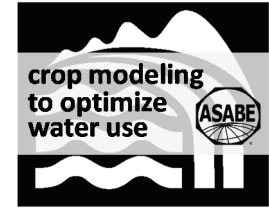


# IMPLEMENTING STANDARDIZED REFERENCE EVAPOTRANSPIRATION AND DUAL CROP COEFFICIENT APPROACH IN THE DSSAT CROPPING SYSTEM MODEL



K. C. DeJonge, K. R. Thorp

**ABSTRACT.** While methods for estimating reference evapotranspiration ( $ET_o$  or  $ET_r$ ) and subsequent crop ET ( $ET_c$ ) via crop coefficient ( $K_c$ ) and dual crop coefficient ( $K_{cb}$ ,  $K_e$ ) methods have been standardized since 2005 and 1998, respectively, the current version of the DSSAT cropping system model (CSM) has not been updated to fully implement these methods. In this study, two major enhancements to the model's ET routines were evaluated: (1) addition of the ASCE Standardized Reference Evapotranspiration Equation so that both grass and alfalfa reference ET were properly calculated using the most recent reference ET standard and (2) addition of the FAO-56 dual crop coefficient approach to determine potential ET, which combined an evaporative coefficient ( $K_e$ ) for potential evaporation with a dynamic basal crop coefficient ( $K_{cb}$ ) for potential transpiration as a function of simulated leaf area index. Previously published data sets for maize in Colorado (five years) and cotton in Arizona (seven years) were used to parameterize the model. Simulations of  $ET_o$  were compared to outputs from Ref-ET software, and simulated crop coefficients were contrasted among three crop coefficient methods: the current approach ( $K_{cs}$ ), a previously published adjustment to the model's  $K_c$  equation ( $K_{cd}$ ), and a new dual  $K_c$  approach that follows FAO-56 explicitly ( $K_{cb}$ ). Results showed that crop coefficient simulations with the new  $ET_o$ - $K_{cb}$  method better mimicked theoretical behavior, including spikes in the soil evaporation coefficient ( $K_e$ ) due to irrigation and rainfall events and basal crop coefficient response as associated with simulated crop growth. Simulated  $ET_c$  and yield with the new  $ET_o$ - $K_{cb}$  method were up to 4% higher and 28% lower for cotton and up to 13% higher and 26% lower for maize, respectively, than that with the current  $ET_o$ - $K_{cs}$  method, indicating that the seasonal  $ET_c$  effects were minimal while yield effects were more substantial. Use of FAO-56 concepts and current ET standards in DSSAT-CSM demonstrated a well-accepted ET benchmark to guide assessment of other ET methods in the model and made the model much more conceptually relevant to irrigation and ET specialists.

**Keywords.** Cotton, DSSAT, Evaporation, Evapotranspiration, FAO-56, Maize, Reference crop ET, Standardization, Transpiration.

Evapotranspiration (ET), the combined result of soil surface evaporation and plant transpiration, is an important component of agricultural water management and landscape hydrology, particularly in the field of irrigation management. Adequate quantification

of ET is imperative as demand for freshwater resources increases. Several U.S. states such as Colorado use quantification of ET as a "consumptive use" in water rights transfer legal cases. Many past studies have shown a direct physiological relationship between crop yield and ET (Doorenbos and Kassam, 1979; Hunsaker et al., 2015; Trout and DeJonge, 2017) and particularly yield and transpiration (Paredes et al., 2014; Steduto et al., 2012). Furthermore, accurate estimation of ET partitioning into evaporation (E) and transpiration (T) is paramount in irrigated and water-limited systems (Jensen and Allen, 2016; Kool et al., 2014; Pereira et al., 2015; Phogat et al., 2016). Ideally, these subcomponents of ET (i.e., E and T) should be evaluated independently rather than as a residual of each other (Kool et al., 2014). The Appendix reviews recent institutionally supported efforts to standardize procedures for ET quantification on several scales, which should be well known material for ET experts but is made available for readers who are unfamiliar with the subject. Full details of the FAO-56 dual crop coefficient methodology are available in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998) and ASCE Manual 70 (Jensen and Allen, 2016) and have recently been summarized by Pereira et al. (2015). According to ASCE Manual 70, these

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standards were developed to establish benchmark ET equations, which represent the current state of the art in estimating ET.

Over many decades, researchers have also developed complex cropping system models, which aim to comprehensively simulate the hydraulic processes, nutrient transformation and transport processes, and crop growth and development processes that occur in a cropping system. Such models have wide applicability for crop management, yield gap analysis, crop improvement, yield forecasting, synthesis of agronomic research, and assessment of policy (Boote et al., 1996). Because ET is often a large component of the water balance, simulation of the ET process is central to the calculations of these models, and accurate calculations of crop growth and yield depend on accurate ET calculations. However, the ET methods implemented among different models are often variable, and many do not incorporate the published ET standards as a simulation option. Generally, programming updates to the ET algorithms in the models have not kept pace with the development of new ET standards. Furthermore, preliminary results from a recent crop model intercomparison study demonstrated large variability in ET simulation results from 29 maize models parameterized for Iowa conditions (Kimball et al., 2016), which highlights the divergent nature of existing ET methods in crop models.

Inclusion of current ET standards as a simulation option in crop models offers several advantages for improvement of model functionality, interpretation of simulation results, and assessment of alternative ET simulation methods. Fundamentally, the standard ET methods should be considered a “benchmark” ET method in crop models, because the theory and equations are explicitly defined in the literature, well-accepted in the irrigation and ET community, and, most importantly, standardized by organizations with broad interest in ET and water management issues. Efforts to incorporate the ET standards into crop models should therefore proceed with minimal deviation from the accepted standardized equations and algorithms, thereby providing a benchmark ET method within the crop model to which other ET simulation options can be compared. Note that “benchmark” ET method does not necessarily imply “preferred” ET method but simply a benchmark standard that sets the performance baseline for any other ET method. As demonstrated herein, one advantage of incorporating standardized ET methods is to assist the identification of coding or behavioral errors in other ET simulation options. Comparatively, it is easier to program an algorithm from existing standardized equations than to (1) program a completely novel ET algorithm without error or (2) debug an existing ET algorithm that is misbehaving due to syntactical or conceptual errors. In each of these cases, coding improvements can be facilitated by comparisons to the benchmark ET standard.

The motivation for the present study arose from the authors’ independent work to use the Decision Support System for Agrotechnology Transfer (DSSAT) cropping system model (CSM) for irrigation management applications in semi-arid to arid environments of the western U.S.: maize in Colorado (DeJonge et al., 2011, 2012a) and wheat and cotton in Arizona (Thorp et al., 2010, 2014). Those studies highlighted issues with the ET methods of DSSAT-CSM, which

the authors sought to remedy by bringing the model code into agreement with accepted standardized ET methods. The efforts have led to a new ET simulation option in DSSAT-CSM that implements the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005) with an FAO-56 dual crop coefficient ( $K_{cb}$ ) approach (Allen et al., 1998) that calculates basal crop coefficients from simulated leaf area index (LAI). The main objective of the present study was to fully document the development of this new ET approach in DSSAT-CSM. Specific objectives were to use data from five maize growing seasons in Colorado and seven cotton growing seasons in Arizona to:

- Demonstrate improvements in DSSAT-CSM reference ET simulations by using ASCE  $ET_o$  standards (eq. A2; Allen et al., 2005) as compared to past and current DSSAT-CSM  $ET_{pm}$  (eq. A1) calculation methods.
- Compare crop coefficient simulations from the new dual  $K_c$  approach with that from alternative ET methods in the model.
- Evaluate the sensitivity of simulated crop yield and seasonal  $ET_c$ , T, and E to the parameters required for the new dual  $K_c$  method.

## BACKGROUND

### CURRENT DSSAT ET MODULE

DSSAT-CSM (ver. 4.6.0.040) programmatically synthesizes current knowledge of cropping system processes and uses mass balance principles to simulate the carbon, nitrogen, and hydrologic processes and transformations that occur within a cropping system (Jones et al., 2003). Simulations of crop development and growth for over 28 crops are possible, including the CERES family of models for maize and sorghum and the CROPGRO family of models for soybean and cotton. Simulated plant growth responds to management practices, cultivar selection, soil properties, and meteorological conditions. Minimum data requirements for FAO-56  $ET_{pm}$  (eq. A1) simulations include daily meteorological values for minimum and maximum air temperature, solar irradiance, dew point temperature, and wind speed.

The DSSAT-CSM soil water balance uses a one-dimensional “tipping bucket” approach, which simulates soil water flow and root water uptake for individual user-defined soil layers. Each soil layer requires information on initial soil water and nutrient content, wilting point, field capacity, and saturated water content (Ritchie, 1985). Potential ET (i.e., not reference ET) is calculated by DSSAT-CSM and can be defined here as  $ET_c$  based on environmental evaporative demand, under conditions of no crop water stress and a wet soil surface to supply soil water evaporation. Potential ET in DSSAT-CSM can be calculated with several reference ET methods, including Priestley-Taylor (Priestley and Taylor, 1972), and since DSSAT v4.0 (Hoogenboom et al., 2004) the Penman-Monteith combination equation for a short reference crop (eq. A1, denoted “FAO56” in DSSAT), but ASCE standardized procedures (eq. A2; Allen et al., 2005) are not explicitly followed. For Arizona conditions, a preliminary comparison of (1)  $ET_o$  calculated by DSSAT-CSM, (2)  $ET_o$

calculated by an Arizona Meteorological Network (AZMET) station, and (3)  $ET_o$  from a custom Python script that followed the ASCE reference ET guidelines (Allen et al., 2005) demonstrated that the DSSAT-CSM  $ET_o$  was on average 1.5 mm d<sup>-1</sup> lower than standard  $ET_o$  calculations. Furthermore, simulation of a tall reference crop ET ( $ET_r$ ) is not currently available as an option in DSSAT-CSM. Based on these preliminary assessments, updates to the DSSAT-CSM reference ET calculations were deemed warranted and necessary.

Crop coefficients ( $K_{cs}$ ) are calculated for the current Penman-Monteith ET approach in DSSAT-CSM as:

$$K_{cs} = 1.0 + (\text{EORATIO} - 1.0) \frac{\text{LAI}}{6.0} \quad (1)$$

where LAI is the simulated leaf area index, EORATIO is defined as the maximum  $K_{cs}$  at LAI = 6.0 (Sau et al., 2004; Thorp et al., 2010), and  $K_{cs}$  is the DSSAT-CSM crop coefficient. This formula ensures that  $K_{cs}$  varies daily between 1.0 and EORATIO. Values of EORATIO less than 1.0 should not be used, as this would actually decrease the ET with increases in LAI. Typical values of EORATIO are between 1.0 and 1.4. Currently, EORATIO is implemented only for the CROPGRO-based crop models (e.g., soybean and cotton); for the remaining crops (e.g., maize) the parameter is hard coded to EORATIO = 1.0. This fixes  $K_{cs}$  at 1.0 for the entire simulation, making it thus static and limiting mid-season crop coefficient options for crops such as maize, which have recommended mid-season  $K_c$  values of 1.2 and above (Allen et al., 1998). DSSAT-CSM employs the following formula for calculation of  $E0$  (potential crop ET):

$$E0 = K_{cs} ET_{pm} \quad (2)$$

As noted by DeJonge et al. (2012a),  $K_{cs}$  is not necessarily the same as crop coefficients described in FAO-56 (i.e.,  $K_c$  in eq. A4). While it is true that the DSSAT-CSM crop coefficient  $K_{cs}$  is multiplied by a reference ET, the resulting value ( $E0$ ) denotes ET potential, therefore demand, and not necessarily actual ET.

