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HOURLY AND DAILY SINGLE AND BASAL EVAPOTRANSPIRATION CROP COEFFICIENTS AS A FUNCTION OF GROWING DEGREE DAYS, DAYS AFTER EMERGENCE, LEAF AREA INDEX, FRACTIONAL GREEN CANOPY COVER, AND PLANT PHENOLOGY FOR SOYBEAN

S. Irmak, L. O. Odhiambo, J. E. Specht, K. Djaman

ABSTRACT. Hourly evapotranspiration (ET) crop coefficients (K_c) are needed to optimize the effectiveness and efficiency of high-frequency micro- and sprinkler irrigation practices involving the application of water multiple times a day. However, not much is known about the daily and seasonal patterns and magnitudes in hourly K_c values for soybean. In addition, locally developed K_c values are necessary for more robust within-season irrigation management, crop ET estimation, and water balance analyses. Hourly and daily K_c functions were developed for soybean in south-central Nebraska through extensive field research. Actual crop evapotranspiration (ET_a) was measured using a Bowen ratio energy balance system. Daily crop coefficients were calculated as $K_c = ET_a/ET_{ref}$, wherein reference (potential) evapotranspiration (ET_{ref}) was calculated using the Penman-Monteith equation with a fixed canopy resistance for both alfalfa-reference (ET_r) and grass-reference (ET_o) surfaces. The K_c values were derived in two forms: (1) a single (normal or average K_c) K_{cr} based on ET_r and K_{co} based on ET_o ; and (2) a basal coefficient (K_{cbr}) based on ET_r and K_{cbo} based on ET_o . The seasonal patterns of variation of K_{cr} , K_{co} , K_{cbr} , and K_{cbo} were examined on five different temporal base scales: days after emergence (DAE), cumulative growing degree days (GDD), leaf area index (LAI), fractional green canopy groundcover (CC), and plant phenology (V and R stages). The 2007 and 2008 growing season ET_a totals were 535 and 514 mm, respectively. Extreme hourly K_c values were frequently observed in the early morning and late afternoon hours when ET_a was very low relative to ET_r and ET_o . Daily means of the 10 to 13 hourly values computed for K_{cr} ranged from 0.25 to 1.06 in 2007 and from 0.15 to 1.02 in 2008, whereas those computed for K_{co} ranged from 0.39 to 1.37 in 2007 and from 0.22 to 1.29 in 2008. Daily K_{cr} and K_{co} values calculated based on daily data ranged from 0.20 to 1.12 and from 0.27 to 1.47, respectively. Comparison of all daily means of hourly coefficients with the corresponding daily coefficients in one-to-one graphs and zero-origin based regression of the former on the latter revealed linear regression coefficients of 0.92 (2007 K_{cr}), 0.95 (2008 K_{cr}), 0.96 (2007 K_{co}), and 0.97 (2008 K_{co}), with R^2 values of 0.78 or better. On average, hourly K_c values were about 4% to 8% lower than the corresponding daily values. Substantial diurnal variability was observed in K_{co} and K_{cr} measured during daylight hours (ranging from 0.1-0.2 to 1.5-1.6) from early morning to late afternoon (8:00 to 18:00), and the range of variability was substantially dependent on the coincident V and R stages. The relationship between K_c and LAI was best represented by two regression trend lines: one representing crop development from its beginning up to the start of senescence, and the other representing crop development thereafter. A similar break in the regression trend line was observed in the relationship between basal K_c and GDD. In contrast, the relationship between K_c and fractional CC was not biphasic and could be modeled with one regression trend line. The FAO-56 tabulated K_{co} values and those measured in this research were significantly different ($p < 0.05$). Thus, the FAO-56 values, if used for south-central Nebraska soil, climate, and management practices or similar conditions, would not be able to provide accurate ET_a and crop water requirement estimates. Because this research proved that K_{co} and K_{cr} values are not constant during the day from dawn to dusk, using daily average K_{co} or K_{cr} values would not be able to provide robust and precise determination of crop irrigation requirements for irrigation practices delivered more than once per day. The crop coefficients developed in this research as a function of several base scales should provide crop consultants, extension service personnel, agronomists, irrigation practitioners, and other irrigation and water management professionals with robust and accurate methods for choosing and applying crop coefficients to be used for more precise determination of ET_a and water requirements, thus leading to more efficient and effective seasonal soybean irrigation management.

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Soybean [*Glycine max* (L.) Merr.] is Nebraska's second leading field crop after maize and is grown on approximately 2 million ha located primarily in the eastern half of the state. In the soybean growing areas, annual precipitation ranges from 550 to 600 mm in the west to over 850 mm in the southeast. Soybean cultivars of Maturity Groups II and III are best adapted to Nebraska's latitude span. A variety of production systems are used in soybean production, and these include both narrow-row and wide-row planting into conventional, reduced, and no-till seedbeds. The 1972-2008 USDA National Agricultural Statistics data (USDA-NASS, 2010; www.nass.usda.gov) document a gradually increasing soybean yield trend in Nebraska for both rainfed and irrigated production systems, but large season-to-season fluctuations occur in the rainfed soybean yields due to substantial intra-annual and inter-seasonal variance in the amount and distribution of rainfall events. Specht et al. (1999) attributed the observed increase in yield trends to improved soybean genetics, improved management in soybean production systems, and to a lesser degree, the gradual increase in atmospheric carbon dioxide (CO₂) concentration. Irrigated soybean yields are increasing at a much higher annual rate than are rainfed soybean yields, thereby making it less risky and more profitable for producers to invest farm inputs in irrigated soybean. Currently, about 46% (0.9 million ha) of Nebraska's total soybean planted area is irrigated. Center-pivot sprinkler irrigation is the predominant irrigation on ~75% to 80% of the irrigated area, and the rest is irrigated using gravity (mostly furrow) irrigation method. Fields with installed subsurface drip irrigation (SDI) systems currently account for a very small fraction of irrigated soybean production, with producer interest increasing, dependent on the economic value of the crop that can be grown in those systems.

The response of soybean yield and its components to irrigation timing and amounts has been documented in the literature. Sionit and Dramer (1977) found that water stress during flower induction and flowering stage resulted in fewer flowers, pods, and seeds because of a shortening of the flowering period and the abortive loss of some of the flowers. Korte et al. (1983a, 1983b) reported that irrigation during flowering increased the number of pods and seeds per plant, but without follow-up irrigation these increases in seed number were offset by decreased average seed weight, resulting in little effect on ultimate seed yield. However, they also reported that irrigation during pod elongation increased the number of pods per plant, seeds per plant, and seed weight, resulting in increased seed yield. They noted that irrigation during seed enlargement greatly increased seed weight and also resulted in increases in seed yield. Pandey et al. (1984a, 1984b) found that water stress occurring throughout the growing season resulted in reduced soybean leaf area, leaf duration, crop growth rate, shoot dry matter, number of pods per square meter, and number of seeds per pod. Ritter and Scarborough (1988) observed that full-season irrigation of soybean in Delaware did not increase yields significantly more than the yields attained when soybean was irrigated from flowering to ma-

turity. Irmak et al. (2013) investigated soybean yield response to various seasonal irrigation amounts using an SDI system in south-central Nebraska and found that deferring irrigation until the pod development stage of R3, but then practicing full irrigation thereafter, resulted in yields that were similar to yields obtained with a full-season irrigation practice with substantial reduction in irrigation applications. They also investigated soybean water productivity and evapotranspiration response to various new irrigation approaches for enhancing soybean water productivity.

The above-cited studies show that soybean yield is most sensitive to water stress during its reproduction stages, and thus adequate water supply during this period is a major factor determining soybean yield. To achieve effective and efficient soybean irrigation management requires accurate quantification of crop water use (i.e., actual crop evapotranspiration, ET_a), which in theory is equivalent to the amount of water a crop removes from the soil. In an agricultural production field, ET_a is the cumulative amount of water transpired daily and seasonally from leaf stomata in plant canopies coupled with the cumulative amount of daily and seasonal evaporation of water from wet soil and wet plant surfaces. Direct measurement of ET_a is a difficult, time-consuming, laborious process that requires expensive instrumentation and expert knowledge in the use of surface energy balance methods and mathematics to ensure accuracy and precision. Therefore, in many cases, it is preferable to quantify ET_a using experimentally derived crop coefficients (K_c) coupled with values of measured or estimated reference (potential) evapotranspiration (ET_{ref}), which is expressed as $ET_a = K_c \times ET_{ref}$. The K_c value for a given crop is assumed to intrinsically account for the effects of crop characteristics (height, albedo, canopy resistance, groundcover, etc.) that distinguish the crop's surface from the commonly used reference surfaces of grass or alfalfa. The accuracy of estimated ET_a depends to a large extent on the accuracy of the K_c value used in the above expression to relate ET_{ref} to ET_a. It must be kept in mind that the K_c value is not a seasonal constant, but instead has a value reflective of its covariate relationship with the growth and development stage of the specific annual crop.

Various time-based scales have been used in normalizing K_c . Some scales are easy to impute or implement, others less so. Scales used to date include days after emergence (Stegman et al., 1977), crop growth stage (Doorenbos and Kassam, 1979), percentage of time from harvest to harvest in cutting cycles of alfalfa (*Medicago sativa* L.) (Wright, 1982), percentage of time from planting to full cover and then elapsed days after full cover (Wright and Jensen, 1978), cumulative ET_o (Hill et al., 1983), fraction of thermal units (Amos et al., 1989), and leaf area development (Wright, 1982). Wright (1982) expressed K_c as a function of time, where time can be the Julian date or days after either planting (DAP) or emergence (DAE). Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) expressed K_c as a function of different growth stages by dividing the crop development cycle into the following four phases: an initial phase (planting, emergence, and early growth), a crop development phase (rapid vegetative growth and early repro-

ductive development), a mid-season phase (full canopy development and reproductive phases including bloom, pollination, fruiting, and early maturation), and a final ending phase (senescence, fruit maturity, grain filling, and dry down). The number of days in each stage is then specified. Jensen (1974) used a dual-time scale that expressed the time from planting until full or effective full canopy cover in percent (%), and then they used a day scale after effective cover. Sammis et al. (1985) and Stegman (1988) used polynomial functions to fit crop coefficients to relative growing degree days (GDD). Amos et al. (1989) and Irmak (2005) applied fraction of thermal unit (i.e., GDD) to develop K_c curves. Djaman and Irmak (2013) measured maize crop coefficients under fully irrigated, different levels of limited irrigation, as well as rainfed conditions and expressed K_c values as a function of GDD and DAE.

Although the K_c approach can predict daily ET_d values with varying degrees of accuracy for low-frequency irrigation application (daily or weekly irrigation intervals), scheduling irrigation events at a higher frequency (e.g., using subsurface or surface drip irrigation systems or other forms of microirrigation to apply water twice or more in a given day) is best accomplished using hourly K_c values, but unfortunately, such values have yet to be made readily available for that purpose. Furthermore, even though daily K_c values for various crops are available in the literature, including the FAO-24 publication (Doorenbos and Pruitt, 1977) that serves as the primary source of K_c values still in use today (i.e., FAO-56), experimental derivation of K_c values applicable to local conditions provides more accuracy and precision in the estimation of crop water use. Indeed, the transferability of generic crop coefficients to locations with non-generic conditions is very challenging and may result in substantial errors (i.e., 25% or more; Djaman and Irmak, 2013) in ET_d estimates. Today, rapid developments in irrigation management and associated technologies are enabling many producers and researchers to practice high-frequency irrigation scheduling, perhaps even on an intra-day basis. One scenario where irrigation frequency is especially important is crop production on coarse-textured (i.e., sandy) soils, where irrigating several times a day may be necessary for effective management of both water and nutrients when the soil water holding capacity is low and daily crop water requirement is high. Because intra-day K_c values are required when using high-frequency irrigation management, yet such intra-day values are not readily available or derivable from existing K_c values, there is a need to investigate the diurnal pattern of hourly K_c values and how that pattern might change over successive days in the course of the entire growing season. Such research would be a very useful contribution, given the growing interest in high-frequency water and nutrient management systems.

The objectives of this research were: (1) develop intra-day hourly and daily alfalfa- and grass-reference “normal” (average or single) crop coefficients (K_c) and “basal crop coefficient” (K_{cb}) curves for soybean; (2) develop functions relating daily K_c and K_{cb} values to various base scales such as days after emergence (DAE), thermal unit (growing degree days, GDD), leaf area index (LAI), and green canopy

groundcover (CC, %); and (3) develop a table of soybean crop coefficients based on plant phenology that can be used in practical applications by farmers, crop consultants, agronomists, irrigation practitioners and other agricultural water management professionals for within-season irrigation requirement and irrigation management determinations.

