET_m and ET_c (Dual- K_c)	135	3.28	268	2.28	1.97
ET_c (single- K_c) and ET_c (dual- K_c)	135	3.23	268	1.38	1.97
2008 Initial growth stage					
ET_m and ET_c (single- K_c)	21	1.95	40	2.45	2.02
ET_m and ET_c (dual- K_c)	21	3.99	40	0.84	2.02
ET_c (single- K_c) and ET_c (dual- K_c)	21	3.12	40	2.89	2.02

Figure 8. Regression plots of seasonal ET_m and ET_c estimated by the dual- K_c methods at various levels of E_s reduction in 2008 crop season (a) 0%, (b) 2.5%, (c) 5%, and (d) 7.5%.

crop residue had a very small impact on the estimated ET_c . The model performance during the late season growth stage was poor compared to other growth stages. The data in Table 3 show that greater improvement in ET_c estimates can be obtained for both years by splitting the reduction of E_s due to residue cover into two periods as follows: reducing E_s by 2.5% for each 10% of the soil surface covered with crop residue during the initial growth stage and by 5% for each 10% of the soil surface covered with crop residue during the crop development

and mid-season growth stages. The split reduction in E_s by the above percentages resulted in ET_c underestimation by only 3% during the initial stage and overestimation by 5% during the development stage. Reduction of E_s by 7.5% resulted in large underestimations of ET_c during the initial stage (42% in 2007 and 31% in 2008). The overall results indicated that inaccurate selection of percentage reduction in E_s can result in substantial overestimation or underestimation of seasonal ET_c by using the dual- K_c method. The analysis of variance of the means of

Table 2. Summary of statistical analysis used to compare the dual- K_c estimated seasonal ET_c at various levels of E_s adjustment with BREBS-measured ET_m and single- K_c estimated ET_c .

	Total (mm)	Mean (mm d ⁻¹)	Max (mm d ⁻¹)	Min (mm d ⁻¹)	RMSD (mm d ⁻¹)	MBE (mm)	R ²	E
2007								
BREBS	535.4	4.0	8.8	1.1				
Dual- K_c (0% E_s reduction)	581.0	4.4	8.0	0.8	1.083	-0.343	0.64	0.907
Dual- K_c (2.5% E_s reduction)	555.3	4.2	7.8	0.7	0.932	-0.150	0.72	0.930
Dual- K_c (5% E_s reduction)	529.6	4.0	7.6	0.7	0.873	0.043	0.77	0.940
Dual- K_c (7.5% E_s reduction)	503.8	3.8	7.4	0.2	0.939	0.236	0.77	0.932
Single- K_c	535.0	4.0	8.1	0.6	0.975	0.002	0.72	0.926
2008								
BREBS	520.0	3.9	8.7	0.4				
Dual- K_c (0% E_s reduction)	587.9	4.4	9.4	0.1	0.997	-0.503	0.75	0.923
Dual- K_c (2.5% E_s reduction)	549.0	4.1	9.2	0.1	0.838	-0.214	0.83	0.948
Dual- K_c (5% E_s reduction)	532.2	3.9	9.1	0.1	0.810	-0.091	0.83	0.951
Dual- K_c (7.5% E_s reduction)	515.5	3.8	9.0	0.1	0.858	0.033	0.81	0.946
Single- K_c	547.3	4.1	8.5	0.1	1.063	-0.203	0.63	0.904

Figure 9. Cumulative ET measured by BREBS and estimated by the dual- K_c method at 0%, 2.5%, 5%, and 7.5% reductions in E_s (a) 2007 and (b) 2008.

estimated ET_c obtained by the dual- K_c method at 0, 2.5, 5 and 7.5% reductions in E_s for each 10% of soil surface covered with crop residue are given in Table 4. The results indicate that the differences between ET_c obtained at various levels of E_s reduction were not significantly different except for the period during the initial growth stage in 2007.

Table 3. Percent overestimation or underestimation in ET_c estimated by the dual- K_c at various levels of reduction in E_s for each 10% of soil surface covered with crop residue as compared to BREBS-measured ET_m .

Crop growth stage	Percent reduction in E_s for each 10% of soil surface covered with crop residue			
	0%	2.5%	5.0%	7.5%
2007				
Initial	+16.6	-3.2	-23.1	-41.8
Crop development	+18.2	+11.7	+5.1	-1.4
Mid-season	-4.2	-5.2	-6.2	-7.1
Late-season	+51.0	+43.2	+136.0	+27.4
Total crop season	+8.5	+3.7	-1.1	-5.8
2008				
Initial	+16.5	-3.0	-17.3	-31.4
Crop development	+13.7	+8.6	+4.9	+1.1
Mid-season	+3.0	+1.6	+1.1	+0.6
Late-season	+75.4	+37.6	+34.7	+31.6
Total crop season	+13.1	+5.6	+2.3	-0.9