$E0$  is then partitioned into potential plant transpiration ( $EP_o$ ) and potential soil water evaporation ( $ES_o$ ):

$$EP_o = E0(1 - \exp[-\text{KEP}(\text{LAI})]) \quad (3)$$

$$ES_o = E0 \exp[-\text{KEP}(\text{LAI})] = E0 - EP_o \quad (4)$$

where KEP (typically ranging from 0.5 to 0.8) is defined as an energy extinction coefficient of the canopy for total solar irradiance, used for partitioning  $E0$  to  $EP_o$  and  $ES_o$  (Ritchie, 1998). The model calculates ET partitioning in the following order: (1)  $ES_o$  via equation 4, (2) actual E from one of two algorithms (Ritchie, 1972; Ritchie et al., 2009), (3)  $EP_o$  as the minimum of equation 3 and  $E0$  minus actual E, and (4) actual T as the minimum of  $EP_o$  and available water supplied by the soil through the simulated root profile. The  $ES_o$  calculation in equation 4 is implemented for the CSM-CERES-Maize model and several other crop models. However, the  $ES_o$  calculation is different for the CROPGRO models, including CSM-CROPGRO-Cotton, as discussed later.

Actual soil water evaporation is calculated as the minimum of  $ES_o$  and results from one of two soil water evaporation algorithms. The Ritchie (1972) algorithm evaporates water using a two-stage drying process based on the water content of the upper soil layer only, commonly specified with a depth of 5 cm. The Ritchie et al. (2009) method adds an upward flux calculation for all soil layers based on diffusion theory, and actual evaporation is the minimum of the surface soil layer upflux and  $ES_o$ . Soil-limited plant (root) water uptake ( $EP_r$ ) is calculated based on simulated root growth and available water supply in each user-defined soil layer (Ritchie, 1998). The actual plant water uptake is calculated as the minimum of  $EP_r$  and  $EP_o$ . If the potential plant transpiration can be supplied by the soil water, then this demand is fully met. Otherwise, transpiration is limited to the supply, and water deficit stress factors are calculated based on the ratio of plant-available water supply ( $EP_r$ ) and potential transpiration demand ( $EP_o$ ). Because the stress factors are used primarily for limiting simulated crop growth in response to water deficits and other stresses, accurate calculation of potential transpiration demand is an essential aspect of crop growth simulations in DSSAT-CSM.

#### RECENT STUDIES OF DSSAT ET MODULE

In a recent CERES-Maize study in semi-arid Colorado, the DSSAT-CSM  $ET_{pm}-K_{cs}$  method consistently predicted higher  $ET_c$  than observed (DeJonge et al., 2011). These researchers later performed a sensitivity analysis of EORATIO (eq. 1) between values of 1.0 and 1.3 for both fully irrigated (non-stressed) and limited irrigation treatments (DeJonge et al., 2012a). They found that by increasing EORATIO above 1.0, the  $ET_c$  under no stress increased, but under limited irrigation there was no change. Additionally, they found that changing the energy extinction coefficient (KEP, eqs. 3 and 4) had no effect on cumulative  $ET_c$  for either treatment. In other words, adjustments of neither EORATIO nor KEP were able to bring ET closer to observed values.

Because the results using existing  $ET_c$  methods in DSSAT-CSM were unsatisfactory, an alternative approach was created that used a dynamic approach to  $K_c$  as a direct function of simulated LAI. The primary factor causing an increase in the crop coefficient is an increase in plant cover or leaf area (Jensen and Allen, 2016); thus,  $K_c$  is correlated with LAI. Using  $K_c$  and LAI comparisons from the literature, DeJonge et al. (2012a) created a dynamic crop coefficient for DSSAT-CSM to replace  $K_{cs}$  in equation 1:

$$K_{cd} = K_{cdmin} + (K_{cdmax} - K_{cdmin})(1 - \exp[-SK_c(\text{LAI})]) \quad (5)$$

where  $K_{cdmin}$  is the minimum crop coefficient or  $K_{cd}$  at LAI = 0,  $K_{cdmax}$  is the maximum crop coefficient at high LAI, and  $SK_c$  is a shaping parameter that determines the shape of the  $K_{cd}$  versus LAI curve. Similar to equation 2,  $E0$  is calculated as the product of  $K_{cd}$  and  $ET_{pm}$ . Recommended values for  $K_{cdmin}$  and  $K_{cdmax}$  can be found in FAO-56, and DeJonge et al. (2012a) recommended  $0.5 < SK_c < 1.0$  as a typical shape to match past literature on the subject. Note that  $K_{cdmax}$  in equation 5 is different from  $K_{cmax}$  in equation A6. By running CERES-Maize with the dynamic crop coefficient  $K_{cd}$  (eq. 5) using a five-year maize data set from field experiments that tested full and limited irrigation, there was reduced error in

limited irrigation ET (RMSD from 80.9 to 49.9 mm) and water use efficiency (yield divided by ET; RMSD from 5.97 to 2.86 kg ha<sup>-1</sup> mm<sup>-1</sup>), while error in limited irrigation yield increased slightly (RMSD from 1229 to 1451 kg ha<sup>-1</sup>). Model output under full irrigation was essentially unchanged. These results were found by changing only the crop coefficient equation, without any recalibration of the model. The  $K_{cd}$  technique of equation 5 was implemented by Thorp et al. (2014) using the CSM-CROPGRO-Cotton model, and they also added the ASCE Standardized Reference  $ET_o$  Equation (eq. A2) in DSSAT-CSM and verified  $ET_o$  simulations with  $ET_o$  from a local meteorological network station at their field site in Arizona. This study also found improved  $ET_c$  simulations using these methods.

While the incorporation of equation 5 into DSSAT-CSM improved results of ET and water use efficiency (WUE) under limited irrigation (DeJonge et al., 2012a), some researchers expressed concern that the method was redundant with the partitioning of potential ET into potential evaporation and transpiration (eqs. 3 and 4). Equation 5 uses an exponential function of LAI to scale reference ET to potential ET through  $K_{cd}$ , while equations 3 and 4 use a similar expression for partitioning E and T, leading to the claim of redundancy. Further investigation has shown that the original approach (eq. 1) and the DeJonge et al. (2012a) approach (eq. 5) both have advantages and disadvantages, and the strengths of the two approaches must be combined for DSSAT-CSM simulations of  $K_c$  to mimic theoretical patterns, as described in FAO-56 and observed through various techniques (e.g., lysimetry). To accomplish this goal, a dual crop coefficient approach was added to DSSAT-CSM.

## METHODS AND MATERIALS

### DATASETS

The locations used in this study were chosen to evaluate ET in arid (Arizona) and semi-arid (Colorado) areas with high evaporative demand where irrigation is required, water use is closely monitored, and ET decision support is common. The crops used in this study were the prevalent high water commodity crops in these areas: maize in eastern Colorado and cotton in central Arizona. The selected crops also cover both the CERES (maize) and CROPGRO (cotton) families of models in DSSAT, each of which has its own nuances of ET simulation, as demonstrated below.

In a prior study, the CSM-CERES-Maize model was evaluated using data from a multi-replicate field research experiment near Fort Collins, Colorado (40° 39' 19" N, 104° 59' 52" W) from 2006-2008. Complete experimental details can be found in DeJonge et al. (2011, 2012a). Two irrigation treatments were applied to continuous maize during the 2006-2010 growing seasons: full irrigation (ET requirement met by irrigation throughout the season) and limited irrigation (no irrigation before the V12 growth stage unless necessary for emergence, and then full irrigation afterwards). Irrigations were applied with a linear-move sprinkler system, generally at a weekly interval. Irrigation amounts were determined by crop need (using a daily checkbook method and soil water content measurements via neutron scattering

probe) and supported by potential ET estimates from on-site meteorological measurements. Typical soils at the site were loam. An on-site weather station (station FTC03; 40° 39' 9" N, 105° 0' 0" W; elevation 1557.5 m) within the Colorado Agricultural Meteorological Network (CoAgMet; <http://ccc.atmos.colostate.edu/~coagmet/>) continually recorded daily precipitation, solar radiation, minimum and maximum temperature, vapor pressure (which was converted to dew point temperature), and wind run. This dataset was also used in a global sensitivity and uncertainty analysis of CERES-Maize yield, ET, and growth responses to input variability (DeJonge et al., 2012b).

Thorp et al. (2014, 2017) described the evaluation of CSM-CROPGRO-Cotton using data sets from seven cotton experiments conducted near Maricopa, Arizona (33.068° N, 111.971° W) in 1990, 1991, 1999, 2002, 2003, 2014, and 2015. The objectives of the field experiments were variable but tested cotton responses to full and limited irrigation and fertilizer management, planting density, and free-air carbon dioxide enrichment (FACE). The irrigation method differed among the experiments, and subsurface drip, overhead sprinkler, and furrow irrigation methods were all represented. Soil water balance methods based on twice-weekly measurements of soil water content with neutron scattering probes were used to quantify crop water use during each experiment. Typical soil types at the field site included sandy loam and sandy clay loam. The central Arizona cotton growing season is hot and dry, with daily maximum temperatures regularly exceeding 38°C during July and August and seasonal precipitation often amounting to less than 10% of  $ET_o$ . Meteorological data were collected from an Arizona Meteorological Network (AZMET; <http://ag.arizona.edu/azmet/>) station within 1 km of each experimental site.

### UPDATES TO DSSAT-CSM ET MODULE

Due to unsatisfactory performance of the DSSAT-CSM ET routines for Arizona conditions (Thorp et al., 2010), Thorp et al. (2014) added an algorithm based strictly on the ASCE Standardized Reference ET procedures (Allen et al., 1998, 2005) and evaluated CSM-CROPGRO-Cotton using the DeJonge et al. (2012a) crop coefficient method (eq. 5). By explicitly following ASCE Standardized Reference ET procedures, both short ( $ET_o$ ) and tall ( $ET_r$ ) reference ET could be calculated in this algorithm according to equation A2. The model's original code for calculation of  $ET_{pm}$  via equation A1 remained unmodified as an independent algorithm from the equation A2 updates. Because  $ET_o$  is the most widely used ET reference worldwide and because DSSAT versions 4.0 and above approximated  $ET_o$  (eq. A2) via  $ET_{pm}$  (eq. A1), results in this study focus on the short reference crop ( $ET_o$ ). However, changes made to the model are also applicable to users of the tall ( $ET_r$ ) reference, with specification of proper crop coefficients. Although Thorp et al. (2014) first described the addition of ASCE Standardized Reference ET to the model, they did not report comparisons of their algorithm with other  $ET_o$  software or with other DSSAT-CSM ET methods.