MATERIALS AND METHODS

SITE DESCRIPTION AND CROP MANAGEMENT

Field measurements to develop crop coefficients for soybean were conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory (UNL-SCAL) near Clay Center, Nebraska (40° 34' N, 98° 8' W, 552 m above mean sea level). The research site was a 13.5 ha field that had an SDI system. The soil in the field is classified as Hastings silt loam, which is well drained and has 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, the permanent wilting point (θ_{wp}) is 0.14 m³ m⁻³, and the saturation point (θ_{sat}) is 0.51 m³ m⁻³ (Irmak, 2010). The climate in south-central Nebraska is generally sub-humid with warm, dry summers and very cold, windy winters. The warmest month is usually July with a mean maximum temperature of 30°C, while the coldest month is January with a mean minimum temperature of -10°C. Precipitation averages about 700 mm annually with significant inter-annual and inter-seasonal variability. The wettest month is usually May with an average rainfall of 120 mm.

The soybean cultivar Pioneer 93M11 (MG III) was ridge-till planted on May 21, 2007, in an east-west row direction at a seeding rate of 388,000 plants per hectare, a planting depth of 0.025 m, and row spacing of 0.76 m. Plants emerged on May 26 and were harvested on October 24. The same cultivar was again planted on May 19, 2008, in the same manner. Plants emerged on May 24 and were harvested on October 1. The 1.52 m spaced SDI laterals were centered between every other pair of ridge-tilled rows at a depth of approximately 0.40 m below the soil surface. The emitter spacing on the SDI laterals was 0.45 m, and the pressure-compensated emitters had a 1.0 L h⁻¹ discharge rate (Netafim-USA, Fresno, Cal.). The timing and amount of water applied in this SDI field was scheduled using soil water content data collected at soil depths of 0.30, 0.60, 0.90, 1.20, 1.50, and 1.80 m on a twice-weekly basis, using a neutron probe soil moisture meter (model 4302, Troxler Electronics Laboratories, Inc., N.C.). The neutron probe access tubes were installed in two replications of each treatment for soil water content measurements, which were used to trigger irrigations when about 35% to 40% of the available water was depleted in the 0-0.90 m soil profile. About two or three irrigations per week were applied with 12 to 14 mm water application in each irrigation event. This practice allowed bringing the soil water status to about 90% of the field capacity to be able to take advantage of potential precipitation events. Leaf area index (LAI) was measured using a plant canopy

analyzer (model LAI-2000, Li-Cor Biosciences, Lincoln, Neb.). LAI measurements were repetitively made on a 7 to 10 day cycle that commenced when LAI was approximately 1.10. A total of 25 LAI measurements were typically made on each measurement day and averaged for that day.

MEASUREMENT OF ACTUAL CROP ET

Actual crop evapotranspiration (ET_a) during the 2007 and 2008 growing seasons was measured about 1.5 m above the canopy using a Bowen ratio (Bowen, 1926) energy balance system (BREBS) (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.) that was installed in the middle of the experimental field. The system's exchangers that housed the relative humidity and temperature sensors were raised up during the growing season as the canopy height increased to keep a relatively constant distance between the soybean canopy and the bottom exchanger tube. Prior extensive use of BREBS has documented its performance in successfully determining evaporative fluxes above various vegetation surfaces, yielding ET_a values that compare well with data from other methods (Lafleur and Rouse, 1990; Ham et al., 1991; Bausch and Bernard, 1992; Fritschen, 1965; Irmak et al., 2008; Irmak, 2010).

Measurements of sensible heat flux (H), soil heat flux (G), net radiation (R_n), and air temperature (T_a) and vapor pressure (e) gradients ($\partial T_a / \partial e$) were made using the BREBS. The BREBS-measured flux data and other datasets used in this research were gathered in conjunction with the Nebraska Water and Energy Flux Measurement, Modeling and Research Network (NEBFLUX) (Irmak, 2010) that operates twelve BREBS and eddy covariance systems over various vegetation surfaces. The NEBFLUX measures all surface energy flux variables, meteorological variables, plant physiological parameters, soil water content (every 0.30 m up to 1.80 m on an hourly basis), soil characteristics, and agronomical components, including biomass production and/or yield for various vegetation surfaces. In this research, a net radiometer (model REBS Q*7.1, REBS, Inc., Bellevue, Wash.) was used to measure R_n . Total incoming radiation (shortwave + longwave), total outgoing radiation (shortwave + longwave), and net radiation values were measured using the REBS model THRDS7.1 double-sided total hemispherical radiometer. The incoming and outgoing shortwave radiation values were measured using the REBS model PDS7.1 double-sided pyranometer. The incoming and outgoing longwave radiation values were determined from the difference between the THRDS7.1-measured total radiation and the PDS7.1-measured shortwave radiation. The albedo values were calculated using the ratio of incoming and outgoing shortwave radiation. The THRDS7.1 is sensitive to wavelengths from 0.25 to 60 μm , and the PDS7.1 is sensitive to wavelengths from 0.35 to 2.8 μm . The radiometers were mounted sufficiently high to obtain a clear view of the underlying surface being measured while minimizing the influence of the mounting tower, other objects, or surrounding canopy surfaces that might affect albedo or longwave radiation from the meas-

ured surface. Proper leveling of the radiometer domes was routinely maintained to ensure accuracy. Soil heat flux was measured using REBS HFT-3.1 heat flux plates and REBS STP-1 soil thermocouples. Three soil heat flux plates were placed at depths between 0.05 and 0.06 m below the soil surface. Three soil thermocouples were installed near soil heat flux plates at depths of 0.04 to 0.05 m below the soil surface. Soil heat flux measurements were adjusted for soil temperature and moisture as measured by three REBS SMP1R soil moisture probes installed in the same location as the soil temperature sensors and soil heat flux plates (Irmak, 2010).

Air temperature and relative humidity gradients were measured using two platinum resistance thermometers and monolithic capacitive humidity sensors (REBS models THP04015 and THP04016, respectively) with resolutions of 0.0055°C for temperature and 0.033% for relative humidity. Measured temperature and relative humidity gradients were used to calculate sensible heat flux density, Bowen ratio, and vapor pressure deficit. The BREBS included a barometric pressure sensor (model 276, Setra Systems, Inc., Boxborough, Mass.). Precipitation was recorded using a tipping-bucket rain gauge (model TR-525, Texas Electronics, Inc., Dallas, Tex.). Wind speed and direction above the canopy were measured using a cup anemometer (model 034B, Met One Instruments, Grant Pass, Ore.) that had a wind speed range of 0 to 44.7 m s^{-1} and threshold wind velocity of 0.28 m s^{-1} . The BREBS used an automatic exchange mechanism that physically exchanged the temperature and humidity sensors every 15 min at two heights above the canopy to minimize the impact of any bias in the top and bottom temperature and humidity sensors on the Bowen ratio calculations. All variables were sampled every 60 s and averaged and recorded on an hourly basis using a CR10X datalogger and AM416 relay multiplexer (Campbell Scientific, Inc., Logan, Utah) (Irmak, 2010; Irmak and Mutibwa, 2010). The extensive maintenance procedures described by Irmak (2010) were followed weekly in this research to ensure continuous and good-quality data collection. Detailed descriptions of the microclimate measurements, ET_a , H , G , R_n , and other microclimatic variables (e , T_a , RH, and wind speed) and instrumentation are presented by Irmak (2010).

REFERENCE (POTENTIAL) ET, CROP COEFFICIENTS, AND GROWING DEGREE DAYS

The weather data needed for calculating potential or reference evapotranspiration (ET_{ref}) were collected at a nearby automated weather station. The ET_{ref} was calculated using the Penman-Monteith equation, which is based on Penman (1948), Monteith (1965), and Monteith and Unsworth (1990) using the same coefficients described in ASCE-EWRI (2005) with a fixed canopy resistance (for hourly time steps, ET_o : 50 s m^{-1} for daytime hours and 200 s m^{-1} for nighttime hours; for ET_r : 30 s m^{-1} for daytime hours and 200 s m^{-1} for nighttime hours) as also described by Irmak et al. (2012). Crop coefficients (K_c) are empirically defined as ratios of ET_a to ET_{ref} (ET_o or ET_r) as:

$$K_c = ET_a / ET_{ref} \quad (1)$$

where K_c (K_{co} or K_{cr}) is the dimensionless crop coefficient for a particular crop at a given growth stage and soil moisture condition, and ET_a is the actual crop evapotranspiration. The K_c value in equation 1 includes effects of evaporation from both plant and soil surfaces, and thus is influenced by the available soil water within the plant root zone and the wetness of the exposed soil surface. In addition to “normal” (i.e., average or single) K_c values, basal crop coefficients (K_{cb}) were also developed to represent the ratio of ET_a to ET_{ref} in those conditions when the soil surface layer is dry so that evaporation of water from the soil surface is minimal, yet the average soil water content in the root zone is adequate to sustain crop transpiration at a potential rate, which was typically the case here for SDI-irrigated soybean. The following expression was used to calculate a coefficient derived from the adjustment of K_{cb} values for water stress and for greater soil water evaporation after rainfall or irrigation events:

$$K_{cc} = K_{cb} K_s + K_e \quad (2)$$

where K_{cc} is the adjusted daily crop coefficient, K_s is the adjustment factor for water stress, and K_e is the adjustment for increased soil evaporation, which occurs after rain events. All single and basal soybean crop coefficients were developed for hourly and daily time steps for both growing seasons. The initial, mid-season, and late-season K_{cb} values for soybean were taken from FAO-56, which are derivatives of the values that were originally introduced and published by Doorenbos and Pruitt (1977) in FAO-24.

The GDD parameter (i.e., thermal unit, TU) is based on an accumulation of daily air temperatures between some high and some low temperatures judged to be growth-limiting and is commonly expressed as:

$$GDD = \sum_{i=1}^n \left(\frac{T_{max} + T_{min}}{2} - T_{base} \right) \quad (3)$$

where T_{max} is the maximum air temperature, T_{min} is the minimum air temperature, T_{base} is the base temperature threshold (10°C), and n is the number of days. The base temperature for calculating GDD is the minimum threshold temperature below which plant growth ceases. In this research, maximum and minimum temperature thresholds of 30°C and 10°C, respectively, were chosen for soybean. All temperature values exceeding the upper threshold value were reduced to 30°C, and values below 10°C were taken as 10°C. If the average daily temperature $[(T_{max} + T_{min})/2]$ was below the base temperature, then the GDD value was assumed to be equal to zero (Djaman and Irmak, 2012).

RESULTS AND DISCUSSION

WEATHER CONDITIONS DURING RESEARCH PERIOD

Monthly means of weather variables during the May to September growing seasons of 2007 and 2008 are presented in figures 1a to 1d, along with the 25-year (1983-2008) monthly means. Air temperature (T_a), relative humidity (RH), wind speed, and solar radiation in each year were similar and consistent with the long-term magnitudes and trends, indicating that both years were representative of the typical annual weather that can be expected at the research location. The vapor pressure deficit (VPD) (fig. 1e) is defined as the difference between the ambient (actual) vapor pressure and the saturation vapor pressure of the water present in the atmosphere at a given temperature. Because VPD has a strong relationship to the rate of evapotranspiration and other measures of evaporation, it is an effective measure of the evaporative demand of the atmosphere