4. Summary and conclusions

This study compared the accuracy of the single- K_c and dual- K_c methods for estimation of daily ET_c in a cropping system with soil surface residue cover and determined the magnitude by which ET_c is reduced for each 10% of soil surface covered with crop residue. The ET_c estimates from the two methods were compared to the BREBS-measured ET_m . The results indicate that the single- K_c underestimated ET_m during the initial crop growth stage by 21.1% in 2007 and 33.6% in 2008 while the dual- K_c unadjusted for residue cover overestimated ET_m during the same growth stage by 16.8% in 2007 and 16.5% in 2008. Both single- K_c and unadjusted dual- K_c methods overestimated ET_m during the crop development stage at about the same level. The single- K_c method overestimated ET_m during the development stage by 16.1 and 11.0% in 2007 and 2008, respectively, and the unadjusted dual- K_c method overestimated ET_m during the same stage by 18.1 and 13.8% in 2007 and 2008, respectively. Both methods accurately estimated ET_m during the mid-season stage and there was no difference between them. The single- K_c and unadjusted dual- K_c methods underestimated ET_m during the mid-season growth stage by 4.2 and 4.4% in 2007, respectively, but in 2008 both methods overestimated ET_m by 3%. There was, however, poor agreement between ET_c estimated by both methods and

Table 4. Analysis of variance to test the hypothesis that the mean of estimated ET_c values obtained by dual- K_c methods at 0, 2.5, 5 and 7.5% reduction in E_s for each 10% of soil surface covered with crop residue are the same.

Source of variation	Sum of squares	Degrees of freedom	Mean square	Computed F -value	Critical F -value ($\alpha = 0.05$)
2007 Whole crop season:					
Between levels of E_s reduction	24.85	3	8.28	2.56	2.62
Within data set	1708.98	528	3.24		
Total	1733.82	531			
2007 Initial growth stage:					
Between levels of E_s reduction	29.07	3	9.69	8.56	2.72
Within data set	90.60	80	1.13		
Total	119.66	83			
2008 Whole crop season:					
Between levels of E_s reduction	21.42	3	7.14	1.94	2.62
Within data set	1971.79	536	3.68		
Total	1993.21	539			
2008 Initial growth stage:					
Between levels of E_s reduction	25.97	3	8.66	2.27	2.72
Within data set	305.12	80	3.81		
Total	331.09	83			

the ET_m towards the end of the late season stage showing that both methods had poor performance in estimating initial and late season stage ET_c . There was no statistical significant difference between the seasonal mean of BREBS-measured ET_m and the seasonal mean of single- K_c estimated ET_c for both 2007 and 2008. The seasonal mean of dual- K_c estimated ET_c was significantly different from the BREBS-measured ET_m in 2008 but not in 2007. Comparison between the seasonal means of ET_c estimated by the single- K_c and dual- K_c methods also showed statistical significant difference in 2008 but not in 2007.

Downward adjustments in E_s for every 10% of the soil surface covered with crop residue improved the performance of the dual- K_c method. The E_s component of ET_c estimated using the dual- K_c method was test-adjusted at four levels to determine the percentage reduction for each 10% surface cover that best represents the field conditions. The testing levels were set at 0, 2.5, 5, and 7.5% reduction in E_s for each 10% of surface covered by the residue. The most notable changes in ET_c due to adjustments in E_s occur during the initial growing stage. The best results were obtained by reducing E_s by 5% for every 10% of surface covered with residue in 2007 ($R^2 = 0.77$, $RMSD = 0.87 \text{ mm d}^{-1}$, $E = 0.94$) and 2008 ($R^2 = 0.83$, $RMSD = 0.84 \text{ mm d}^{-1}$, $E = 0.95$). In terms of cumulative ET_c , the dual- K_c adjusted at 2.5% reduction in E_s for each 10% of soil surface covered with crop residue gave best results for the initial stage and adjustment at 5% reduction in E_s gave best results for the crop development and mid-season growth stages. The t -test of significance difference also showed that the differences in means of ET_c obtained at various levels of E_s reduction were not significantly different except for the period during the initial growth stage in 2007. The differences in percent reduction in E_s between the two years may be due to the fact that residue cover in 2007 was predominantly from a previous year maize crop and residue cover in 2008 was predominantly from the soybean harvested at the end of the 2007 crop season. These results indicated that inaccurate selection of percentage reduction in E_s can result in substantial overestimation or underestimation of seasonal ET_c by the dual- K_c method. Results also emphasize that the single and dual K_c -values are influenced differently by the same management practice (i.e., tillage, residue). Given the tremendous amount of variability in soil and crop management, climate conditions, irrigation method and irrigation regime practiced, and many other factors, the K_c -values reported in the literature, including the FAO-56 values, should be adjusted for local management conditions for more accurate ET_c estimates.

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