Novel in the present study, a dual crop coefficient approach was incorporated into DSSAT-CSM to determine potential soil evaporation and plant transpiration separately by

independently determining  $K_e$  and  $K_{cb}$ , respectively (eq. A4). Evaporative coefficients ( $K_e$ ) were determined by following the methods described in equations A5 through A9 (Allen et al., 1998). Transpiration or basal crop coefficients ( $K_{cb}$ ) were calculated using an exponential extinction function similar to current partitioning in DSSAT-CSM (eq. 3) and more closely resembling the  $K_{cd}$  dynamic crop coefficient (eq. 5) (DeJonge et al., 2012a):

$$K_{cb} = K_{cbmin} + (K_{cbmax} - K_{cbmin})(1 - \exp[-SK_c(LAI)]) \quad (6)$$

where  $K_{cbmin}$  is the minimum basal crop coefficient representing a dry, bare, or nearly bare soil surface.  $K_{cbmax}$  is user-defined and obtained from recommended crop-specific coefficients in FAO-56. Both equation 5 and equation 6 are similar in form to equation 97 in FAO-56, as well as equations 10-25a and 10-28 in ASCE Manual 70 (Jensen and Allen, 2016). The approach uses model-simulated LAI to calculate the  $K_{cb}$ , which means  $K_{cb}$  is more dynamic and responsive to cultivar, weather, and soil variability, as simulated by the model (Thorp et al., 2017). This is in contrast to the fixed trapezoidal crop coefficient curves recommended by FAO-56. Similar to equations 3 and 4, daily potential plant transpiration ( $EP_o$ ) and soil evaporation ( $ES_o$ ) were then determined from  $K_{cb}$  and  $K_e$ , respectively, in the following equations:

$$EP_o = K_{cb}ET_o \quad (7)$$

$$ES_o = K_eET_o \quad (8)$$

Because the aim of equation 8 is potential soil evaporation,  $K_e$  is obtained from equation A5 with  $K_r = 1.0$ .

Similar to the current  $K_{cs}$  method (eqs. 1 through 4), actual T is less than  $EP_o$  if soil water available to the plant root system is too low, essentially  $T = K_{cb}K_sET_o$  from FAO-56. However, rather than implementing the FAO-56  $K_s$  method, the native DSSAT-CSM routines for calculating water stress effects on crop growth (discussed above) were used. Table 1 summarizes the enhancements to calculations of reference ET and dual crop coefficients for plant transpiration ( $K_{cb}$ ) and soil water evaporation ( $K_e$ ) in DSSAT-CSM. Similar to

equation 5 for the  $K_{cd}$  method, the minimum  $K_{cb}$  value ( $K_{cbmin}$ ) is defined and here assumed as 0. Understanding that this deviates slightly from true FAO-56 recommendations, there are several important reasons for considering a null  $K_{cbmin}$  in crop model simulations. First, within the FAO-56 water balance approach,  $K_{cbmin}$  is used to account for upflow from deep soil layers (Richard Allen, personal communication). However, the evaporation routine in DSSAT-CSM already accounts for this (Ritchie et al., 2009). Second, DSSAT-CSM is often used for sequential simulations of crop rotations, including fallow periods when transpiration simulations should be zero. Finally, specifying  $K_{cbmin} > 0$  leads to a discontinuity in simulated  $K_{cb}$  on the day of emergence if the simulation is initiated prior to emergence.

Other assumptions were required to merge the FAO-56 and DSSAT-CSM methods. In FAO-56,  $K_r$  (eq. A5) is calculated as a function of soil moisture depletion in the FAO-56 soil surface profile and is used for direct calculation of reduced evaporation as the soil surface profile dries. On the other hand, the soil water evaporation routines in DSSAT-CSM are specific to its layered soil profile and therefore deviate, with good reason, from the FAO-56 approach. Thus, the  $K_r$  term in the DSSAT-CSM implementation of FAO-56 was fixed at 1.0 in the calculation of  $K_e$  (eq. A5), and the native DSSAT-CSM soil evaporation routines, e.g., the Suleiman-Ritchie (Ritchie et al., 2009) approach for maize and the Ritchie (1972) approach for cotton, were used to reduce actual evaporation from potential evaporation as the soil profile dried. Similarly, FAO-56 uses  $K_s$  (eq. A4) to directly reduce transpiration under water limitation, and  $K_s$  is calculated from soil moisture depletion in the simple FAO-56 soil profile. However, DSSAT-CSM considers soil moisture simulations in a layered profile and capacity for root growth to extract water from the soil layers. Thus,  $K_s$  in DSSAT-CSM was not explicitly simulated, and native DSSAT-CSM routines were instead used to account for effects of water limitation by calculating water stress coefficients (discussed above), which are conceptually similar to  $K_s$  but with different formulation. With these assumptions,  $K_e$  and  $K_{cb}$  in DSSAT-CSM were used only to calculate potential E and T,

**Table 1. Standardized, current DSSAT-CSM, and proposed DSSAT-CSM ET methodologies.**

Operation	Standard	Current DSSAT-CSM	Model Issues	Proposed Model Improvement
Reference ET: ET <sub>o</sub> = short "grass" reference, and ET <sub>r</sub> = tall "alfalfa" reference	ASCE ET <sub>o</sub> and ET <sub>r</sub> , which assume well-watered, non-stressed vegetation.	"FAO-56 P-M" ET <sub>pm</sub> (eq. A1)	Methodology varies slightly from ASCE ET <sub>o</sub> , meaning it is not in full agreement with current standards.	ASCE ET <sub>o</sub> and ET <sub>r</sub> added as options, methodology explicitly follows the ASCE standard (Allen et al., 2005) (eq. A2)
Crop coefficient for potential ET	$K_c = K_s K_{cb} + K_e$ (eq. A4)	$K_{cs} = 1.0 + (EORATIO - 1.0)$ $\times (LAI/6.0)$ (eq. 1)	Mathematically, $K_{cs} \geq 1$ always, which does not follow FAO-56 methods.	$K_c = K_s K_{cb} + K_e = 1.0(K_{cb}) + K_e$ used for calculation of potential ET, so $K_s = 1$ (potential ET assumes no stress)
Potential crop ET	$ET_c = ET_o K_c$ (eq. A3)	$E0 = K_{cs} ET_{pm}$ (eq. 2)	Because $K_{cs} \geq 1$ , $E0 \geq ET_{pm}$ always (i.e., even in fallow)	$ET_c = ET_o(K_{cb} + K_e)$ (eqs. A3 and A4)
Potential plant transpiration	$K_{cb}$ from FAO-56, a trapezoidal function of days after planting.	Partitioned from potential ET (E0): $EP_o = E0(1 - \exp[-KEP(LAI)])$ (eq. 11)	The model first calculates "potential ET" and then partitions E and T based on LAI. FAO-56 calculates E and T separately based on explicit crop coefficient calculations.	$EP_o = ET_o K_{cb}$ $K_{cb} = K_{cmax}(1 - \exp[-SK_c(LAI)])$ (eqs. 6 and 7) Dynamic $K_{cb} = f(LAI)$ , mimics FAO-56 trapezoidal function
Potential soil evaporation	$K_e$ from FAO-56, which allows high-E events with wet soil surface and low canopy cover.	Partitioned from potential ET (E0): $ES_o = E0(\exp[-KEP(LAI)])$ $ES_o = E0 - EP_o$ (eqs. 3 and 4)		$ES_o = ET_o K_e$ $K_e = \min[K_{cmax} - K_{cb}, f_{ew}, K_{cmax}]$ where $K_{cmax} = f(u_2, RH_{min}, h, K_{cb})$ and $f_{ew} = \min(1 - f_c, f_w)$ (eqs. 8 and A5-A8)

**Table 2. Reference ET methods and ET partitioning methods with corresponding abbreviations.**

Methods	Symbol
Reference ET	
DSSAT-CSM v4.6 FAO-56 P-M	$ET_{pm}$
ASCE $ET_o$ short reference (Allen et al., 2005)	$ET_o$
ASCE $ET_r$ tall reference (Allen et al., 2005)	$ET_r$
ET partitioning	
DSSAT-CSM v4.6 (eqs. 1-4)	$K_{cs}$
DeJonge et al. (2012a) (eqs. 2-5)	$K_{cd}$
FAO-56 (Allen et al., 1998) (eqs. A4-A9 and 6-8)	$K_{cb}$

respectively (eqs. 7 and 8), while the native DSSAT-CSM algorithms were used to calculate actual E and T from potential. In addition,  $f_w$  (eq. A8) was assigned as 1.0, assuming that water applications (both precipitation and irrigation) were distributed over the entire ground surface.

The reference ET and ET partitioning methods used in this study were tested in various combinations, and for clarity are hereafter specified using the symbols in table 2 (e.g.,  $ET_{pm}-K_{cs}$  for the existing DSSAT-CSM v4.6 method and  $ET_o-K_{cb}$  for the new method).

## SIMULATIONS

Maize simulations used the Colorado data set described earlier, including five years (2006-2010) and two treatments each year (full and limited irrigation). Cotton simulations used the Arizona data sets described earlier, including seven cotton seasons (1990-1991, 1999, 2002-2003, 2014-2015). Simulations were conducted using weather files and calibration results from several prior studies for the maize data set (DeJonge et al., 2011, 2012a, 2012b) and cotton data sets (Thorp et al., 2014, 2015, 2017).

Model simulations of daily reference ET were compared for five growing seasons in both Colorado and Arizona. Specifically, calculations of  $ET_{pm}$  from DSSAT-CSM (ver. 4.5.1.005),  $ET_{pm}$  from DSSAT-CSM (ver. 4.6.0.040), and FAO-56 based  $ET_o$  from a custom algorithm added to the DSSAT-CSM code were compared to FAO-56  $ET_o$  calculations from Ref-ET software (Allen, 2011), which is designed to calculate standardized reference ET for comparison with other computer programs such as DSSAT-CSM. Simulations from the older DSSAT-CSM version 4.5 were included to highlight a major issue with the wind height transfer function, which led to deeper investigation of the DSSAT-CSM ET methods (Thorp et al., 2010, 2014) and development of new methods presented herein.

Qualitative graphical comparisons between the  $ET_o-K_{cs}$ ,  $ET_o-K_{cd}$ , and  $ET_o-K_{cb}$  methods were conducted to demonstrate differences in simulated daily crop coefficients. The reference ET method was  $ET_o$  for all three cases to focus comparisons on the crop coefficient method alone. The 2008 maize growing season and the 2015 cotton growing season were used for graphical representation of crop coefficient time series. Simulated crop yield and seasonal ET among the ET partitioning methods were also compared for both crops in all five growing seasons. Simulations with the  $ET_o-K_{cb}$  method used values of  $K_{cbmax} = 1.15$  and  $SK_c = 0.5$  for maize, and  $K_{cbmax} = 1.15$  and  $SK_c = 0.6$  for cotton (eq. 6; table 3).  $K_{cbmax}$  values were determined from tabular values of mid-season  $K_{cb}$  found in FAO-56 (Allen et al., 1998). Values for

**Table 3. Parameter values used to simulate three DSSAT-CSM ET partitioning methods ( $K_{cs}$ ,  $K_{cd}$ , and  $K_{cb}$ ) for maize and cotton.**

Crop	Partitioning Method	KEP	$SK_c$	$K_{cmin}^{[a]}$	$K_{cmax}^{[a]}$
				$K_{cbmin}^{[b]}$	$K_{cbmax}^{[b]}$
Maize	$K_{cs}$	0.5	-	-	1.0
	$K_{cd}$	0.5	0.5	0.3	1.2
	$K_{cb}$	-	0.5	0	1.15
Cotton	$K_{cs}$	0.7	-	-	1.1
	$K_{cd}$	0.7	0.6	0.35	1.2
	$K_{cb}$	-	0.6	0	1.15

[a] For  $K_{cd}$  method only.

[b] For  $K_{cb}$  method only.

[c] For  $K_{cs}$  method only.