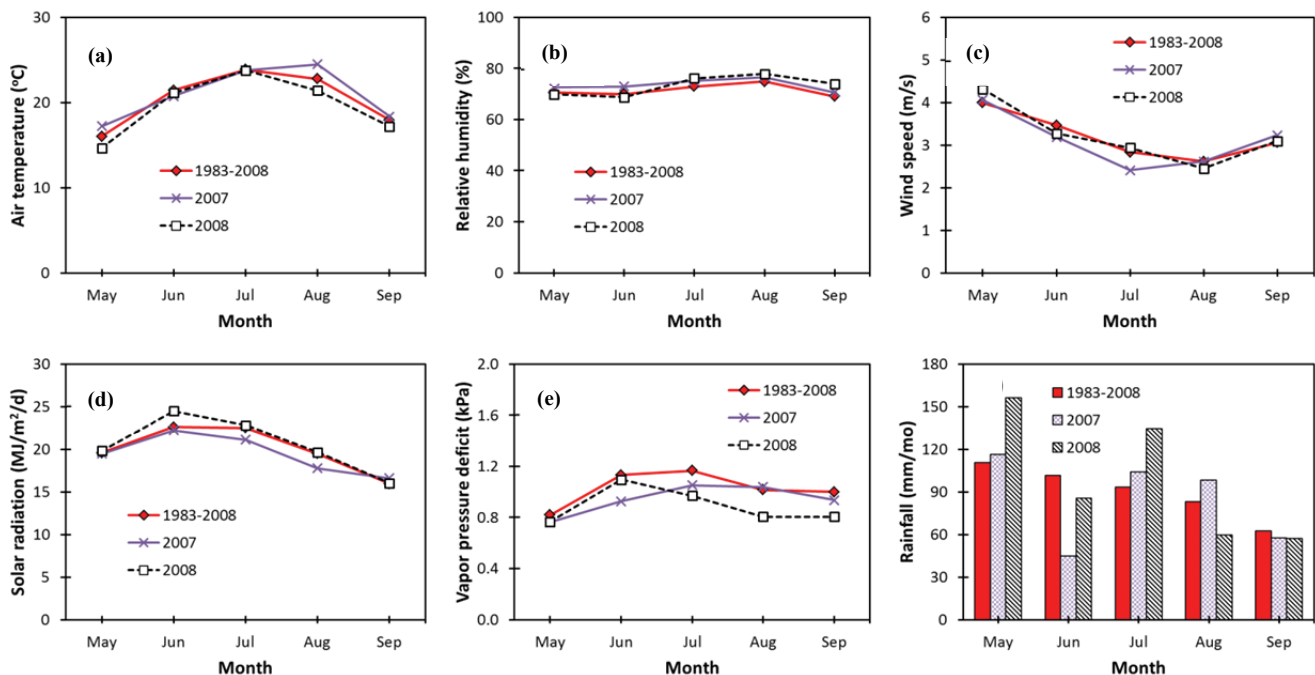


Figure 1. Monthly means for some key weather variables measured at the experimental site during the 2007 and 2008 growing seasons as compared with the long-term 25-year (1983-2008) monthly means.

above the canopy. The 2007 growing season exhibited a slightly lower atmospheric evaporative demand as compared with the 25-year averages in June and July, whereas the atmospheric evaporative demand in the 2008 growing season was lower than the long-term average for July, August, and September. Past studies have indicated that a unit change in VPD can result in as much as 10% to 30% change in the estimated reference (potential) ET (Saxton, 1975; Yoder et al., 2005; Irmak et al., 2006). However, in the present research, the largest difference in VPD between 2007 and 2008 and between those years and the long-term averages was less than 0.25 kPa. The 2007 rainfall pattern closely mirrored the long-term averages except for June, which was drier (45 mm) than normal (102 mm) (fig. 1f). Growing season rainfall totaled to 421 mm in 2007 and 492 mm in 2008, as compared with the long-term average of 451 mm. Despite the greater than normal rainfall in 2008, the June rainfall of 85 mm and August rainfall of 60 mm were well short of the respective long-term averages of 102 mm for June and 83 mm for August.

SOIL WATER STATUS IN CROP ROOT ZONE

The crop coefficients used for estimating ET_a are normally determined when plant growth is not limited because of a lack of sufficient moisture or impacted by any other climatological or physiological factors. Crop coefficient values determined from water stress-free crops are typically adjusted to account for the occurrence of water stress conditions. In this research, soil fertility was optimum, and there were no salt toxicity, waterlogging, pest, or disease issues. Water was applied to the crop using the SDI system with the amounts and times scheduled by monitoring available soil water content in the root zone. The amounts of measured total soil water content in the root zone during the 2007 and 2008 growing seasons are presented in figure 2. The average fraction of total available soil water (TAW) that can be depleted from the soybean root zone before the plants experience water stress is generally assumed to be between 0.4 and 0.6 of TAW (Rosadi et al., 2007; Raes et al., 2012). A midpoint value of 0.5, as sug-

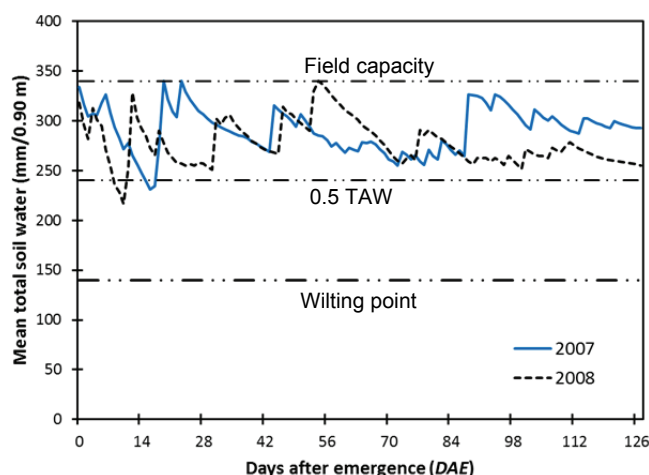


Figure 2. Mean total soil water measured in the crop root zone (0 to 0.90 m) from emergence to harvest during the 2007 and 2008 growing seasons. Horizontal lines denote the field site soil water holding parameters and the 0.5 fraction of total (plant) available water (TAW).

gested for use in the FAO AquaCrop model, was chosen for this research. Figure 2 shows that the field was well-watered in both 2007 and 2008, and only on one occasion each year did the depletion exceed the TAW = 0.5 criterion. In 2007, plants may have experienced mild water stress on 16 and 17 DAE, and in 2008, slight water stress may have occurred around 8 to 10 DAE. In both cases, the effective root zone soil depth was still shallow (only 0.2 m) with a partial canopy cover, leading to conditions wherein the top soil layer was likely dry due to soil water evaporation, although deeper soil depths were likely near field capacity because of water storage from spring and winter precipitation.

MEASURED ACTUAL CROP ET AND ESTIMATED REFERENCE (POTENTIAL) ET

Daily ET_a measured above the soybean canopy and estimated ET_r and ET_o are plotted as a function of DAE for the 2007 and 2008 growing seasons in figures 3a to 3d. Daily ET_a ranged between 1.1 and 8.8 mm d⁻¹ with a mean of 4.0 mm d⁻¹ in 2007 and between 0.5 and 8.7 mm d⁻¹ with a mean of 4.0 mm d⁻¹ in 2008. The highest daily ET_a occurred on 93 DAE (August 27) in 2007 and on 51 DAE (July 14) in 2008. In general, the highest daily ET_a occurred between 52 and 100 DAE (early September) in both years. The two south-central Nebraska growing season ET_a totals were similar (i.e., 535 mm in 2007 and 514 mm in 2008). In Kansas, Kanemasu et al. (1976) measured soybean ET_a with a weighing lysimeter and reported a seasonal estimated ET_a of 651 mm for the 1974 growing season. Hattendorf et al. (1988) later reported seasonal ET_a of 591 mm for irrigated soybean in Manhattan, Kansas, and 491 mm in Tribune, Kansas. In a three-year (2002-2004) experiment involving deficit and full irrigation research in a semi-arid climate at North Platte, Nebraska, Payero et al. (2005) reported soybean ET_a ranging from 261 to 541 mm in the deficit irrigation settings and from 791 mm to 801 mm in the fully irrigated settings.

In the present research, the 2007 alfalfa-reference ET (ET_r) values ranged between 1.2 and 11.2 mm d⁻¹ with a mean of 5.7 mm d⁻¹, whereas the 2008 ET_r values ranged between 0.5 and 10.6 mm d⁻¹ with a mean of 5.6 mm d⁻¹. With respect to the grass-reference ET (ET_o) values, these ranged between 1.0 and 7.7 mm d⁻¹ with a mean of 4.5 mm d⁻¹ in 2007 and between 0.5 and 7.5 mm d⁻¹ with a mean of 4.6 mm d⁻¹ in 2008. The soybean ET_a closely followed the ET_r and ET_o from about 60 DAE until about 112 DAE, and the later date coincides with the start of stage R7 (physiological maturity). Before and after that 60 to 112 DAE period, ET_r and ET_o values were substantially greater than ET_a .

HOURLY AVERAGE (NORMAL OR SINGLE) CROP COEFFICIENTS

Hourly crop coefficients are rarely reported in the literature, and we are not aware any report that provides hourly K_c data and in-depth analyses of the intra-day and daily patterns of this variable for soybean. Some researchers simply use daily crop coefficient values to schedule high-frequency irrigation. Among very limited diurnal K_c re-

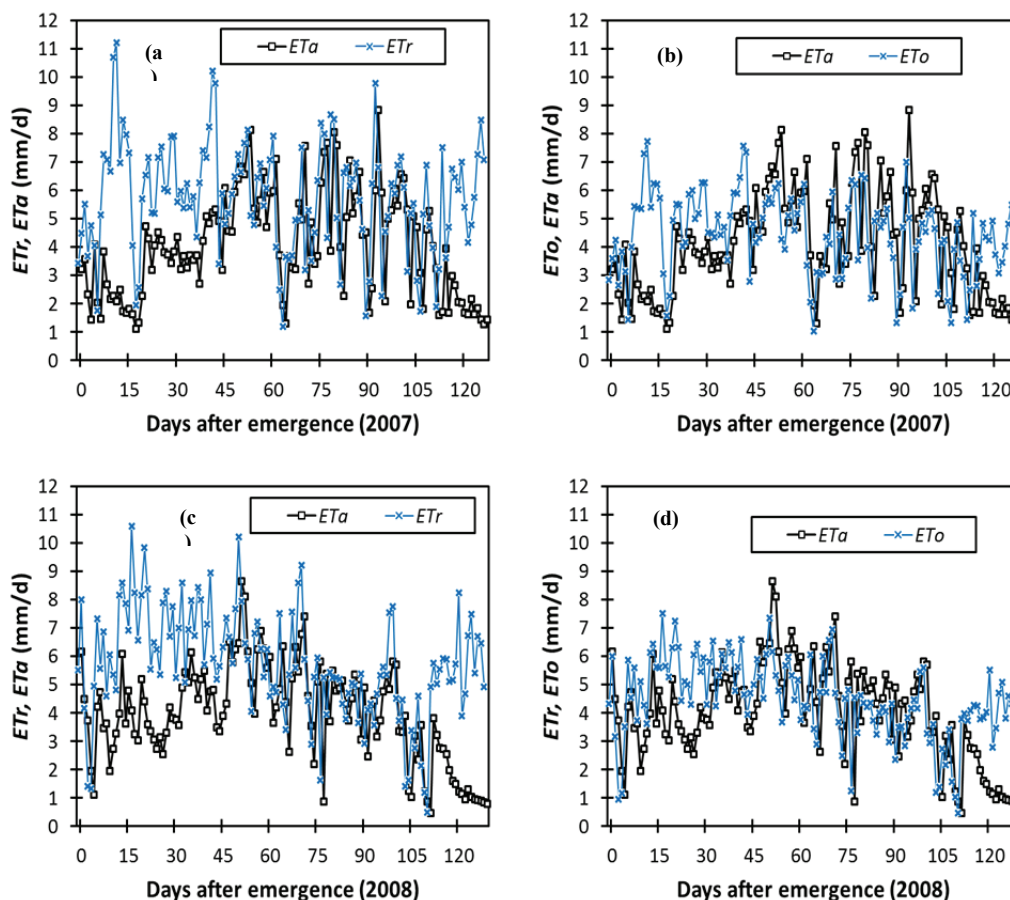


Figure 3. Measured actual daily crop evapotranspiration (ET_a) above the soybean canopy and estimated reference evapotranspiration for alfalfa (ET_r) and grass (ET_0) reference surfaces as a function of days after emergence (DAE) in the 2007 and 2008 growing seasons.

search, Colaizzi et al. (2006) showed that K_c for grain sorghum varied with solar energy exchange, and K_c measured around solar noon represented the best values for use as daily average value. In earlier work, van Zyl and de Jager (1992) showed that hourly K_c for potato varied over the course of the day and attributed that variation to the combined influences of diurnal changes in radiation, ambient temperature, vapor pressure deficit, and wind speed.

Figures 4a and 4b show the distribution of hourly alfalfa-reference (K_{cr}) and grass-reference (K_{co}) normal (average) crop coefficients of soybean calculated using ET_a and ET_0 values observed during daylight hours (8:00 to 18:00 central standard time) in 2007 and 2008. Hourly K_{cr} values ranged from 0.03 to 6.10 in 2007 and from 0.03 to 6.43 in 2008, whereas hourly K_{co} values ranged from 0.05 to 9.15 in 2007 and from 0.03 to 9.15 in 2008. Note, however, that most of the hourly K_c data points in figures 4a to 4d fall into a range bounded by 0.2 and 1.5. The magnitude and distribution of the K_{cr} and K_{co} data were very similar between the two years. In both years, hourly K_{cr} and K_{co} data exhibited a typical K_c curve that progressively increased from about 20 DAE to 90 DAE and then gradually decreased thereafter to the end of the growing season, where the transpiration component of evapotranspiration decreased due to leaf aging and senescence. Thus, the majority of the hourly data distribution mimicked the typical daily K_c data distribution, but not necessarily the magnitudes.