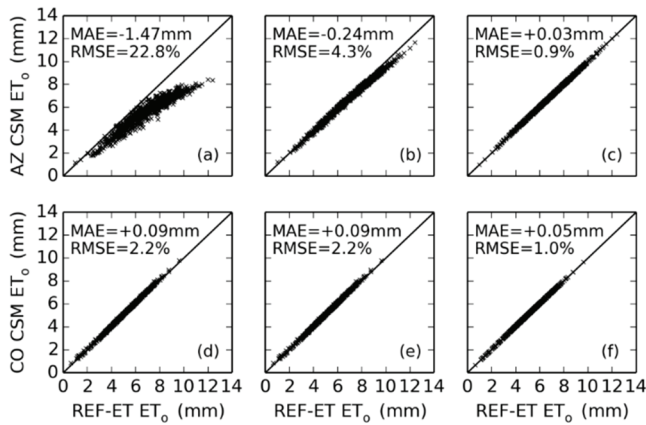
$SK_c$  were determined from the recommended range (generally 0.5 to 1.0) for shaping the relationship of  $K_{cd}$  (eq. 5) and by prior testing to create a reasonable relationship between  $ET_c$  and yield. Simulations with the  $ET_o-K_{cs}$  and  $ET_o-K_{cd}$  methods were parameterized as described by DeJonge et al. (2011) and Thorp et al. (2014); EORATIO for maize simulations was hard-coded to 1.0 within DSSAT-CSM. Because the objective was to compare simulation results among different ET methods, the only adjustments to model parameterization were the choice of ET simulation method and associated ET parameters. This strategy ensured that the simulation results demonstrated differences due to ET method alone. Future efforts with the new ET method will likely require recalibration of non-ET parameters to improve agreement between measured and simulated data; however, this was beyond the focus of the present study.

A sensitivity analysis of yield,  $ET_c$ , E, and T responses to parameters in equation 6 was conducted using the new  $ET_o-K_{cb}$  approach. The analysis was conducted using all five maize seasons (2006-2010) but only two cotton seasons (2014-2015) because cotton responses to full and limited irrigation were not available for every growing season and were best quantified in 2014 and 2015. The value of  $K_{cbmax}$  was varied between 0.9 and 1.4 with a base level of  $K_{cbmax} = 1.15$ , which is the tabular value from FAO-56 (Allen et al., 1998) for both crops. The value of  $SK_c$  was varied between 0.4 and 0.9 with a base level of 0.5 for maize and 0.6 for cotton from prior calibration efforts (DeJonge et al., 2011; Thorp et al., 2014). With an assumption of  $K_{cbmin} = 0$  as described before, the values of  $K_{cbmax}$  and  $SK_c$  were varied to understand the influence of these variables on simulated yield and  $ET_c$  for maize and cotton.

## RESULTS

### REFERENCE ET METHODS

Any crop model or other program used to calculate  $ET_o$  should produce very similar results as obtained by specifically following the standardized methods, justifying why Ref-ET software was developed (Allen, 2011). As compared to older  $ET_{pm}$  simulations with DSSAT-CSM, simulations of  $ET_o$  using the new algorithm based explicitly on the ASCE standard (Allen et al., 2005) were in closest agreement with  $ET_o$  calculated by Ref-ET software (fig. 1). The root mean squared errors (RMSE) between Ref-ET  $ET_o$  and DSSAT-CSM  $ET_o$  were less than 1.0% for both Arizona and Colorado conditions, while the RMSE values between Ref-ET



**Figure 1.** Daily reference evapotranspiration outputs for DSSAT-CSM versus Ref-ET software: (a) CSM v4.5  $ET_{pm}$  method for Arizona (AZ) data ( $n = 872$  days over five cotton growing seasons), (b) CSM v4.6  $ET_{pm}$  method for AZ data, (c) new CSM standardized  $ET_o$  method for AZ data, (d) CSM v4.5  $ET_{pm}$  method for Colorado (CO) data ( $n = 626$  days over five maize growing seasons), (e) CSM v4.6  $ET_{pm}$  method for CO data, and (f) new CSM standardized  $ET_o$  method for CO data. MAE = mean average error, and RMSE = root mean squared error.

$ET_o$  and DSSAT-CSM  $ET_{pm}$  were greater than 2.0%. The results demonstrate that the new DSSAT-CSM  $ET_o$  algorithm better aligned with published ET standards (Allen et al., 2005) and accepted software for standardized ET calculations (Allen, 2011). Errors between the Ref-ET  $ET_o$  and DSSAT-CSM  $ET_o$  results are likely due to minor numerical errors arising from differences in the formulation of the two algorithms.

With an RMSE of 22.8%, drastic discrepancies were found in the comparison of Ref-ET  $ET_o$  and  $ET_{pm}$  from DSSAT-CSM version 4.5 for Arizona conditions (fig. 1a). In 2014, the authors linked the problem to a misspecification of the equation used to adjust wind speed measurements to a standard height of 2.0 m. In DSSAT-CSM, this calculation is accomplished with the following equation:

$$u_2 = u_z \left( \frac{2.0}{z_w} \right)^\alpha \quad (9)$$

where  $u_2$  is the calculated wind speed at a standard height of 2.0 m,  $u_z$  is the measured wind speed at a height of  $z_w$ , and  $\alpha$  is an empirically derived coefficient that is hard-coded but varies based on the stability of the atmosphere. In DSSAT-CSM v4.5, the model erroneously used  $\alpha = 2.0$ , which was corrected to  $\alpha = 0.2$  in DSSAT-CSM v4.6. This coding error in DSSAT-CSM version 4.5 (and likely prior versions) greatly affects  $ET_{pm}$  calculations for weather networks with anemometers at heights other than 2.0 m, such as AZMET in Arizona, but has no effect on networks with anemometers at 2.0 m, such as CoAgMet in Colorado. The use of independent standardized software such as Ref-ET is highly recommended in crop model development efforts to verify ET algorithms and ensure quality of simulated ET data.

Although the wind speed adjustment coefficient ( $\alpha$  in eq. 9) has been corrected in DSSAT-CSM version 4.6, the update does not match the ASCE standard equation (Allen et al., 2005) for adjusting wind speed measurements to a standard height of 2.0 m:

$$u_2 = u_z \left( \frac{4.87}{\ln(67.8z_w - 5.42)} \right) \quad (10)$$

Thus, differences between  $ET_{pm}$  (figs. 1b and 1e) and  $ET_o$  (figs. 1c and 1f) calculations in DSSAT-CSM version 4.6 are partially attributed to different wind speed adjustment equations for each method (eqs. 9 versus 10, respectively). Incorporation of current reference ET standards (Allen et al., 2005) in DSSAT-CSM not only helped identify coding errors in the model's existing ET methods but also established the appropriate reference ET calculations ( $ET_o$  or  $ET_r$ ) as intended for use with FAO-56 crop coefficient approaches.

## CROP COEFFICIENT METHODS

To visually illustrate the crop coefficients simulated by DSSAT-CSM, figure 2 shows the behavior of crop coefficients for Colorado maize under full and limited irrigation in 2008 using the  $ET_o-K_{cs}$  method, the  $ET_o-K_{cd}$  method, and the new  $ET_o-K_{cb}$  method, and figure 3 shows similar results for Arizona cotton in 2015. These figures show simulated values for crop coefficients  $K_e (= E/ET_o)$ ,  $K_{cb}K_s (= T/ET_o)$ , and  $K_c (= ET_c/ET_o)$ . As described in equations A3 and A4, these coefficients represent the ratio of E, T, or  $ET_c$  to the reference evapotranspiration ( $ET_o$ ), which was calculated from the daily DSSAT-CSM outputs for each ET method. As discussed above,  $K_s$  and  $K_r$  were not explicitly calculated in DSSAT-CSM because the model used alternative algorithms to calculate the effects of water limitation. However, by calculating  $K_e$ ,  $K_{cb}K_s$ , and  $K_c$  from the model output of E, T,  $ET_c$ , and  $ET_o$ , the resulting crop coefficient plots are conceptually similar to the description of these terms in FAO-56. In particular, the  $K_{cb}K_s$  terms in figures 2 and 3 represent the basal crop coefficient adjusted for water stress effects. If high transpiration demand is calculated by equation 1, 5, or 6 for  $K_{cs}$ ,  $K_{cd}$ , or  $K_{cb}$ , respectively, but soil water is not available to meet that demand, then the simulated transpiration would be a lesser value and is represented in figures 2 and 3 as  $K_{cb}K_s$ . By calculating FAO-56 crop coefficients from model-simulated ET, different ET methods can be evaluated and contrasted for adherence to theoretical crop coefficient responses (Allen et al., 1998). Gross deviations from accepted theory highlight issues with the implementation of a particular ET method and suggest that further coding modifications are needed.

Early in the growing season, there was little canopy cover, and ET was mostly surface soil water evaporation (maize in fig. 2 and cotton in fig. 3). As canopy cover increased with vegetative growth, the transpiration portion exceeded the evaporation portion of ET, beginning around DOY 165 for maize and DOY 175 for cotton. When the crop reached full canopy (around DOY 185 for maize and DOY 200 for cotton), transpiration was the majority of ET. As the crop began to senesce (around DOY 265 for maize and DOY 270 for full-irrigation cotton), the transpiration demand decreased until maturity, and very abruptly for cotton. During early crop development (e.g., DOY 120 to 165 for maize), there was very little vegetation, leading to low transpiration, so evaporation was very important at this time. According to FAO-56, plots of daily  $K_e$  and overall  $K_c$  should demonstrate

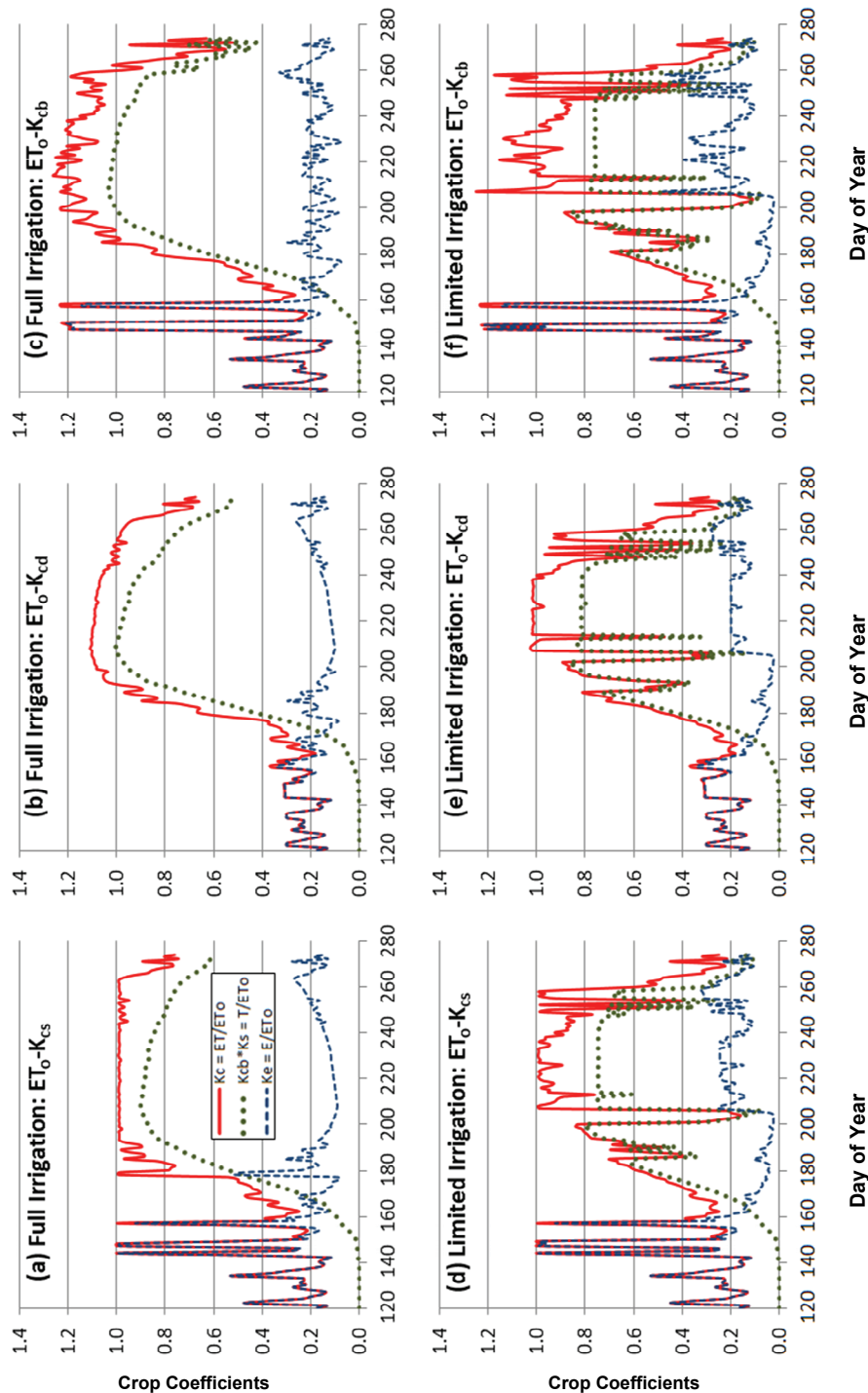


Figure 2. Crop coefficients versus day of year for Colorado maize in 2008 for (a-c) full irrigation and (d-f) limited irrigation using three different ET modules: (a and d) the  $ET_o$ - $K_{cs}$  method (DeJong et al., 2012a), (b and e) the  $ET_o$ - $K_{cd}$  method, and (c and f) the new  $ET_o$ - $K_{cb}$  method.

periodic sharp increases or spikes due to irrigation events and particularly rainfall (e.g., figs. 2c and 3c), which wets the entire soil surface. While the  $ET_o$ - $K_{cs}$  method was responsive to these evaporative spikes, the  $ET_o$ - $K_{cd}$  method was much less responsive with less surface evaporation for both full and limited irrigation. The  $ET_o$ - $K_{cb}$  method was more similar to the  $ET_o$ - $K_{cs}$  method, although evaporation was slightly higher in this period.

As mentioned earlier and in table 1, the  $ET_o$ - $K_{cs}$  method fixes  $K_{cs}$  at 1.0 for maize (eq. 1), which limits overall  $K_c$  to a

maximum of 1.0, as was found in three instances of high precipitation during the early season (figs. 2a and 2d). During these same periods in the  $ET_o$ - $K_{cb}$  method, both  $K_e$  and overall  $K_c$  exceeded the value of 1.0 because  $K_e$  is limited instead by evaporative demand, as computed according to FAO-56 methods in equations A5 and A6. Likewise, early season evaporative spikes in cotton (fig. 3) are limited to values very close to 1.0 because low LAI forced  $K_{cs}$  close to 1.0 (eq. 1). The new revision of ASCE Manual 70 (Jensen and Allen, 2016) states that for an  $ET_o$  reference, these early-



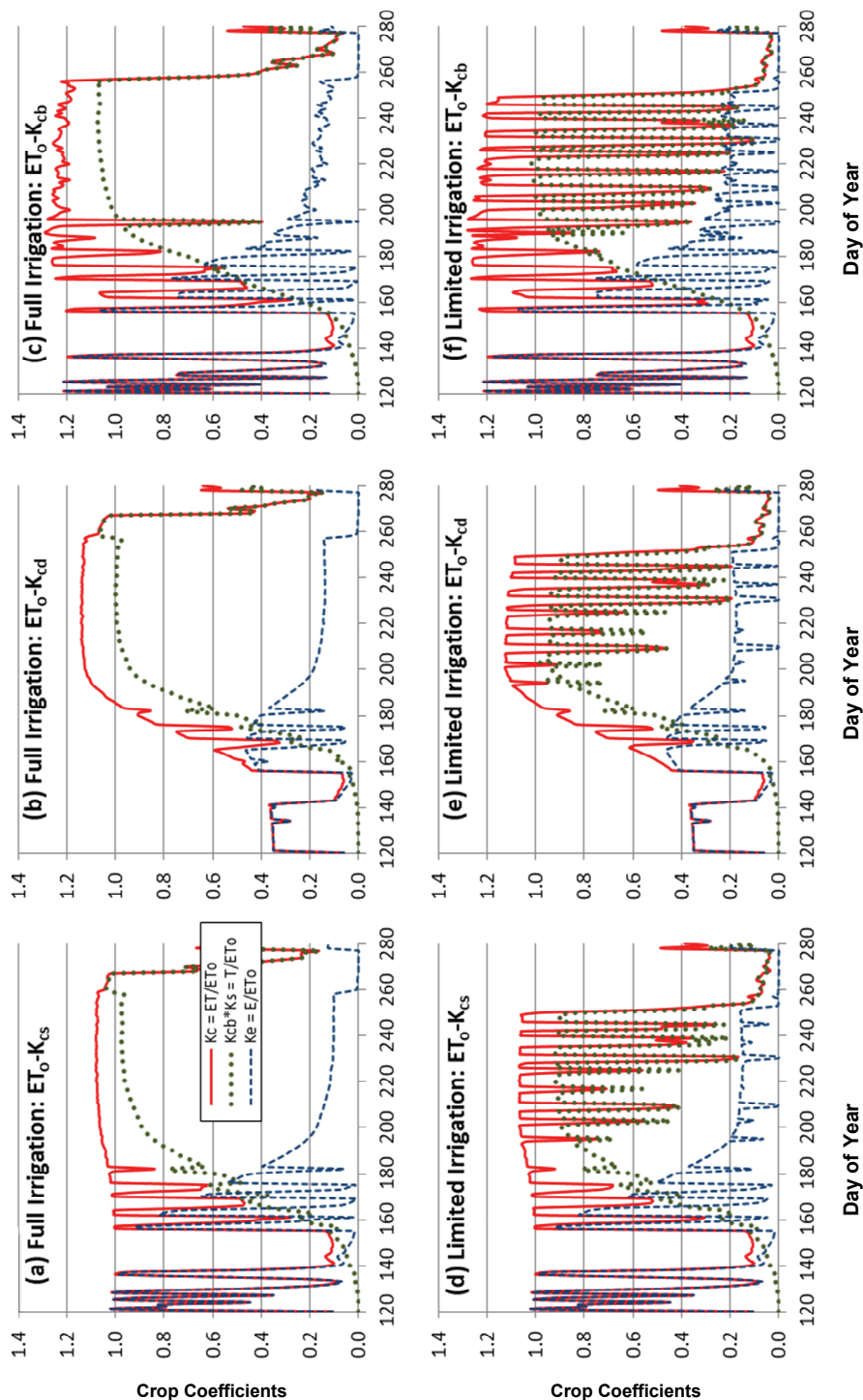


Figure 3. Crop coefficients versus day of year for Arizona cotton in 2015 for full (a-c) and limited (d-f) irrigation, using three different ET modules: (a and d) the  $ET_0-K_{cs}$  method (DeJonge et al., 2012a), (b and e) the  $ET_0-K_{cd}$  method, and (c and f) the new  $ET_0-K_{cb}$  method.

season spikes in  $K_c$  and  $K_e$  should typically approach maximum values of 1.0 to 1.2, which is here achieved only by the new  $ET_0-K_{cb}$  method in DSSAT-CSM (figs. 2c, 2f, 3c, and 3f). It is important to note that during the early season, the  $ET_0-K_{cb}$  method was otherwise very similar to  $ET_0-K_{cs}$  overall.

In the mid-season,  $ET_c$  as shown by  $K_c$  was lower for the  $ET_0-K_{cs}$  method than for both the  $ET_0-K_{cd}$  and  $ET_0-K_{cb}$  methods and for both irrigation treatments, especially compared to  $ET_0-K_{cb}$  under full irrigation. In maize, from DOY 190 to 260,  $K_c$  for  $ET_0-K_{cs}$  was unrealistically limited to 1.0 due to

the hard-coded  $EORATIO = 1.0$  in the CERES-Maize model (eq. 1). For cotton,  $EORATIO$  was parameterized to 1.1 (table 3), and while this allowed  $K_c$  from  $ET_0-K_{cs}$  to be more dynamic with cotton than with maize (e.g., comparing figs. 2 and 3), the upper values for  $K_c$  were still minimally responsive, especially when compared with the new  $ET_0-K_{cb}$  method. Because cotton  $K_c$  was generally higher in the mid-season for the  $ET_0-K_{cb}$  method than for the  $ET_0-K_{cs}$  method, the model simulated more crop water use and some stress events, even under full irrigation (fig. 3c).

During late-season senescence, the crop coefficient plots

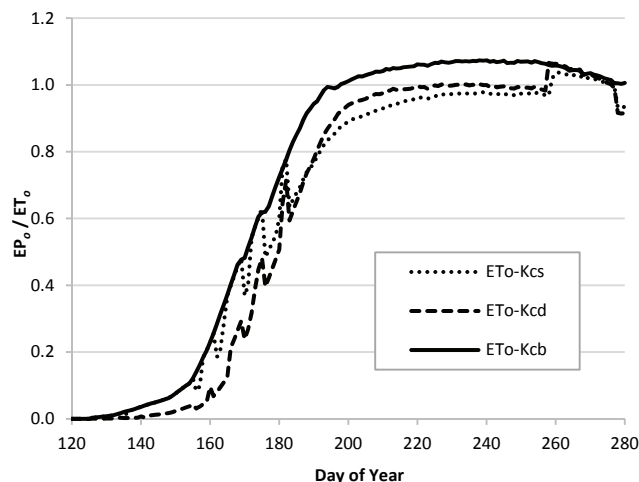
showed that both E and T generally declined. Cotton ET declined rapidly after irrigation was terminated on DOY 247, but crop coefficients increased prior to DOY 280 due to two rainfall events at that time. The  $ET_o-K_{cd}$  method was very similar in shape to the  $ET_o-K_{cs}$  method, especially under limited irrigation. The  $ET_o-K_{cb}$  method was very different from the  $ET_o-K_{cs}$  method under full irrigation but was fairly similar under limited irrigation.

A notable difference between the crop coefficient behavior in figures 2 and 3 is that the cotton crop had more daily variation in the magnitude of  $K_c$ , especially under limited irrigation. This was because the Arizona climate had much higher ET demand during the growing season (fig. 1) and less frequent and productive rainfall. The cotton experiment was also conducted on a sandy clay loam soil, which may have limited water availability to the crop. As evidenced by  $K_c$  for the limited irrigation cotton treatment in 2015 (fig. 3f), the simulated crop experienced water stress for short intervals on a weekly basis as a result of the suboptimal irrigation schedule. Additional irrigation applications would be necessary to fully alleviate this issue and eliminate drops in mid-season  $K_c$ .