The high K_{cr} and K_{co} values for the two weeks or so after emergence were due to the greater (than later) surface soil water evaporation (as measured by the BREBS). Extreme values were frequently observed in mid-season, but these were generally observed late in the day (near sunset) or during cloudy daylight periods when net radiation was low and the estimated ET_r and ET_0 are extremely low as compared with measured ET_a . The distribution of hourly K_{cr} and K_{co} varied with the progression of crop development stages on successive days after emergence. In addition, significant numbers of extreme data points of K_{cr} and K_{co} were observed in mid-season from about 45 DAE (July 10) to 95 DAE in 2007, although very high K_{cr} and K_{co} values were also observed from 15 to 30 DAE, primarily because of surface water evaporation. In 2008, most of the extreme K_{cr} and K_{co} values occurred later than mid-season, during the 80 to 120 DAE timeframe. Unlike daily K_{cr} and K_{co} values that have been used in water management practices for decades, hourly K_c values would be able to account for the abrupt intra-day changes in weather that have a significant impact on ET_a and crop water requirements. The response of hourly K_c values to such abrupt changes and ET_a is evident in the varied daylight hourly data patterns shown in figures 4e to 4i during the daylight hours of selected days after emergence. These graphs make clear that the utility of having hourly K_c values that could be used to improve the estimation of the water requirement needed for

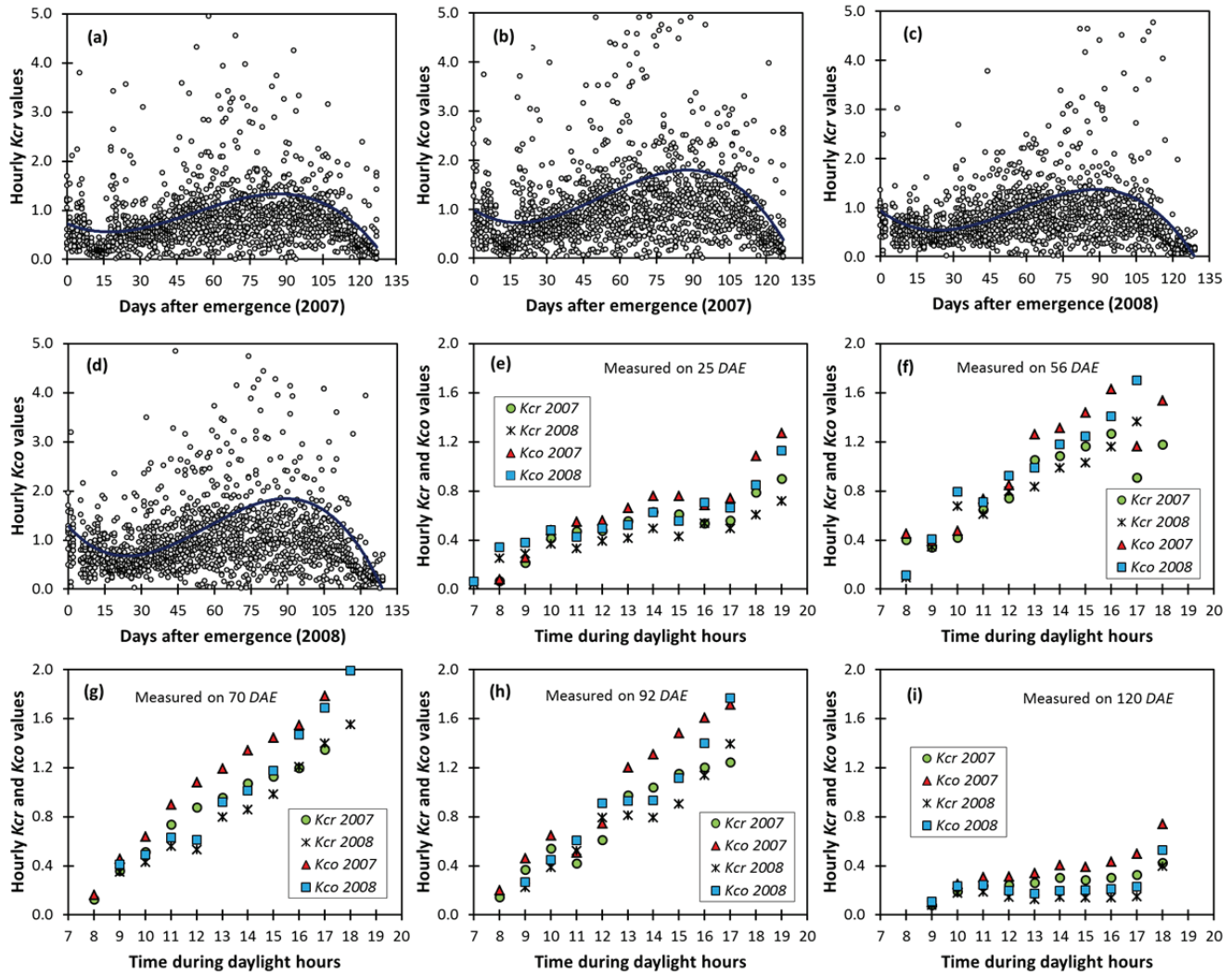


Figure 4. (a to d) Seasonal distribution of hourly alfalfa-reference (K_{cr}) and grass-reference (K_{co}) crop coefficients for soybean during the 2007 and 2008 growing seasons, and (e to f) intra-day distribution graphs for the same two coefficients in each year for selected successive days after emergence, i.e., 25, 56, 70, 92, and 120 DAE (daylight hours = 8:00 to 18:00).

each of possibly multiple intra-day irrigation events.

The K_{cr} and K_{co} values were expressed as a function of different scales on the x-axis. The relationships between DAE and hourly K_{cr} and K_{co} were modeled as third-order polynomials, expressed by equations 4 and 8 for figures 4a and 4b and by equations 6 and 7 for figures 4c and 4d:

$$K_{cr2007} = -0.0000028704DAE^3 + 0.0004129574DAE^2 - 0.0089482032DAE + 0.6032379748 \quad (4)$$

$$K_{co2007} = -0.0000037574DAE^3 + 0.0005576685DAE^2 - 0.0134831241DAE + 0.7995394825 \quad (5)$$

$$K_{cr2008} = -0.0000033851DAE^3 + 0.0005240586DAE^2 - 0.0163432882DAE + 0.7020999349 \quad (6)$$

$$K_{co2008} = -0.0000043438DAE^3 + 0.0006888092DAE^2 - 0.0230508020DAE + 0.9357884337 \quad (7)$$

These polynomial regression equations provided good fits to the nonlinear relationships between DAE and the corresponding conditional means of K_{cr} and K_{co} . The daily mean of hourly K_{cr} ranged from 0.25 to 1.06 in 2007 and

from 0.15 to 1.02 in 2008, and the daily means of hourly K_{co} ranged from 0.39 to 1.37 in 2007 and from 0.22 to 1.29 in 2008. As expected, the K_{cr} values were lower than the K_{co} values due to ET_o being always lower than ET_r . Daily means of hourly values of K_{cr} and K_{co} reached the peak value at 80 DAE in both the 2007 and 2008 cropping seasons. In equations 4 to 7, polynomial regression equations relating means of hourly crop coefficients to DAE are presented separately for the 2007 and 2008 data. How well the 2007 and 2008 equations matched each other was determined by pairwise comparisons of the estimated daily means of hourly crop coefficients from the two years' data. The parameters used to evaluate the equations were the coefficient of determination (R^2), the slope of the trend line (S), and the standard error of the estimate (S_{yx}); an examination of those parameters indicated little or no difference between the 2007 and 2008 equations (i.e., $R^2 = 0.96$, $S = 0.95$, and $S_{yx} = 0.04$ for the K_{cr} equations; $R^2 = 0.94$, $S = 0.93$, and $S_{yx} = 0.06$ for the K_{co} equations). Thus, either equation can be used to predict daily mean hourly crop coefficients for soybean as a function of DAE, indicating

the robustness of the measurements and consistency in the K_{cr} and K_{co} values developed in the two different years of this research.

The intra-day variation in hourly soybean crop coefficients during daylight hours (8:00-18:00) on randomly selected, but successive days corresponding to specific stages of crop development was examined. Diurnal variation in K_{co} and K_{cr} from early morning to late afternoon revealed substantially different patterns among the selected days. There is apparently less variation in hourly K_{cr} and K_{co} early in the season (fig. 4e) and later toward the end of the season (fig. 4i). However, during the initial development to mid-season (figs. 4f to 4h), the hourly soybean crop coefficients exhibited large diurnal fluctuations, ranging from as low as 0.1 early in the day to above 1.5 in the late afternoon. For example, at 25 DAE, K_{co} and K_{cr} ranged from a low of 0.1-0.2 to a high of 1.1-1.2. However, the range of the upper limit subsequently increased to 1.6 on 56 DAE, peaked at 2.0 on 70 DAE, slightly declined to 1.8 on 92 DAE, and then fell to 0.6-0.80 on 120 DAE, a date near the end of the season. In that regard, K_{co} and K_{cr} exhibited similar patterns within a given year. In the earliest (25 DAE) and latest (120 DAE) parts of the growing season, K_{co} and K_{cr} exhibited a modest increase after sunrise from early morning hours until about 13:00-14:00 in the afternoon, plateaued to a constant level that held until 17:00 (probably because atmospheric evaporative demand is usually at its peak during that time), and then increased again in the later afternoon and early evening before sunset. The increase in K_c values at and shortly after solar noon is due to increase in vapor pressure deficit, and thus decrease in stomatal resistance, which increases transpiration and ET_a (ET_a rates measured by BREBS) at a rate greater than increase in ET_{ref} , which causes increase in K_c values (based on eq. 1) shortly after solar noon. ET_a increases at a greater rate than ET_{ref} because BREBS-measured ET_a measures soil evaporation plus plant transpiration, and variable stomatal resistance response to increase in vapor pressure deficit, air temperature, and solar radiation is embedded in the measured transpiration plus evaporation (ET_a), whereas ET_{ref} does not account for decrease in stomatal resistance due to increase in these environmental variables. Consequently, the ET_{ref} term becomes smaller than ET_a in equation 1, resulting in increases in K_{co} and K_{cr} values after solar noon. Relatively stable behavior in K_{co} and K_{cr} values during the solar noon hours might be due to the reduction in transpiration as a response of partial stomatal closure or regulation by soybean plants if they are not able to keep pace with increased atmospheric evaporative demand for water vapor transport. However, most of the diurnal fluctuations in hourly K_c values could be attributed to using a "fixed" canopy resistance term in the ASCE Penman-Monteith equation, which is not able to fully account for the impact of changes in climatic factors on stomatal behavior that drives transpiration. Plants constantly regulate their stomatal response to changing environmental variables, using a constant aerodynamic and (relative to plant stomatal response) potential evapotranspiration value, resulting in diurnal fluctuations in K_c . Using variable resistance terms in the ASCE Penman-Monteith equation

would provide a better representation of plant response to changing environmental variables through dynamic K_c values than a constant daily K_c value, which is commonly used in practice. While almost all environmental and climatic variables as well as most plant physiological functions, including stomatal resistance, continuously change throughout the day, which in turn results in changes in diurnal transpiration and evaporation, it is not realistic to expect the K_c values to remain constant throughout the day. These results clearly indicate that the K_{co} and K_{cr} values are not constant during the day, and using daily average K_{co} or K_{cr} values would not be able to provide robust and accurate estimates when used for calculating crop water requirement for high-frequency irrigation management.

DAILY AVERAGE (NORMAL OR SINGLE)

CROP COEFFICIENT CURVES

Daily crop coefficients for annual crops are mostly reported as a function of time, where time can be Julian days, days after planting (DAP), or DAE. Crop coefficient functions that are based on DAP do not account for variation in time from planting to plant emergence. That timeframe can vary substantially, as was documented by Bastidas et al. (2008). The number of days from planting to emergence is dependent on many factors, including soil conditions, weather, planting date, and cultural practices such as tillage, planting depths, and seed treatment. Therefore, using DAE as a base for expressing crop coefficients is more accurate because it eliminates the variable period preceding emergence and provides functions that relate crop coefficients directly to days within the above-ground crop growing period, which starts from emergence (VE) and continues until physiological maturity (R7).