The cotton simulations for  $ET_o-K_{cs}$  and  $ET_o-K_{cd}$  revealed unrealistic patterns of sharply increasing  $K_{cb}K_s$ , most clearly visible on DOY 181 and DOY 259 (figs. 3a and 3b). There is no practical reason why T should sharply increase on these dates, particularly because they correspond to the latter days of a drying cycle when soil water is less available. The  $K_{cb}K_s$  results for  $ET_o-K_{cb}$  did not reveal these unrealistic patterns (fig. 3c), and none of the ET methods for the maize simulations demonstrated this behavior (fig. 2). With deeper inspection of the model code, the calculation of  $ES_o$  for the CROPGRO model was found to deviate from the rest of the crop models. Instead of using equation 4 for  $ES_o$ , the CROPGRO model currently uses the following expression:

$$ES_o = \begin{cases} E0(1.0 - 0.39LAI) & \text{if } LAI \leq 1.0 \\ (E0/1.1)\exp(-0.4LAI) & \text{if } LAI > 1.0 \end{cases} \quad (11)$$

Thus, CROPGRO bypassed the use of KEP for  $ES_o$  calculations but used KEP for  $EP_o$  calculations. Comparing the results of equation 4 (with  $KEP = 0.7$  from table 3) and equation 11 for identical  $E0$  and  $LAI$ , the latter approach consistently calculated higher  $ES_o$  for the 2015 cotton season (not shown). As a result,  $ES_o$  and  $EP_o$  no longer summed to  $E0$  (eq. 4). The major problem arose when  $EP_o$  was calculated as the minimum of equation 3 and  $E0$  minus actual E. Because equation 11 permitted higher  $ES_o$  than equation 4,  $E0$  minus actual E was often lower than the result of equation 3, particularly following wetting events, which led to a drop in  $EP_o$ . As the soil dried, equation 3 eventually determined  $EP_o$  again, because little water was available for actual E. The result was several unrealistic discontinuities in the temporal  $EP_o$  calculations for the  $ET_o-K_{cs}$  and  $ET_o-K_{cd}$  methods (fig. 3), which subsequently affected actual T and  $K_{cb}K_s$  calculations (figs. 3a and 3b). Because the  $ET_o-K_{cb}$  method used  $K_e$ ,  $K_{cb}$ , and  $ET_o$  to calculate  $ES_o$  and  $EP_o$  (eqs. 7 and 8) independently, this problem was averted for  $ET_o-K_{cb}$ , and the  $EP_o$  curve was more realistic (fig. 4). Similar to the identification of problems for reference ET calculations (fig. 1), this



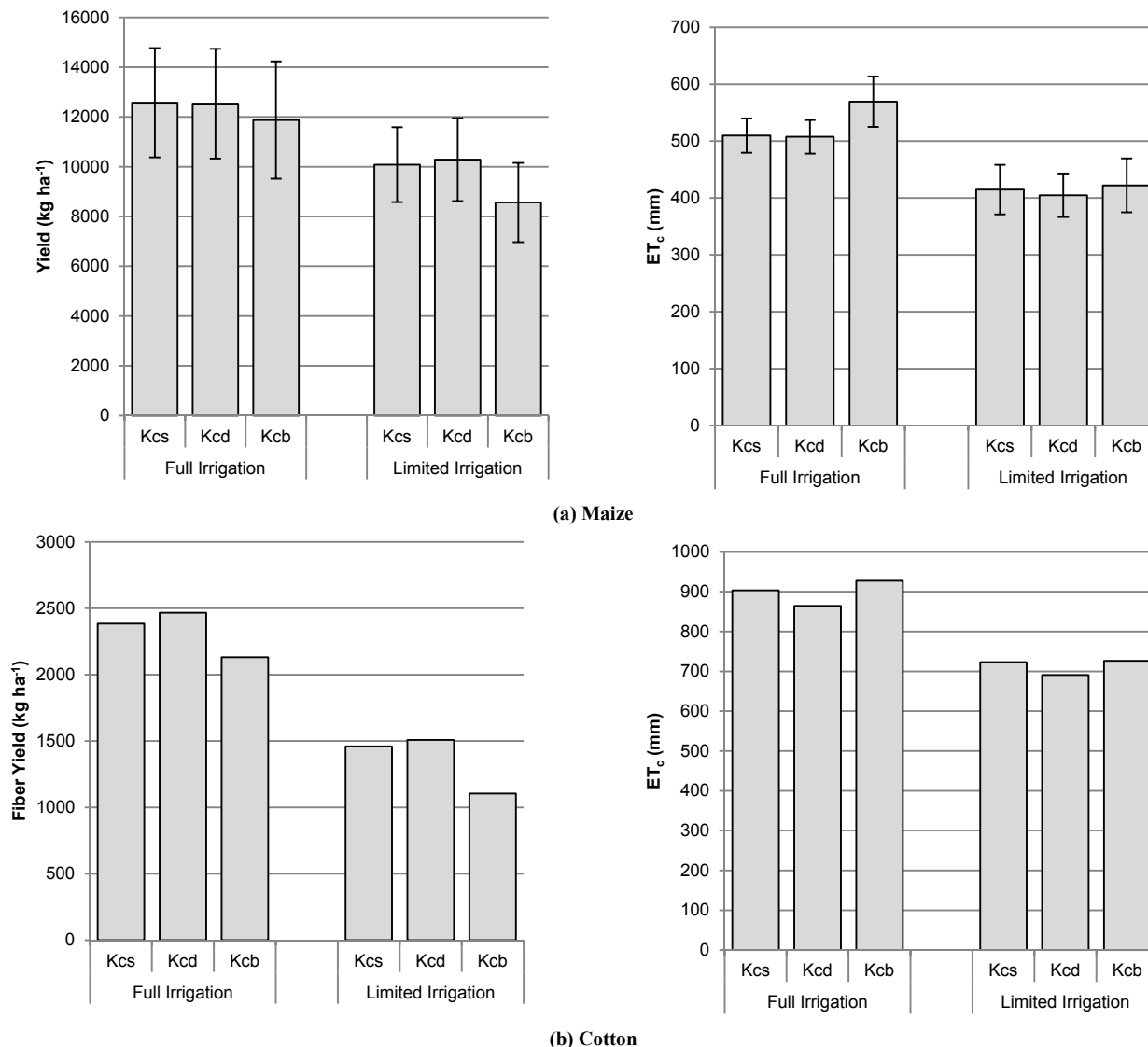
**Figure 4.** Ratio of potential transpiration ( $EP_o$ ) and grass reference ET ( $ET_o$ ) for three ET methods ( $ET_o-K_{cs}$ ,  $ET_o-K_{cd}$ , and  $ET_o-K_{cb}$ ) as simulated by CSM-CROPGRO-Cotton for the 2015 well-watered Arizona cotton treatment.

problem with ET partitioning was revealed only after incorporating existing ET standards into DSSAT-CSM and using FAO-56 theory to scrutinize the model's ET output.

Overall, the results demonstrate how crop coefficient calculations from daily crop model outputs of E, T, ET, and  $ET_o$  can be used to assess the adherence of different ET methods to expected crop coefficient patterns, as reported in FAO-56. Deviations from the expected patterns can help diagnose issues with an ET method, while inclusion of the  $ET_o-K_{cb}$  method establishes the benchmark standard to which any other approach can be compared.

#### YIELD AND $ET_c$ SENSITIVITY TO ET METHOD

When adjusting only the ET method and associated input parameters (table 3), simulated patterns in yield and seasonal  $ET_c$  were similar among the two crops for the three ET methods (fig. 5). Similar to the results of DeJonge et al. (2012a), maize yield and seasonal  $ET_c$  values for  $ET_o-K_{cd}$  were minimally changed as compared to the  $ET_o-K_{cs}$  module. While seasonal  $ET_c$  simulations were sometimes similar, simulated  $K_c$  (figs. 2 and 3) demonstrated that the daily  $ET_c$  simulations were not at all similar among the methods. Thus, if the ET methods compute relatively similar seasonal  $ET_c$  amounts, it is through fundamentally different daily  $ET_c$  simulations. For the  $ET_o-K_{cb}$  method with both crops, simulated yield was up to 28% lower for both full and limited irrigation. This result is likely related to higher  $EP_o$  for the  $ET_o-K_{cb}$  approach (fig. 4). Additionally, the  $ET_o-K_{cb}$  method with both crop models resulted in up to 13% higher  $ET_c$  for full irrigation, while differences among the ET methods were small for limited irrigation. These results indicate the need for the new module to be more fully evaluated using measured data from multiple locations, as the updates obviously influenced the main outputs of yield and  $ET_c$ . High-quality daily  $ET_c$  data, such as the data obtained from lysimetry (Evelt et al., 2016), would be best for such evaluations, but none of the field experiments for the present study included crop water use data from lysimeters. While this study does not specifically



**Figure 5. Mean yield and  $ET_c$  for (a) maize and (b) cotton under full and limited irrigation, comparing the  $ET_o-K_{cs}$  method,  $ET_o-K_{cd}$  method (DeJonge et al., 2012a), and new  $ET_o-K_{cb}$  method. Error bars for maize indicate standard deviations over five years; error bars for cotton are omitted due to only having two years in sample (2014 and 2015).**

compare simulation results to measured values, it has shown that there were fundamental differences in daily ET calculations (figs. 2 and 3) that led to impacts on simulated yield (fig. 5). Additionally, the findings demonstrate how some methods follow existing ET standards more closely than others. Presumably, this should correspond to improved ET simulations when compared to field measurements. However, because the goal was to develop the new  $ET_o-K_{cb}$  module and compare it to existing ET modules, only the ET parameters were adjusted (table 3), while the soil and cultivar parameters remained consistent among the ET methods. In reality, soil and cultivar parameters could be adjusted to different values for each ET method to improve agreement between measured and simulated yield and  $ET_c$ . Future studies will address this issue through model calibration efforts against high-quality daily  $ET_c$  data.

#### YIELD AND ET SENSITIVITY TO $ET_o-K_{cb}$ PARAMETERS

Under full irrigation,  $K_{cbmax}$  with the  $ET_o-K_{cb}$  method had

little influence on maize and cotton yield for  $0.9 < K_{cbmax} < 1.15$ , but simulated yield decreased rapidly for  $K_{cbmax} > 1.15$  (fig. 6a). However, under limited irrigation, yield increased with decreasing  $K_{cbmax}$ , likely due to the reduced transpiration demand via equation 6 and therefore less simulated water stress.

Simulated ET was not sensitive to changes in  $K_{cbmax}$  for values above 1.15 due to conservation of mass, but as  $K_{cbmax}$  decreased there was some additional  $ET_c$  loss under full irrigation for maize (fig. 6c).