The daily K_{cr} and K_{co} values were plotted as a function of DAE using the combined data for 2007 and 2008, as presented in figures 5a and 5b. At the start of the growing season between 0 and 30 DAE, K_{cr} and K_{co} values were higher than the 0.15 value normally recommended for the initial growth period. K_{cr} was in the range 0.20 to 1.12, whereas K_{co} was in the range 0.27 to 1.47. The high values of K_{cr} and K_{co} during this period were due to the frequent occurrence of rainfall events that resulted in wet soil surfaces, and thus greater water evaporation from the soil surface than would have occurred in the absence of rain in an SDI field. The values of K_{cr} and K_{co} increased with crop development and reached relatively constant values (around 1.10 for K_{cr} and 1.30 for K_{co}) between 47 and 95 DAE, which coincided with complete canopy cover. The maximum K_{cr} and K_{co} at full effective cover were 1.34 and 1.56, respectively, which occurred on 90 DAE in 2007 when there was a 78.6 mm rainfall event. At physiological maturity, K_{cr} and K_{co} declined to 0.15 and 0.22, respectively. In general, the 2007 growing season had slightly higher K_{cr} and K_{co} values than the 2008 season. Fluctuation in both K_{cr} and K_{co} was larger from emergence until about 45 DAE, an early-season pattern observed consistently in both years, when soil water evaporation was the dominant component of ET_a during partial canopy. In figure 4, it appears that the initial-season period for soybean could be temporally defined as the first 50 days (0 to 50 DAE), the mid-season

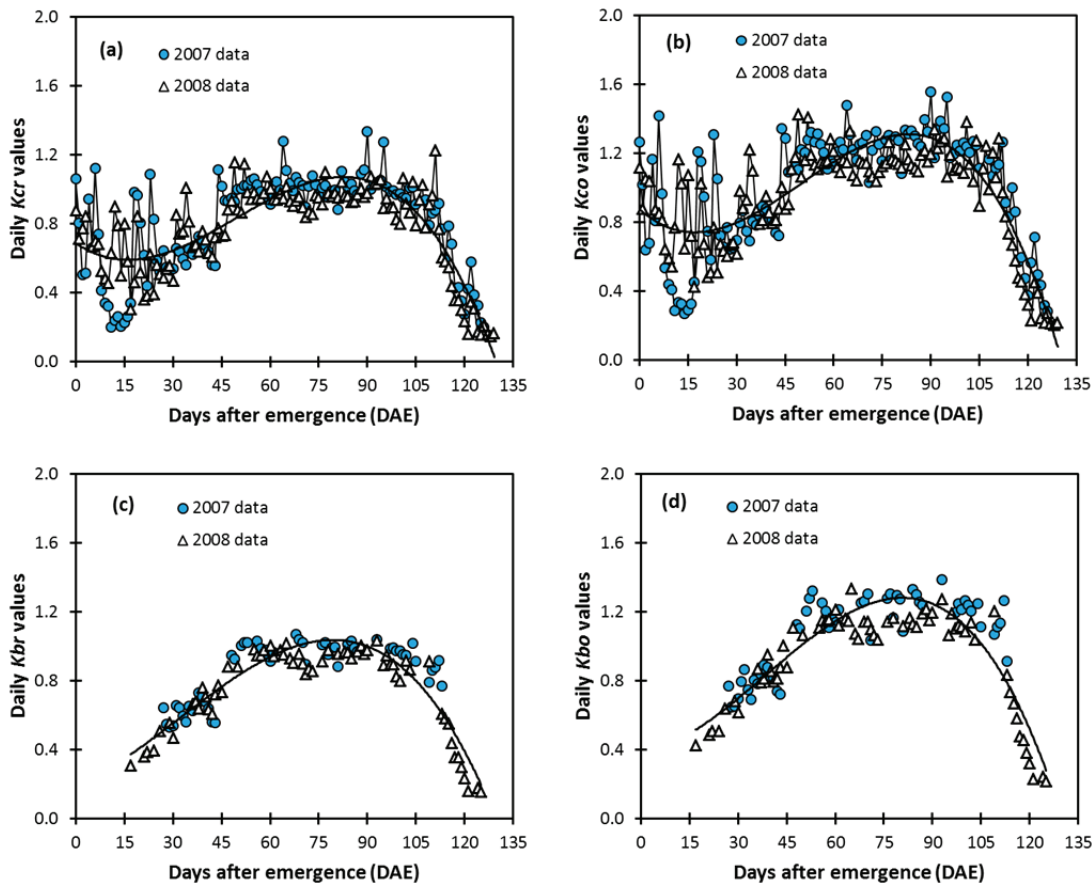


Figure 5. Seasonal trends in mean daily alfalfa- and grass-reference single crop coefficients: (a) K_{cr} and (b) K_{co} , and basal crop coefficients: (c) K_{cbr} and (d) K_{cbo} for soybean using a time scale of days after emergence.

stage as the second 50 days (50 to 100 DAE), and late-season as the last 30 to 35 days (100 to 135 DAE). A t -test was performed to determine if the means of the two years were significantly different, and the results indicated otherwise (i.e., $t = 0.938$, standard deviation = 0.263, degrees of freedom = 246, and type I error probability = 0.35). The fact that both sets of K_{co} and K_{cr} values did not differ between years demonstrates the similarity in climatic conditions as well as the robustness and consistency of the experimental procedures used to derive ET_a and K_c values that could be used for either year, and thus in future years.

BASAL CROP COEFFICIENT CURVES

Since K_{cr} and K_{co} are calculated from data that include days with rainfall, the resultant crop coefficient values are influenced by the frequency and amounts of rainfall that occur in a particular year. To obtain crop coefficients that are fairly independent of the yearly rainfall variations, basal crop coefficients were calculated and adjusted for soil surface wetness. Figures 5c and 5d show the generalized basal crop coefficient curves based on alfalfa-reference (K_{cbr}) and grass-reference (K_{cbo}) surfaces determined by fitting a polynomial regression curve to the time distribution of the K_{cbr} and K_{cbo} data. The regressions used in the graphs provided good fits based on $R^2 = 0.84$ for K_{cbr} and $R^2 = 0.81$ for K_{cbo} . The relationships between DAE and daily K_{cbr} and K_{cbo} were modeled as third-order polynomials, as expressed by equations 8 and 9 for figures 5c and 5d:

$$K_{cbr} = -0.0000021253DAE^3 + 0.0002024916 DAE^2 + 0.0079942852 DAE + 0.1901341792 \quad (8)$$

$$K_{cbo} = -0.0000029536DAE^3 + 0.0003381381DAE^2 + 0.0031290639DAE + 0.3800693864 \quad (9)$$

When normal (single) K_{cr} and K_{co} values (figs. 5a and 5b) were adjusted to develop basal crop coefficients (K_{cbr} and K_{cbo}) (figs. 5c and 5d), the fluctuations in K_c values as a result of soil evaporation from precipitation was minimized. The K_{cbr} and K_{cbo} data exhibited similar distribution to the K_{cr} and K_{co} values with similar lower and upper limits in both years.

DAILY CROP COEFFICIENTS VERSUS DAILY MEANS OF HOURLY CROP COEFFICIENTS

To quantify the differences between the daily and hourly K_c values, hourly crop coefficient data were averaged for each day and reported as daily means of the 10 to 13 hourly crop coefficients. These mean-of-hourly crop coefficients for a given day were regressed on daily crop coefficients calculated for the same day using daily ET_a and ET_{ref} data. The results are presented in the 1:1 graphs in figure 6. The mean-of-hourly crop coefficients and corresponding daily crop coefficients are visibly highly correlated in both years. For the K_{cr} data (figs. 6a and 6b), the zero-origin based regression lines had a regression coefficient and R^2 value of 0.92 and 0.84, respectively, in 2007 and 0.95 and 0.83, re-

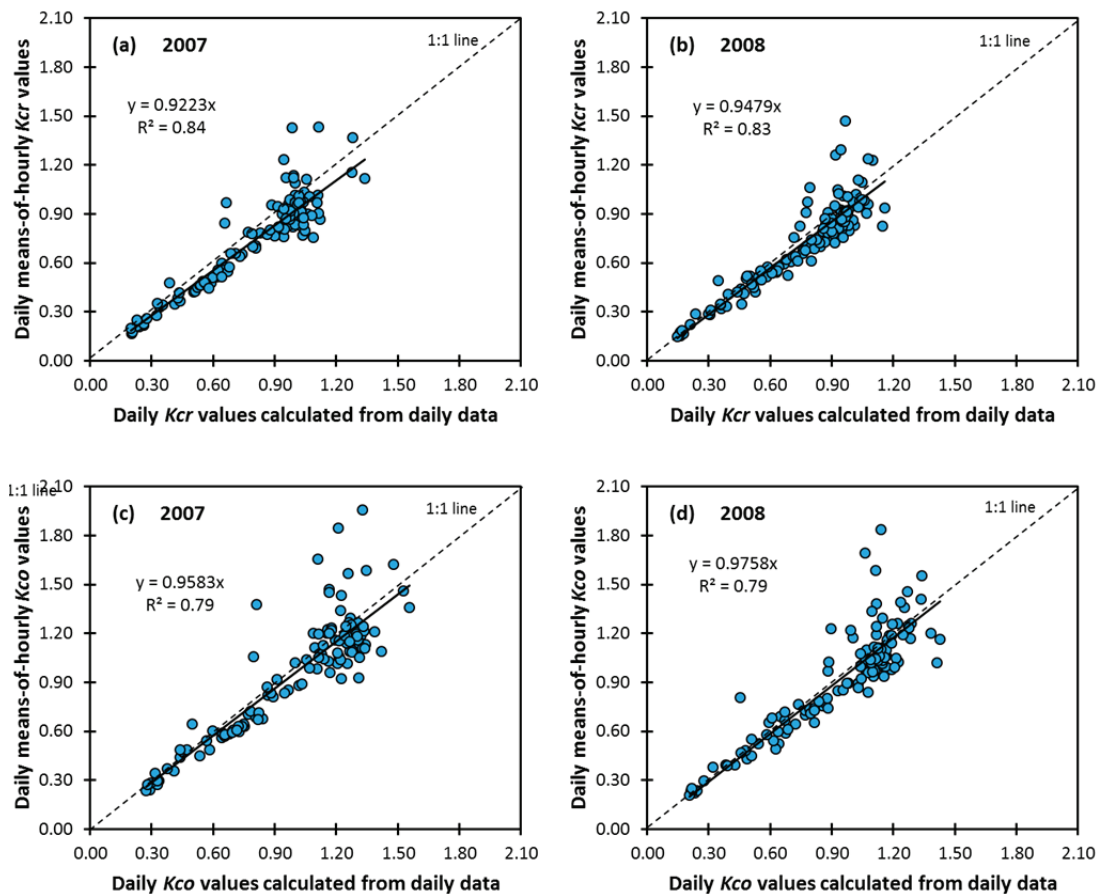


Figure 6. Relationships between daily means-of-hourly crop coefficient and corresponding daily crop coefficient for the alfalfa-based crop coefficients (K_{cr}) in (a) 2007 and (b) 2008 and for the grass-based crop coefficients (K_{co}) in (c) 2007 and (d) 2008.

spectively, in 2008. For the K_{co} data (figs. 6c and 6d), the regression coefficient and R^2 values were 0.96 and 0.79, respectively, in 2007 and 0.98 and 0.79, respectively, in 2008. The root mean squared difference (RMSD) between the mean-of-hourly crop coefficients and daily crop coefficients was 0.13 and 0.17 mm d⁻¹ for K_{cr} in 2007 and 2008, respectively, and 0.12 and 0.15 mm d⁻¹ for K_{co} in 2007 and 2008, respectively. On average, the daily crop coefficient data were slightly higher (by about 8%) than the mean-of-hourly crop coefficients throughout the growing season, although there were a few days in which the mean-of-hourly crop coefficients were higher than the crop coefficients calculated from daily data. The deviation between the two sets of K_c values at higher K_c range was greater for K_{co} than K_{cr} . This indicate that using daily average K_{cr} , K_{co} , K_{cbr} , or K_{cbo} to calculate ET_a and/or irrigation requirement can result in greater error at the higher ET_a range, and using hourly K_c values can mitigate this potential issue.