Amounts of E and T were very sensitive to  $K_{cbmax}$  changes with the new  $ET_o-K_{cb}$  module (figs. 6e and 6g). Generally, as  $K_{cbmax}$  increased, seasonal soil evaporation decreased and transpiration increased. This was mostly due to the effect of  $K_{cbmax}$  on partitioning of E and T; however, overall  $ET_c$  changed very little (fig. 6c). This result has drastic implications for model calibration using measured separate E and T data, rather than  $ET_c$  data alone, because  $K_{cbmax}$  adjustments affect simulated E and T much more than  $ET_c$ . Ideally, high-

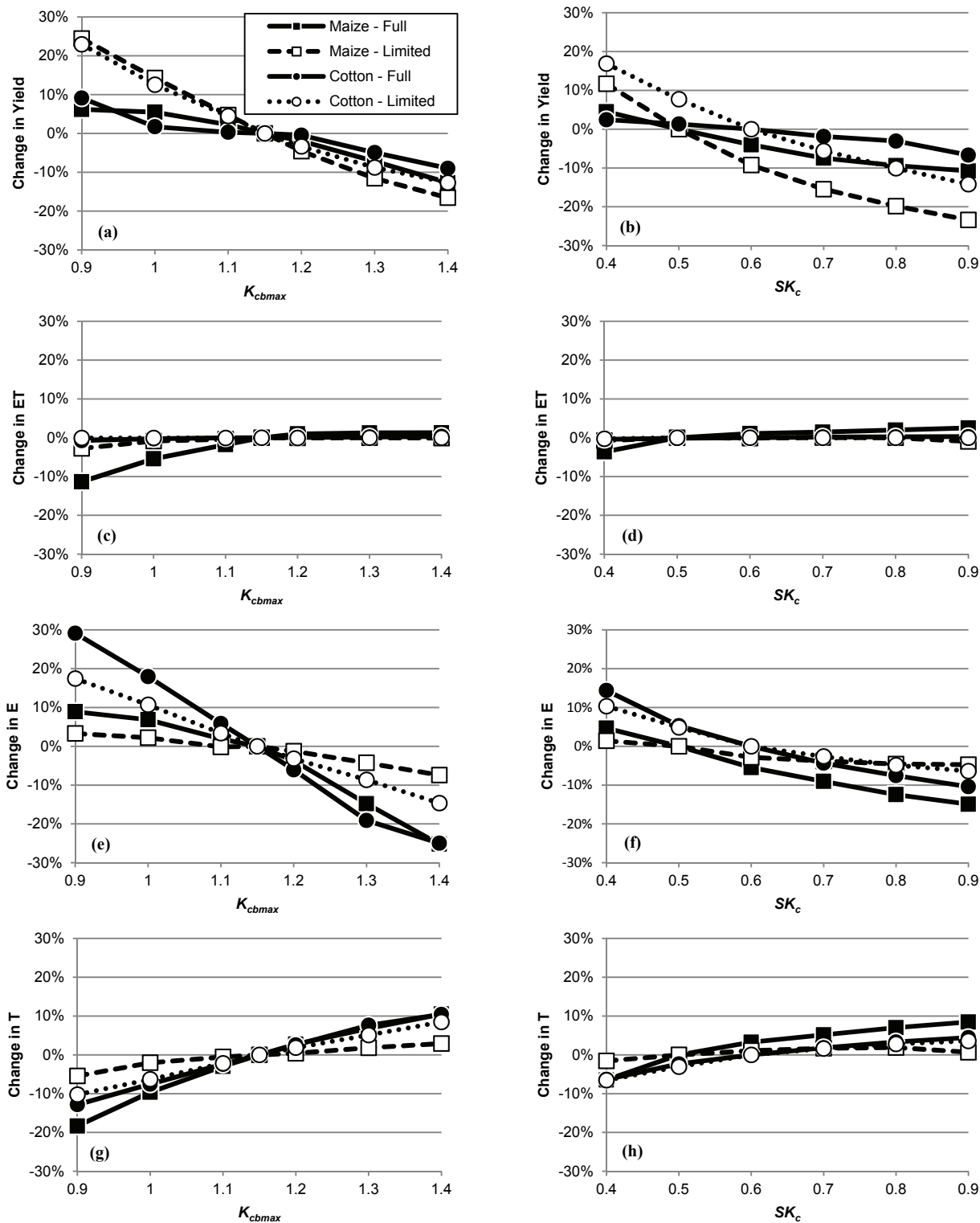


Figure 6. Sensitivity analysis of (a-b) yield, (c-d)  $ET_c$ , (e-f)  $E$ , and (g-h)  $T$  from changes in  $K_{cbmax}$  and  $SK_c$  using the  $ET_{\sigma}-K_{cb}$  method (eq. 6). Both maize and cotton models used  $K_{cbmax} = 1.15$  from the FAO-56 tables as the base value (i.e., no change), while maize used  $SK_c = 0.5$  and cotton used  $SK_c = 0.6$  as base values from previous calibration efforts.

quality data on  $E$  and  $T$  independent from  $ET_c$  are needed to adjust the parameterization of  $K_{cbmax}$ . Otherwise, it is recommended to obtain values from the  $K_{cb}$  tables in FAO-56.

The shaping parameter  $SK_c$  is very interesting because it influenced yield more than seasonal  $ET_c$  (figs. 6b and 6d). Similar to  $K_{cbmax}$ , this is likely due to the effects of the

parameter on simulated potential  $T$  demand with subsequent impacts on water stress factors (eqs. 6 and 7).  $SK_c$  also influenced changes in  $E$  and  $T$  in an inversely proportional manner (figs. 6f and 6h), but it had much less impact on the overall  $ET_c$  (fig. 6d). Similar to  $K_{cbmax}$ , this result has major implications for the adjustment of  $SK_c$  to calibrate the

DSSAT-CSM  $ET_c$  simulation, particularly when separate E and T data are not available, because  $SK_c$  adjustments affects  $ET_c$  to a much lesser degree than E and T simulations individually. While  $SK_c$  provides a parameter to adjust the portions of  $ET_c$  attributed to E and T, calibrating  $SK_c$  to  $ET_c$  alone does not guarantee accurate simulations of E and T individually. If E and T data are unavailable, values of  $SK_c$  from 0.5 to 0.7 are recommended. While total  $ET_c$  data are much easier to obtain than partitioned E and T, the results highlighted the robustness gained by using dual crop coefficient procedures to partition E and T as compared to single crop coefficient approaches (figs. 2 and 3). Therefore, dual crop coefficient procedures combined with crop growth simulation is advantageous for in-depth analyses of crop water use efficiency and water production functions.

## DISCUSSION

Current potential ET methods in DSSAT-CSM include the Priestley-Taylor (Priestley and Taylor, 1972) and  $ET_{pm-K_{cs}}$  approaches. The Priestley-Taylor method (which was not tested herein) is advantageous for simulations requiring long-term weather data in areas with limited meteorological stations because it requires only minimum and maximum air temperature and solar radiation and does not require humidity and wind speed data. However, the Priestley-Taylor method is subject to substantial underestimation under advective conditions often experienced in the western U.S. (Jensen and Allen, 2016). Furthermore, most modern meteorological stations in developed countries include all of the required inputs for the ASCE Standardized Reference ET Equation (Allen et al., 2005), i.e., air temperature, humidity, solar radiation, and wind speed. The capabilities of modern cropping system models should reflect the capabilities of meteorological data collection systems. The inclusion of both grass and alfalfa reference ET calculations based explicitly on the ASCE standard (Allen et al., 2005) is a strong step forward for ET simulation in DSSAT-CSM.

The current  $ET_{pm-K_{cs}}$  approach in DSSAT-CSM does not follow established ET standards in two main ways. First, it approximately calculates  $ET_o$  (fig. 1), but it uses older Penman-Monteith equation settings (eq. A1), explicitly calculates resistance terms from grass reference crop characteristics, uses a non-standard wind speed adjustment equation (eq. 9) with known errors in DSSAT v4.5, and does not incorporate an alfalfa reference ET calculation. All of these problems were updated and resolved by adding the ASCE Standardized Reference ET algorithm (eq. A2; Allen et al., 2005) to DSSAT-CSM. Second, the crop coefficient approach in the  $ET_{pm-K_{cs}}$  method does not truly follow FAO-56 protocol, even though the method has historically been named “FAO-56” in the model. As described herein, an FAO-56 dual crop coefficient ( $K_{cb}$ ) approach was implemented to scale reference ET to potential ET and to partition potential E and T, while native DSSAT-CSM algorithms were used to calculate actual E and T based on available soil water and root system growth. According to ASCE Manual 70 (Jensen and Allen, 2016), this reference ET and crop coefficient method (i.e.,  $ET_o-K_{cb}$ ,  $ET_r-K_{cb}$ ) has more consistent

and standardized procedures than the direct resistance-based Penman-Monteith equation (eq. A1) and is more appropriately applicable under water-stressed conditions.

Both the  $ET_o-K_{cs}$  and the  $ET_o-K_{cd}$  methods have issues in model behavior with respect to the FAO-56 conceptualization of ET. The former has limitations on its maximum  $K_c$  value and is not responsive to mid-season evaporation spikes, while the latter has more dynamic mid-season transpiration behavior but is unresponsive to evaporation spikes throughout the season. The new  $ET_o-K_{cb}$  method is a valuable addition that not only follows standardized procedures but also solves the behavioral issues of the prior approaches. The mid-season growth stage, with full canopy, the highest crop coefficients, longer length, and typically the highest evaporative demand (i.e.,  $ET_o$ ), may be considered the most significant growth stage in terms of seasonal  $ET_c$ , so the accuracy of this stage is most important. For the mid-season transpiration portion, the  $ET_o-K_{cs}$  method for maize had the limitation of  $K_{cs} = 1.0$  (fig. 2a) and for cotton was defined very close to 1.0 (fig. 3a). Because the transpiration demand is partitioned from the maximum value, the  $K_e$  had a defined concave shape. The  $ET_o-K_{cd}$  method had a dynamic overall  $K_c$  shape that was not limited to a maximum value like the  $ET_o-K_{cs}$  method, yet the  $K_e$  during midseason has a very similar shape and nearly identical evaporative portion. The similarities between these methods exist because they use the same partitioning algorithm that first calculates potential  $ET_c$  and then separates it into E and T components. However, one major issue with this method is that the mid-season crop coefficients are not responsive to evaporative spikes during full or nearly full canopy growth, from DOY 190 to DOY 260 for both crops (figs. 2 and 3). While these evaporative spikes for  $ET_o-K_{cb}$  are small during this growth stage, they have been verified through studies using water balance methods (da Silva et al., 2012), lysimetry (López-Urrea et al., 2012), energy balance (Anderson et al., 2017), and isotope tracing (Nay-Htoon, 2016); thus, they should be properly simulated by cropping system models. The new  $ET_o-K_{cb}$  method is very responsive to frequent irrigations, with both the evaporation and resulting ET being highly dynamic (figs. 2c and 3c) and more similar to theoretical representations in FAO-56.

Sensitivity of yield,  $ET_c$ , E, and T to  $K_{cbmax}$  and  $SK_c$  (fig. 6) is now available for users and will provide guidance for parameterization. Future studies should use reliable E and T measurements to fully evaluate the  $ET_o-K_{cb}$  method and further compare it to other DSSAT-CSM ET methods. Such a study would provide further guidance on recommended parameterization for  $K_{cbmax}$  and  $SK_c$ . However, the new method facilitates use of the tabular values in FAO-56 and other subsequent references (Allen et al., 1998, 2007; Jensen and Allen, 2016) for initial parameterization of  $K_{cbmax}$ .