CALCULATED DAILY K_{co} VERSUS FAO-56 K_{co}

Figure 7 shows a comparison between the calculated K_{co} and the FAO-56-tabulated K_{co} values (data originally from FAO-24; Doorenbos and Pruitt, 1977). The FAO-56 data, which is reflective of only grass-reference K_{co} values, assumes a constant K_{co} value of 0.5 during the initial growth stage (0 to 15 DAE) and a constant K_{co} value of 1.15 during the mid-season growth stage (46 to 105 DAE). The meas-

ured K_{co} values in this research exceeded the FAO-56 K_{co} values during the period 58 to 99 DAE, reaching a peak of 1.29 between 75 to 84 DAE. The mean, minimum, and maximum values were 0.89, 0.20, and 1.29, respectively, for the measured K_{co} and 0.93, 0.5, and 1.15, respectively, for the FAO-56 tabulated K_{co} . During the period from 15

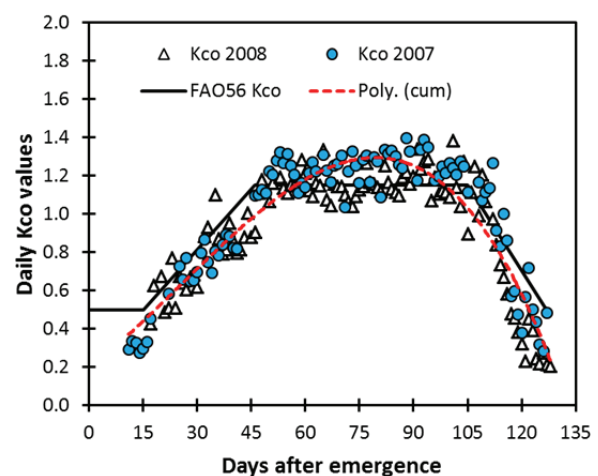


Figure 7. Comparison of the measured grass-reference crop coefficients (K_{co}) obtained in this research and the FAO-56-tabulated values. The black trend line represents the FAO values that are often applied generically at specific locations. The red trend line represents the polynomial equation fit to the combined 2007-2008 data measured in this research in south-central Nebraska.

DAE to end of the crop season at 127 DAE, the maximum difference between the calculated K_{co} and the FAO-56 K_{co} was less than 0.2. A two-sample t -test was used to determine if the two means were equal. The degrees of freedom was 127, and the absolute value of the t -statistic was 4.80, which is greater than the critical value of 1.96. The results indicate that the means are different at the 0.05 significance level, and the K_{co} values measured in this research versus those tabulated in FAO-56 are significantly different ($p < 0.05$). Thus, the FAO-56 values, if used for south-central Nebraska soil, climate, and management conditions, and in other locations that have similar settings, would not be able to provide accurate ET_a and crop water requirement estimations. These analyses also demonstrate the importance of locally measured K_c values for more accurate crop water use and irrigation requirement for within-season irrigation management determinations.

DAILY BASAL AND NORMAL (SINGLE) CROP COEFFICIENTS BASED ON GDD

Presenting soybean crop coefficients as a function of time is convenient for projecting crop water needs and scheduling irrigation for shorter time steps. However, it has the disadvantage of not taking into account the environmental factors, including air temperature, daylength, and crop management factors, that often influence the rate of soybean growth and development. In crops whose development is not greatly affected by daylength, such as maize, crop coefficients that are based on temperature summation expressed as GDD have been shown to account for variation in plant development that arises as a result of differences in environmental conditions or planting dates (Amos et al., 1989; Sammis et al., 1985; Nielsen and Hinkle, 1996; Stegman, 1988; Irmak, 2005). However, development in soybean cannot be adequately predicted by GDD alone because soybean growth and development are dominantly influenced by growing season temperature as well as by daylength (Johnson et al., 1960; Major et al., 1975a, 1975b; Cregan and Hartwig, 1984; Hesketh et al., 1973). Temperature generally increases the rate of soybean development, while longer daylengths slow the development rate. The literature on GDD-based crop coefficients for soybean is extremely limited.

In this research, differences between the planting dates and emergence dates in 2007 and 2008 were just 3 and 2 days, respectively. In essence, the 2-day difference between years in emergence dates was not biologically significant, given the trivial difference in the seasonal change in photoperiod that the 2007 and 2008 crops experienced. The relationships between K_{cr} and K_{co} versus GDD are presented in figures 8a and 8b. The relationships between K_{cbr} and K_{cbo} versus GDD were also developed and are presented in figures 8c and 8d. The cumulative GDD values for the 2007 and 2008 growing seasons are presented in figure 8e.

Generalized basal crop coefficient curves were derived by fitting a polynomial regression curve to the K_{cbr} and K_{cbo} versus GDD data. To improve the predictive accuracy of the K_{cbr} and K_{cbo} curves, the growing season was divided into timeframe 1 and timeframe 2, with the former representing the growing season prior to the start of leaf senes-

cence and the latter representing the growing season thereafter. The corresponding GDD crop coefficient curves (K_{cbr1} and K_{cbr2} , and K_{cbo1} , and K_{cbo2}) are shown in figures 8c and 8d. The regression was highly significant for the data derived prior to the start of senescence, with $R^2 = 0.86$ for K_{cbr1} and $R^2 = 0.84$ for K_{cbo1} . After the start of senescence, the basal crop coefficient data for 2007 and 2008 appeared to diverge, with the 2008 coefficients being lower than the 2007 coefficients. Figure 8e shows that the growing season temperatures for 2007 and 2008 were similar from planting to about 80 DAP, resulting in similar soybean growth rates during vegetative growth phase. After 80 DAE, cumulative GDD values for the 2007 and 2008 seasons deviated from each other to the point that seasonal GDD was higher in 2007 (2,225°C) than in 2008 (2,100°C). After 80 DAE, the 2008 growing season was cooler than 2007, resulting in a slower rate of GDD accumulation. Thus, leaf senescence occurred earlier, and the K_c values declined earlier as well as with a faster rate as compared with the 2008 season. Relatively lower basal crop coefficients after the start of senescence in 2008 are attributed to the relatively lower temperatures that caused slower crop development, resulting in differences in K_c values. The following power function relationships were developed between soybean normal (average) and basal crop coefficients versus GDD (°C):

$$K_{cr} = -0.0000000007GDD^3 + 0.0000017384GDD^2 - 0.0009161686GDD + 0.7396237442 \quad (10)$$

$$K_{co} = -0.0000000008GDD^3 + 0.0000020936GDD^2 - 0.0011421673GDD + 0.9334236143 \quad (11)$$

$$K_{cbr1} = 0.0000000003GDD^3 - 0.0000014893GDD^2 + 0.0025671644GDD - 0.4411724443 \quad (12)$$

$$K_{cbr2} = -0.0000008525GDD^2 + 0.0016146322GDD + 0.7092696006 \quad (13)$$

$$K_{cbo1} = 0.0000000004GDD^3 - 0.0000018494GDD^2 + 0.0030564428GDD - 0.4707047656 \quad (14)$$

$$K_{cbo2} = -0.0000019042GDD^2 + 0.0053281358GDD - 2.3520340927 \quad (15)$$

DAILY BASAL AND NORMAL (SINGLE) CROP COEFFICIENTS BASED ON LAI

Leaf area index (LAI) is an effective variable to infer crop development and can be used as an effective parameter to indicate the level of crop canopy growth and development in relation to K_c , although there is not much information in the literature relative to studies using LAI as a base scale for K_c curves. LAI is defined as the ratio of unit leaf area to unit ground area in which the LAI is measured and is typically reported as $m^2 m^{-2}$. In soybean, LAI of 3 or greater is commonly taken to represent effective full canopy cover, although LAI can be subdivided into photosynthetically active and photosynthetically inactive components. The photosynthetically active component consists of green leaves that photosynthesize and transpire, while the photosynthetically inactive component consisting of physiologically senescent dry leaves that do not photosynthesize

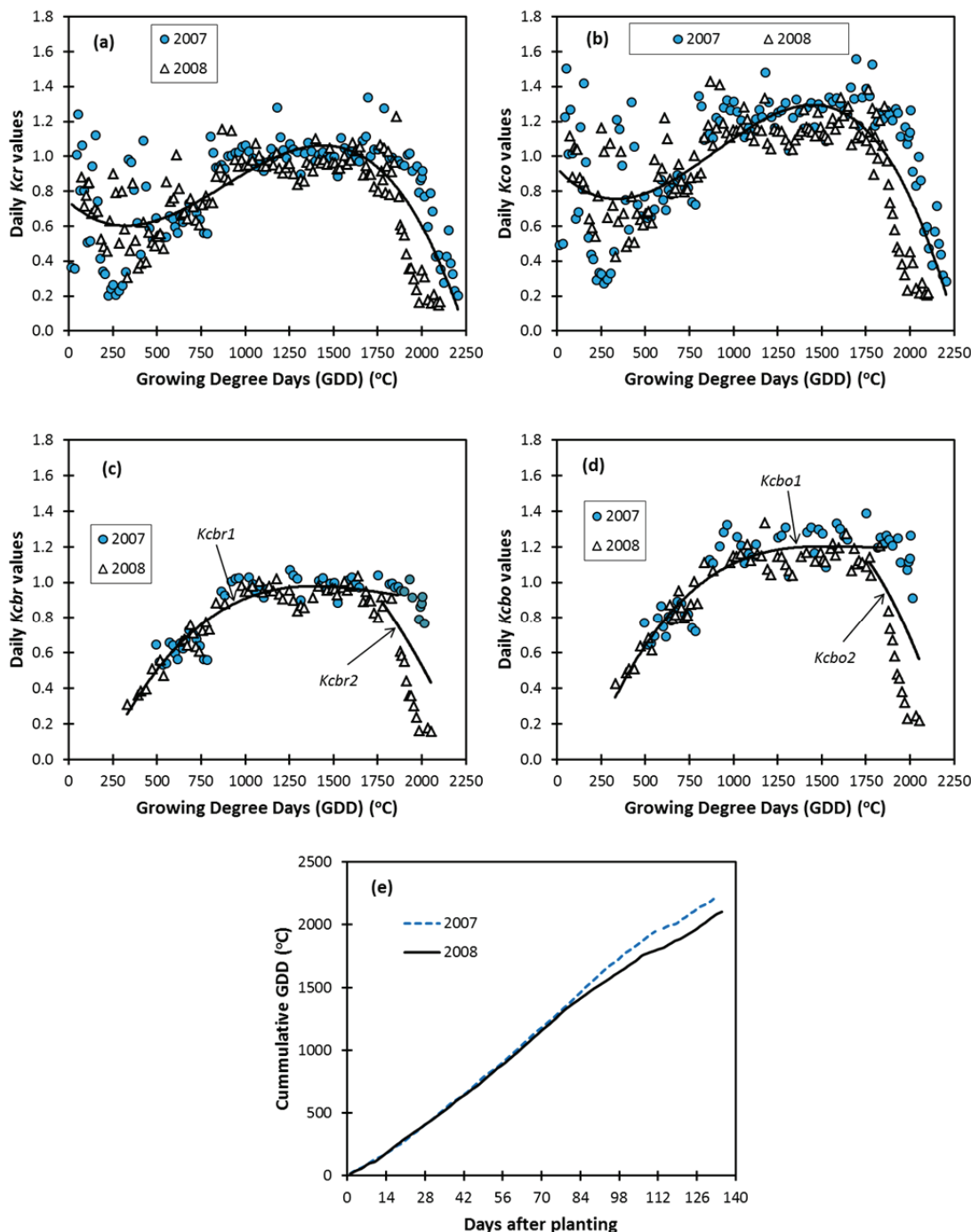


Figure 8. Daily alfalfa- and grass-reference soybean single crop coefficients: (a) K_{cr} and (b) K_{co} and basal crop coefficients: (c) K_{cbr} and (d) K_{cbo} as a function of growing degree days (GDD). Also shown is a comparative graph (e) of the 2007 and 2008 cumulative GDD trends on a time scale of days after planting.

and transpire very little or not at all. In this research, the LAI-2000 instrument that was used to measure LAI deduces the amount of foliage in vegetative canopy by measurements of the degree to which solar radiation is attenuated as it passes through the canopy; hence, it does not separate LAI into photosynthetically active and inactive components.

The regression plots for the combined 2007 and 2008 crop coefficient data in figures 9a to 9d show that the relationship between soybean crop coefficients and LAI results

in two trend lines: one representing the growth period before the start of senescence (a photosynthetically active period), and the other representing the growth period after the start of senescence (an increasingly photosynthetically inactive period). The LAI during the growth period before senescence, in effect, corresponds to LAI. The regression was highly significant for both periods before the start of senescence (K_{cr1} , K_{co1} , K_{cbr1} , and K_{cbo1}) and after start of senescence (K_{cr2} , K_{co2} , K_{cbr2} , and K_{cbo2}) with $R^2 = 0.73$ for K_{cr1} , $R^2 = 0.74$ for K_{co1} , $R^2 = 0.86$ for K_{cbr1} , $R^2 = 0.87$ for

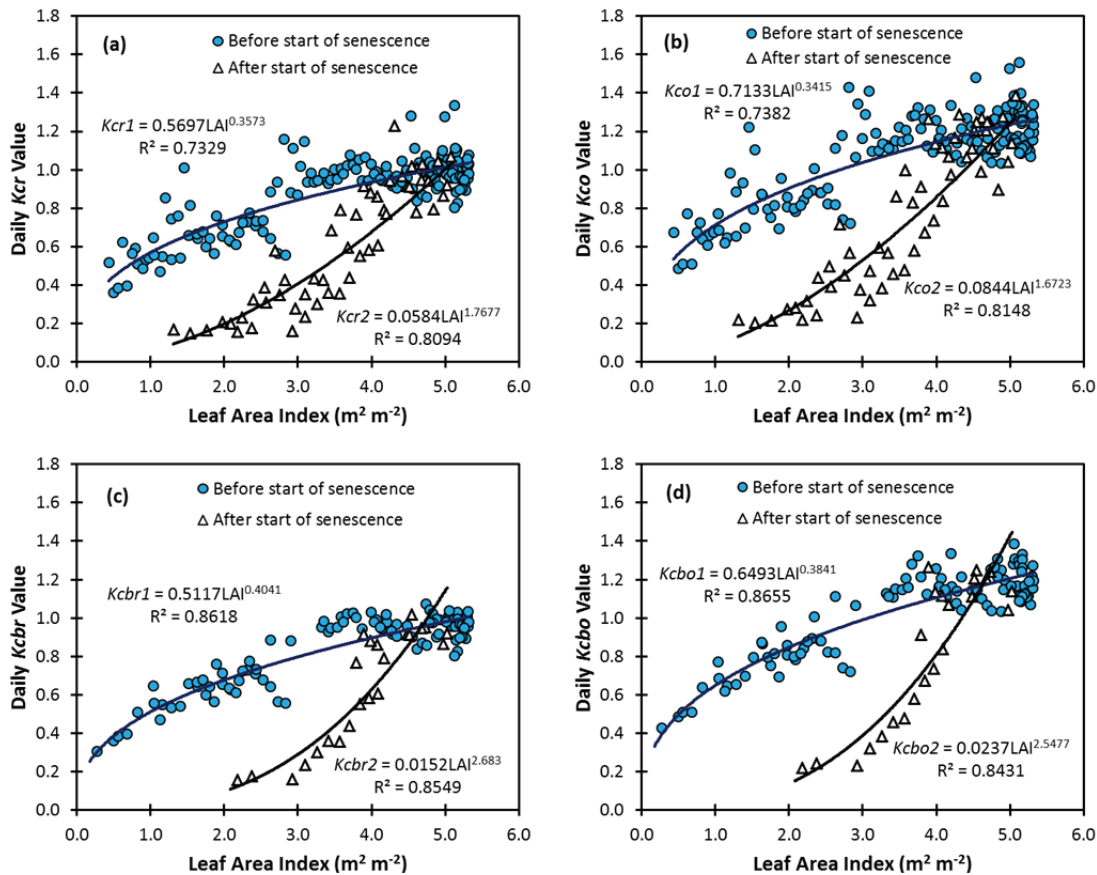


Figure 9. Before and after crop senescence relationships between soybean crop coefficients and leaf area index (LAI) for single alfalfa- and grass-reference crop coefficients: (a) K_{cr} and (b) K_{co} and for basal crop coefficients: (c) K_{cbr} and (d) K_{cbo} . Each data point is a coordinate pair (i.e., daily K_c value and LAI value), so the individual points shown in a given graph relate to a coordinate pair observed in either year.

K_{cbo1} , $R^2 = 0.81$ for K_{cr2} , $R^2 = 0.81$ for K_{co2} , $R^2 = 0.85$ for K_{cbr2} , and $R^2 = 0.84$ for K_{cbo2} . It should be pointed out that as one moves leftward in each graph from an LAI of 5 to an LAI of 2 (or lower), one is moving temporally backward in phenological time in terms of the LAI data points collected prior to senescence, but forward in phenological time in terms of the LAI data points collected after senescence. In any case, these results indicate that the relationship between soybean crop coefficients and LAI before and after senescence can be modeled satisfactorily using two separate power functions. The following power function relationships were developed between soybean normal and basal crop coefficients and LAI:

$$K_{cr1} = 0.5697LAI^{0.3573} \quad (16)$$

$$K_{cr2} = 0.0584LAI^{1.7677} \quad (17)$$

$$K_{co1} = 0.7133LAI^{0.3415} \quad (18)$$

$$K_{co2} = 0.0844LAI^{1.6723} \quad (19)$$

$$K_{cbr1} = 0.5117LAI^{0.4041} \quad (20)$$

$$K_{cbr2} = 0.0152LAI^{2.683} \quad (21)$$

$$K_{cbo1} = 0.6493LAI^{0.3841} \quad (22)$$

$$K_{cbo2} = 0.0237LAI^{2.5477} \quad (23)$$

where subscripts 1 and 2 represent the periods before senescence and after start of senescence, respectively.

One of the advantages of using LAI as the base scale to estimate soybean K_c values is that LAI can be estimated accurately as a function of DAP or cumulative GDD. Mutiibwa and Irmak (2011) developed relationships between LAI (unitless) and DAP and between LAI and cumulative GDD ($^{\circ}\text{C}$) for soybean canopy for the 2007 and 2008 growing seasons in the following forms:

$$LAI_{2007} = -6E-06DAP^3 + 4E-05DAP^2 + 0.138DAP - 3.23 \quad (R^2 = 0.97) \quad (24)$$

$$LAI_{2008} = -2E-05DAP^3 + 0.0025DAP^2 - 0.038DAP + 0.057 \quad (R^2 = 0.99) \quad (25)$$

$$LAI_{2007} = -5E-09GDD^3 + 6E-06GDD^2 + 0.0054GDD - 1.12 \quad (R^2 = 0.97) \quad (26)$$

$$LAI_{2008} = -2E-08GDD^3 + 3E-05GDD^2 - 0.011GDD + 1.82 \quad (R^2 = 0.97) \quad (27)$$

The foregoing experimentally derived equations (eqs. 24 to 27) could be used to estimate LAI values that, in turn, can be used in the equations (eqs. 16 to 23) developed to estimate daily soybean K_c values in practical applications.

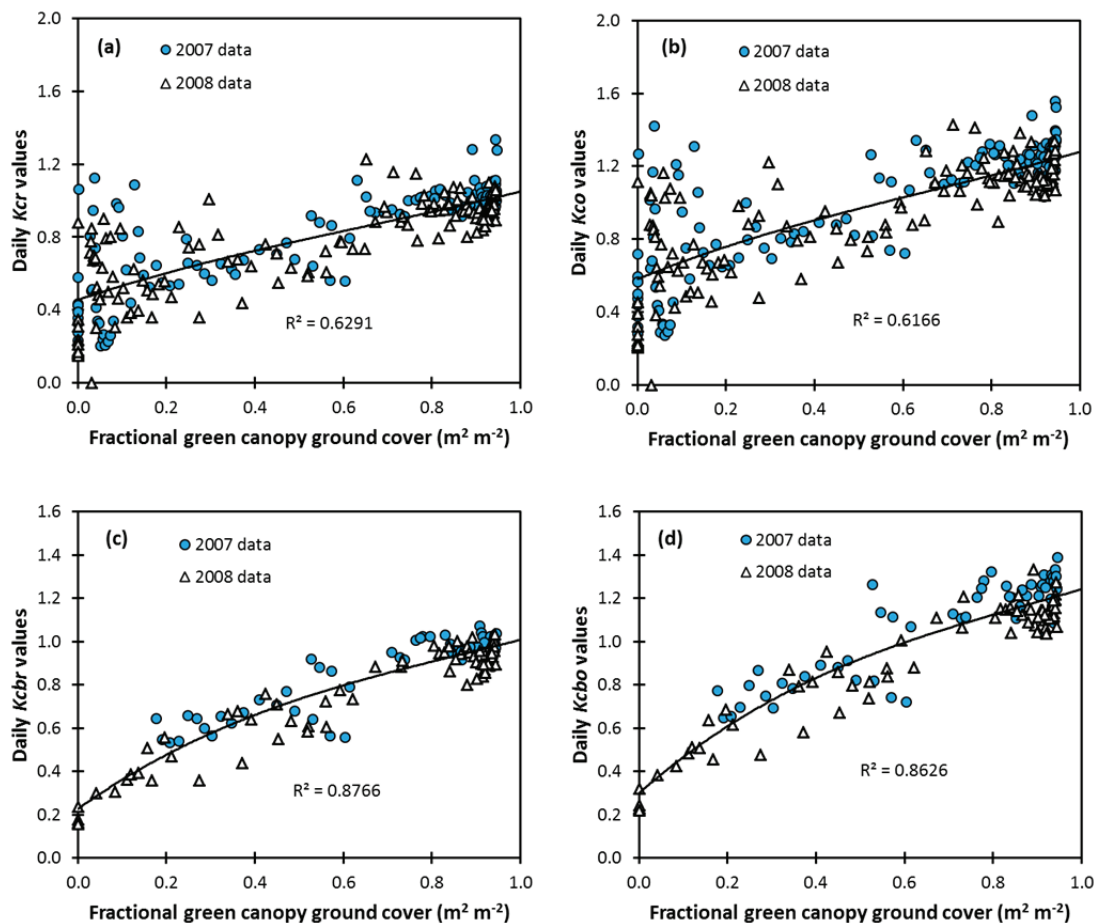


Figure 10. Relationship between 2007 and 2008 measured alfalfa- and grass-reference soybean single crop coefficients: (a) K_{cr} and (b) K_{co} , and basal crop coefficients: (c) K_{cbr} and (d) K_{cbo} as a function of coordinately measured fractional green canopy groundcover (CC).

BASAL AND NORMAL (SINGLE) DAILY CROP COEFFICIENTS BASED ON CC

The use of fractional green canopy groundcover (CC) as the base scale to express the K_c values was also examined in this research. Green canopy cover is different from general canopy shading of the ground in the sense that it accounts for the exposed green leaves that intercept light and support plant transpiration. The CC was simulated by the exponential canopy growth and decay functions presented in the AquaCrop model. The results in figures 10a to 10d show that soybean crop coefficients are almost linearly correlated to CC. The correlation was stronger between the basal crop coefficients and CC ($R^2 = 0.88$ for K_{cbr} and $R^2 = 0.86$ for K_{cbo}) than between the single crop coefficients and CC ($R^2 = 0.63$ for K_{cr} and $R^2 = 0.62$ for K_{co}). In 2007 and 2008 for K_{cr} and K_{co} (figs. 10a and 10b), there was a larger deviation in the data in the early growing season from emergence to about CC of 0.3. During the mid-season, when the green canopy attained full closure (CC between 0.4 and about 0.65), the correlation between K_{cr} and K_{co} versus CC was strongest, with minimum deviation in the data. The deviation became larger again for CC values greater than 0.65 until end-season. There is more scatter in the 2008 data than in 2007 due to a higher amount of rainfall, especially in the early growing season. The early season deviations are largely due to soil evaporation, and the

late-season deviations are mostly due to leaf aging and senescence, when CC alone is not able to fully explain the K_c values. When soil evaporation is accounted for in the K_c values through development of the K_{cbr} and K_{cbo} versus CC relationships (figs. 10c and 10d), the early-season deviation in the data is minimized. However, part of the late-season deviation still remains because CC alone is not able to account for the impact of leaf aging and senescence on K_{cbr} and K_{cbo} values. Similar relationships between crop coefficients and groundcover have been observed for vegetable crops (Gratten et al., 1998), but to the best knowledge of the authors of this article, similar research for soybean had not been reported in the literature. These types of generalized relationships would allow weather-based irrigation management to be based on simple canopy measurements or possibly based on remotely sensed vegetation indices (Trout et al., 2008). The approach of determining crop coefficients from canopy cover should gain interest with the increased research and development of vegetation indices using remote sensing methodologies. For example, recently Mutibwa and Irmak (2013) developed and validated a global relationship between K_c and NOAA satellite-acquired Advanced Very High Resolution Radiometer (AVHRR)-based normalized difference vegetation index (NDVI) to investigate the trends and magnitudes in ET_a originating from increasing irrigation practices in the High

Plains from 1981 to 2008. They quantified ET_a over the entire High Plains region from the spatial crop coefficients and spatial reference (potential) ET. The K_c -NDVI model was able to explain more than 90% of the variability in measured K_c . The model had an R^2 value of 0.71, modeling efficiency of 0.70, and RMSD (between BREBS-measured and estimated K_c) of 0.14. They also quantified the evolution of full canopy cover vegetation (NDVI > 0.70) in relation to the maximum temperature anomalies during the research period.