Criticisms of the new  $ET_o-K_{cb}$  method have largely focused on the empiricisms inherent to the FAO-56 dual  $K_c$  approach, which prevent dynamic calculations of aerodynamic and bulk resistance terms in the Penman-Monteith equation as well as calculations of more complex biophysical relationships between crop growth and water use. However, the most commonly used ET methods in DSSAT-CSM, including Priestley-Taylor and  $ET_{pm-K_{cs}}$ , also suffer from

these limitations. Other ET methods that have a stronger biophysical basis are available in DSSAT-CSM, but they are rarely used due to languished development and lack of resources for thorough testing. By adding the new  $ET_o-K_{cb}$  option based on accepted ET standards, a benchmark ET routine was established in DSSAT-CSM that can be used as a baseline to evaluate and develop any other ET method. As demonstrated herein, the  $ET_o-K_{cb}$  standard method was useful for diagnosis of deficiencies in other DSSAT-CSM ET methods. When unexpected model behavior was encountered in both present and past studies (DeJonge et al., 2012a; Thorp et al., 2014), the issues were more thoroughly understood and resolved by incorporating standardized ET equations into the model and comparing model outputs from existing ET methods to the standard methods. By establishing a performance benchmark, the standard methods highlighted aspects of other ET methods that were not sensible (e.g., figs. 1 and 4). Thus, although the ET standards are somewhat less mechanistic than an ideal ET method that dynamically calculates resistance terms, stomatal conductance effects, and other biophysical intricacies, they are valuable for setting a baseline performance benchmark that any other ET method should at least meet, if not exceed. Likewise, the standard ET methods could similarly be useful in the development of novel ET approaches that aim to establish better mechanistic linkages among simulations of crop biology, soil water conditions, and ET. In this case, the standard ET methods again set the performance benchmark that the new method should aim to improve upon; otherwise, they offer little above what is embodied in the current ET standards. Essentially, the ET standards provide an unbiased, well-accepted protocol for calculating ET, which can shield crop model development from modeler bias and opinion. Statements on the appropriateness of an ET method for use in a crop model have greater scientific foundation when the ET method of question is shown to match or exceed the behavior and performance of the existing ET standard, for example, via daily crop coefficient plots (figs. 2 and 3) or by direct comparison to measured ET data. While the present study did not include comparisons to measurements, future studies are planned to further compare DSSAT-CSM ET methods using high-quality ET data sets.

## SUMMARY

The evapotranspiration module in DSSAT-CSM was revised to incorporate standardized ET procedures. This included explicitly following the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005) for tall and short reference ET ( $ET_r$  and  $ET_o$ , respectively) and explicitly following FAO-56 guidelines for the dual crop coefficient method. With these changes, the reference ET results matched almost exactly with another software package for standardized ET calculations. The new module resulted in more responsive crop coefficients, where the basal transpiration portion was directly linked to canopy cover via LAI, and the evaporation component was responsive to irrigation and rainfall events throughout the season. Newly added parameters need not be extensively calibrated, as they have

referenced values and ranges, but a sensitivity analysis showed how they affect simulated yield and both E and T components of  $ET_c$ . These new methods are an essential step forward for irrigation and ET modelers who use DSSAT-CSM for ET quantification and irrigation management under limited water conditions. In addition, this research demonstrates the use of FAO-56 concepts and existing ET standards to compare and contrast the ET outputs of different ET methods in crop models. The approach has great potential for applicability not only to DSSAT-CSM but also to other crop models, and it can provide a basis for intercomparison of ET methods both within and among crop models for model improvement purposes.

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## APPENDIX

### REVIEW OF STANDARDIZED ET METHODS

As documented in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998), the Penman-Monteith combination equation was adopted as a basis to standardize calculations of crop ET:

$$ET_{pm} = \lambda ET = \frac{\Delta(R_n - G) + \frac{\rho_a c_p (e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (A1)$$

where latent heat flux ( $\lambda ET$ ), net radiation ( $R_n$ ) and soil heat flux ( $G$ ) are in  $W m^{-2}$ , air density ( $\rho_a$ ) is in  $kg m^{-3}$ , specific heat of dry air ( $c_p$ ) is  $1,010 J kg^{-1} ^\circ C^{-1}$ , saturation vapor pressure ( $e_s$ ) and actual vapor pressure ( $e_a$ ) are in kPa,  $r_a$  is aerodynamic resistance in  $s m^{-2}$ ,  $r_s$  is the bulk surface resistance in  $s m^{-1}$ , and the slope of the saturation vapor pressure versus temperature curve ( $\Delta$ ) and the psychrometric constant ( $\gamma$ ) are in  $kPa ^\circ C^{-1}$ . The Penman-Monteith combination equation incorporates parameters that can be measured or calculated from weather data, and FAO-56 provided equations for calculations of  $r_a$  and  $r_s$  from wind measurement characteristics, canopy height, and leaf area index (LAI). Furthermore, FAO-56 demonstrated the simplification of terms in equation A1 as required for ET calculations from a hypothetical grass reference crop ( $ET_o$ ) with height of 0.12 m, surface resistance of  $70 s m^{-1}$ , and albedo of 0.23.

In May 1999, the Irrigation Association (IA) requested that the Evapotranspiration in Irrigation and Hydrology Committee of the ASCE Environmental and Water Resources Institute establish and define a benchmark reference ET equation. The purpose of this equation was to standardize the calculation of reference evapotranspiration and to improve transferability of crop coefficients across regions. Standardized versions of the Penman-Monteith equation were created by the ASCE-EWRI (Allen et al., 2005) to calculate reference ET for both a short crop ( $ET_o$ ) and a tall crop ( $ET_r$ ) following the format adopted by FAO-56. When the supporting parameter equations for  $r_a$ ,  $\rho_a$ , and  $\lambda$  from the Penman-Monteith combination equation (eq. A1) are reduced and combined, the daily time step, FAO-styled, and reduced equation of ASCE-EWRI results:

$$ET_{ref} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)} \quad (A2)$$

where  $ET_{ref}$  applies to both clipped grass and alfalfa reference surfaces.  $ET_{ref}$  has units of  $mm d^{-1}$  for 24 h time steps, net radiation ( $R_n$ ) and soil heat flux ( $G$ ) are in  $MJ m^{-2} d^{-1}$ , mean daily air temperature ( $T$ ) is in  $^\circ C$ , mean daily wind speed at 2 m height ( $u_2$ ) is in  $m s^{-1}$ , saturation vapor pressure ( $e_s$ ) and actual vapor pressure ( $e_a$ ) are in kPa, the slope of the saturation vapor pressure versus temperature curve ( $\Delta$ ) and the psychrometric constant ( $\gamma$ ) are in  $kPa ^\circ C^{-1}$ , and  $C_n$  and  $C_d$  are coefficients that change with reference type (grass  $ET_o$  or alfalfa  $ET_r$ ). For a short reference crop,  $C_n = 900$  and  $C_d = 0.34$ ; for a tall reference crop,  $C_n = 1600$  and  $C_d = 0.38$ . Further details on these coefficients are available in Allen et al. (2005). This form of the equation, at a minimum, requires meteorological inputs of daily minimum and maximum air temperature, minimum and maximum relative humidity or vapor pressure deficit, solar irradiance, and average wind speed. These measurements are common on most modern micrometeorological stations for microclimate monitoring

and ET prediction, and Allen et al. (2005) gave recommendations for estimating missing climatic data when necessary. Both short and tall reference surfaces are adopted worldwide as ET standards, and the preference of short or tall reference surfaces often varies by country or state.

The single crop coefficient approach was introduced in FAO-24 (Doorenbos and Pruitt, 1977) and explained further in FAO-56 and ASCE Manual 70 (Jensen and Allen, 2016), which describes the calculation of crop evapotranspiration ( $ET_c$ , the sum of soil evaporation  $E$  and plant transpiration  $T$ ) under well-watered optimal agronomic conditions (i.e., no limitations due to water stress, salinity stress, pest and disease, weeds, fertility, etc.). In other words, the approach calculates potential ET for a given crop at a particular stage of growth by scaling reference ET ( $ET_r$ , or  $ET_o$  in this case) with a single crop coefficient ( $K_c$ ):

$$ET_c = E + T = K_c ET_o \quad (A3)$$

FAO-56 characterizes seasonal daily crop coefficient ( $K_c$ ) curves using a trapezoidal shape that resembles crop canopy growth over time, often based on days after planting or growing degree days. Recommended  $K_c$  varies by crop and by region; for most agronomic crops,  $K_c$  has an initial or minimum value between 0.3 and 0.5 and a maximum value between 1.0 and 1.2 (see fig. 34 in FAO-56; Allen et al., 1998). FAO-56 also describes a basal crop coefficient approach in which  $K_c$  is divided into evaporation ( $K_e$ ) and transpiration ( $K_{cb}$ ) components, and  $K_s$  is the water stress coefficient:

$$K_c = \frac{E}{ET_c} + \frac{T}{ET_c} = K_e + K_{cb} K_s \quad (A4)$$

where  $K_s = 1$  indicates no stress and  $K_s = 0$  indicates maximum stress and complete transpiration shutdown.

This method has the distinct advantage of separating plant water use from surface (soil) water evaporation losses, as well as reducing ET when the canopy experiences water stress or other stressors (see fig. 10-1 in Jensen and Allen, 2016). This dual approach improves the accuracy of the overall ET estimate by separating  $E$  and  $T$  and improving the accuracy of the  $E$  estimate (Pereira et al., 2015). Proper partitioning of  $E$  and  $T$  is important not only for water management purposes (Kool et al., 2014) but also for yield estimation, as yield is physiologically linked more closely to  $T$  than to the combination of  $E$  and  $T$  (Paredes et al., 2014; Steduto et al., 2012).  $K_{cb}$  typically has a trapezoidal shape similar to  $K_c$  and is described for non-stressed crops in FAO-56.  $K_{cb}$  also can be related to reduced canopy cover due to prior stresses, a potential indirect and delayed result of limited soil water (fig. 10-1 in Jensen and Allen, 2016). The evaporation component ( $K_e$ ) is calculated through several steps:

$$K_e = \min[K_r(K_{cmax} - K_{cb}), f_{ew} K_{cmax}] \quad (A5)$$

where  $K_e$  is the soil evaporation coefficient,  $K_{cb}$  is the basal crop coefficient,  $K_{cmax}$  is the maximum value of  $K_c$  following rain or irrigation,  $K_r$  is a dimensionless evaporation reduction coefficient dependent on the cumulative depth of water evaporated from the topsoil, and  $f_{ew}$  is the fraction of the soil surface that is both exposed and wetted (i.e., the fraction of



soil surface from which most evaporation occurs). Following rain or irrigation  $K_r$  is 1, and evaporation is only determined by the energy available for evaporation. As the soil surface dries,  $K_r$  becomes less than 1, and evaporation is reduced.  $K_r$  becomes 0 when no water is left for evaporation from the upper soil layer. Complete details for calculating  $K_r$  are in FAO-56 and ASCE Manual 70. The upper limit ( $K_{cmax}$ ) is determined for grass reference ( $ET_o$ ) and alfalfa reference ( $ET_r$ ) by equations A6 and A7, respectively:

$K_{cmaxo} =$

$$\max(1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \times (h/3)^{0.3}, K_{cb} + 0.050) \quad (A6)$$

$$K_{cmaxr} = \max(1.0, K_{cb} + 0.05) \quad (A7)$$

where  $h$  is the mean maximum plant height during the period of calculation (m), and all other terms are previously defined. The fraction of evaporable water ( $f_{ew}$ ) is calculated as:

$$f_{ew} = \min(1 - f_c, f_w) \quad (A8)$$

where  $1 - f_c$  is the average exposed soil fraction not covered (or shaded) by vegetation (0.01 to 1), and  $f_w$  is the average fraction of soil surface wetted by irrigation or precipitation (0.01 to 1). Values for  $f_w$  are 1.0 for precipitation and certain types of irrigation (i.e., sprinkler and flood irrigation) but are lower for other types of irrigation (i.e., furrow or drip irrigation). Values for  $f_c$  can be determined by methods used to estimate canopy cover or can be estimated using the relationship described in FAO-56:

$$f_c = \left( \frac{K_{cb} - K_{cmin}}{K_{cmax} - K_{cmin}} \right)^{(1+0.5h)} \quad (A9)$$

where  $K_{cb}$  is the basal crop coefficient for the particular day,  $K_{cmin}$  is the minimum  $K_c$  for dry bare soil with no ground cover, and  $K_{cmax}$  is the maximum  $K_c$  immediately following wetting (eq. A6).