It should be noted that the K_c versus CC approach does not replace ET_a measurement for developing crop coefficient curves, but it does provide a means to estimate and evaluate the change in K_c values with increases or decreases of groundcover for the effects of different plant population densities. The following power function relationships were developed between soybean K_c and CC ($m^2 m^{-2}$):

$$K_{cr} = 0.222530CC^3 - 0.441725CC^2 + 0.814062CC + 0.455558 \quad (28)$$

$$K_{co} = 0.295896CC^3 - 0.591316CC^2 + 0.995319CC + 0.580813 \quad (29)$$

$$K_{chr} = 0.398997CC^3 - 1.064580CC^2 + 1.446714CC + 0.227111 \quad (30)$$

$$K_{cbo} = 0.521796CC^3 - 1.378226CC^2 + 1.799542CC + 0.299701 \quad (31)$$

DAILY CROP COEFFICIENTS BASED ON CROP PHENOLOGY

Soybean crop coefficients based on only DAE or GDD may not fully or accurately track soybean crop development in all of the potentially possible environmental scenarios. Genetic improvement results in new cultivar choices for producers every year, and agronomic research often leads to subtle or periodic substantive changes in crop and soil management practices, both of which may lead to crop coefficients being assigned to improper stages of crop develop-

ment. Crop coefficient assignment based on a well-tracked and readily predictable crop phenology can be exceptionally useful to growers, crop consultants, extension service personnel, agronomists, irrigation practitioners, and related professionals because these users can apply crop coefficients in a timely manner by periodic observation and monitoring of actual crop growth stage in the field. All of the aforementioned professionals are usually familiar with crop staging systems, including the Fehr and Caviness (1977) soybean staging system now commonly used for direct assessment of this crop's stage in the field. Soybean growth and development is nominally separated into vegetative and reproductive phases, although in this crop species the end of the vegetative period overlaps with the start of the reproductive period. The vegetative phase starts from the time the plant emerges from the soil and overlaps with the flowering stage, but eventually slows and ceases at the start of the seed-filling stage (Bastidas et al., 2008). The reproductive phase begins with flowering and continues with podding and seed-filling until the crop attains physiological maturity, when seed-filling ceases, with the crop thereafter entering its final phase of drying down on its approach to harvest maturity. The Fehr and Caviness (1977) soybean staging system has been adopted by researchers around the world. The vegetative (V) growth stages are numbered on the basis of nodes on the main stem, beginning with the cotyledon node assigned the number zero, the unifoliolate leaf node assigned the number one, and subsequent trifoliolate leaf nodes assigned consecutive numbers thereafter. The reproductive (R) developmental stages are numbered from one at the beginning of flowering, continuing through pod development and seed development, and then onward through three plant maturation stages. The soybean V and R stages are presented the leftmost columns of table 1.

In this research, plant growth and development stages were simulated using the soybean phenology model (SOY-SIM) (Setiyono et al., 2007, 2010; Torrión et al., 2011). This model utilizes nonlinear temperature and photoperiod

Table 1. Average (normal or single) alfalfa-reference (K_{cr}) and grass-reference (K_{co}) soybean crop coefficients and basal crop coefficients (K_{chr} and K_{cbo} , respectively) for successive soybean vegetative (V) and reproductive (R) stages of the maturity group (MG) III cultivar used in this research that emerged on 26 May in 2007 and 24 May in 2008. Also shown are the correspondent values for days after emergence (DAE) and cumulative growing degree days (GDD, °C).

V or R Stage	Soybean Stage ^[a]	DAE		GDD ^[b]		Single and Basal Crop Coefficients			
		2007	2008	2007	2008	K_{cr}	K_{co}	K_{chr}	K_{cbo}
VE	Emergence	0	0	75	70	0.69	0.88	0.19	0.38
V0	Cotyledon node	9	8	193	180	0.61	0.77	0.27	0.43
V1	Unifoliolate node	14	12	264	250	0.60	0.75	0.32	0.47
V2	1st trifoliolate node	18	17	338	330	0.59	0.74	0.38	0.52
V3	2nd trifoliolate node	22	22	407	408	0.60	0.75	0.44	0.58
V4	3rd trifoliolate node	26	27	476	486	0.62	0.77	0.50	0.65
V5	4th trifoliolate node	29	31	532	553	0.65	0.80	0.55	0.70
V6	5th trifoliolate node	33	34	601	610	0.67	0.83	0.61	0.75
R1	First open flower	38	41	683	718	0.73	0.90	0.69	0.85
R2	Full bloom	44	47	803	834	0.79	0.97	0.77	0.94
R3	Beginning pod	54	57	982	1019	0.90	1.10	0.89	1.09
R3.5	Mid-pod elongation	61	63	1126	1136	0.96	1.18	0.96	1.17
R4	Full pod	63	66	1163	1193	0.99	1.20	0.98	1.20
R5	Beginning seed	74	77	1375	1396	1.06	1.29	1.03	1.27
R6	Full seed	96	97	1801	1698	1.00	1.23	0.94	1.18
R7	Physiological maturity	110	112	1994	1871	0.73	0.91	0.67	0.85
R8	Harvest maturity	127	128	2219	2094	0.11	0.18	0.10	0.15

^[a] See Fehr et al. (1971) and Fehr and Caviness (1977) for more details of commonly used soybean staging system.

^[b] For soybean, the maximum and minimum temperatures are assumed to be 30°C and 10°C, respectively.

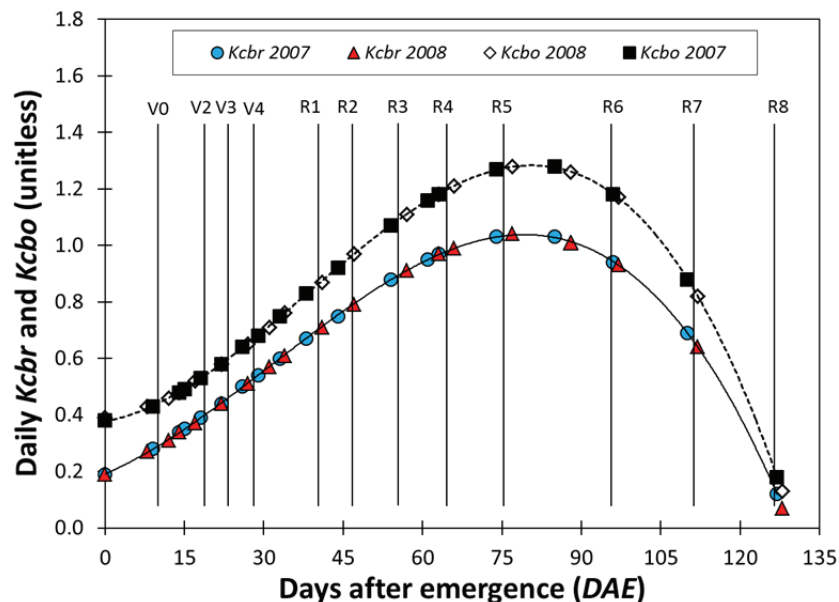


Figure 11. Graph of the 2007 and 2008 seasonal distributions of daily alfalfa- and grass-reference average (normal or single) crop coefficients (K_{cr} and K_{co} , respectively) and corresponding basal soybean crop coefficients (K_{cbr} and K_{cbo} , respectively) as a function of days after emergence (DAE), with vertical lines denoting the coincident successive soybean crop development stages observed with respect to the maturity group (MG) III cultivar used in this research.

functions and separates floral induction and post-induction for simulating the time of soybean growth stages. The growth stages that are observable and predictable by SOY-SIM and the respective estimated average K_{cr} , K_{co} , K_{cbr} , and K_{cbo} values for each soybean V and R stage are presented in table 1. The associated DAE and GDD values are also included in the table for reference. A graph of the seasonal distribution of daily K_{cr} , K_{co} , K_{cbr} , and K_{cbo} values associated with each soybean growth stage is presented in figure 11. The crop coefficients increase gradually from a low value ($K_{cr} = 0.69$, $K_{co} = 0.88$, $K_{cbr} = 0.19$, and $K_{cbo} = 0.38$) at plant emergence, reach a maximum value ($K_{cr} = 1.06$, $K_{co} = 1.29$, $K_{cbr} = 1.03$, and $K_{cbo} = 1.27$) at growth stage R5 (beginning seed), and then fall rapidly to a low value ($K_{cr} = 0.11$, $K_{co} = 0.18$, $K_{cbr} = 0.10$, and $K_{cbo} = 0.15$) at harvest maturity. Table 1 can be very effective in estimating soybean water use and irrigation requirements on a daily basis in practical applications. This information can be used for within-season irrigation management because it presents the crop coefficients as functions of three base scales. The GDD can be easily obtained from various sources, including weather station networks, county Extension offices, irrigation districts, etc., or it can also be calculated using a simple formula presented in equation 3 of this research.

SUMMARY AND CONCLUSIONS

Crop coefficient functions for determining average (normal or single) and basal crop coefficients for soybean were developed in this research using extensive field data measured in south-central Nebraska. Measurements were conducted on a 13.5 ha soybean field that had a subsurface drip irrigation (SDI) system located at the University of Nebraska-Lincoln South Central Agricultural Laboratory (UNL-SCAL) near Clay Center, Nebraska, during the 2007

and 2008 growing seasons. Hourly and daily crop coefficients were calculated as the ratio of actual crop evapotranspiration (ET_a) and reference (potential) evapotranspiration (ET_{ref}). Hourly ET_a and other associated surface energy fluxes and weather variables were measured using a Bowen ratio energy balance system (BREBS) installed in the middle of the experimental field. The single and basal crop coefficients based on an alfalfa-reference surface were designated K_{cr} and K_{cbr} , respectively, and those based on a grass-reference surface were designated K_{co} and K_{cbo} , respectively. The temporal variation of the K_{cr} , K_{co} , K_{cbr} , and K_{cbo} curves were fit to mathematical functions in which the base scales were days after emergence (DAE), cumulative growing degree days (GDD), leaf area index (LAI), fractional green canopy groundcover (CC), or successive vegetative (V) and reproductive (R) stages of plant phenology.

The functions relating crop coefficients to DAE and CC are represented by one crop coefficient curve spanning the entire growing season, whereas the functions relating crop coefficients to LAI and GDD were best represented by the derivation of two regression curves: one spanning crop development prior to the start of senescence, and the other spanning the final phases of crop development after the start of plant senescence. The high hourly K_{cr} and K_{co} values observed during the few hours of daylight just before sunset, or observed on very cloudy hours when net radiation was low, resulted in estimated ET_r and ET_o being extremely low relative to the measured ET_a . There was less variation in hourly K_{cr} and K_{co} values early and then late in the crop season as compared with the variation in mid-season. The daily means of the 10 to 13 diurnally derived hourly K_{cr} values ranged from 0.25 to 1.06 in 2007 and from 0.15 to 1.02 in 2008, whereas the daily mean-of-hourly K_{co} values ranged from 0.39 to 1.37 in 2007 and from 0.22 to 1.29 in 2008. Daily K_{cr} and K_{co} values calcu-

lated using only daily data ranged from 0.20 to 1.12 and from 0.27 to 1.47, respectively. Linear regression of the daily mean-of-hourly crop coefficients on the corresponding daily crop coefficients in each year of the research revealed highly significant zero-origin based regression coefficients in the range 0.92 to 0.98, with R^2 values in the range 0.79 to 0.84, and root mean squared difference (RMSD) values of 0.13 and 0.17 for K_{cr} in 2007 and 2008, respectively, and 0.12 and 0.15 for K_{co} in 2007 and 2008, respectively.

On average, the daily crop coefficients were slightly higher (by about 8%) than the mean-of-hourly crop coefficients throughout the growing season. The deviation between the two sets of K_c values at the higher K_c range was greater for K_{co} than K_{cr} . This indicates that using daily average K_{cr} , K_{co} , K_{cbr} , or K_{cbo} to calculate ET_a and/or irrigation requirement can result in greater error at the higher ET_a range, and using hourly K_c values can potentially mitigate this issue. All five base scales (DAE, GDD, LAI, CC, and plant phenology) were found to be effective in predicting soybean K_c . Each base scale can have advantages or disadvantages in terms of data requirements depending on the conditions in which it is applied for estimating K_c . While it appears that none of the base scales have any significant advantage over the others, the GDD base scale implicitly accounts for some of the plant physiological and development characteristics, and this can be a significant advantage over the other base scales in terms of providing more consistent soybean K_c values between years. The results of this research should aid Nebraska soybean producers (and other producers in locations that have similar climate, soil, and crop management practices) in selecting appropriate crop coefficients for accurately estimating ET_a and irrigation water requirements for soybean to be applied for within-season irrigation management.

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