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Improving evapotranspiration simulations in the CERES-Maize model under limited irrigation

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ABSTRACT

Limitations on water resources for agriculture in places such as Colorado, USA, have caused farmers to consider limited irrigation as an alternative to full irrigation practices, where the crop is intentionally stressed during specific growth stages in an effort to maximize yield per unit water consumed, or evapotranspiration (ET). While crop growth models such as CERES-Maize provide the ability to evaluate numerous management scenarios without the costs associated with multiyear field experiments, recent studies have shown that CERES-Maize performs well under full irrigation but overestimates ET of corn under limited irrigation management. The primary objective of this study was to improve CERES-Maize ET simulation under limited irrigation management while maintaining accuracy of other important model output responses. Field experiments with corn were performed in northern Colorado, USA from 2006 to 2010, where four replicates each of full (ET requirement supplied by irrigation throughout the season) and limited (no irrigation before the V12 growth stage unless necessary for emergence, then full irrigation afterwards) irrigation treatments were analyzed. The local sensitivity of model input parameters affecting ET was evaluated, prompting changes to the model code with a new dynamic crop coefficient (K_{CD}) as a function of the crop leaf area index. The modified CERES-Maize model more accurately represented ET under full and limited irrigation, for example reducing late-season ET potential from a plant with reduced canopy and more closely matched FAO-56 crop coefficient curves under full irrigation. Using the limited irrigation data for evaluation, the modified model showed significant decreases in model error for seasonal cumulative ET (root mean square deviation RMSD from 80.9 mm to 49.9 mm) and water productivity (RMSD from 5.97 kg ha^{-1} mm^{-1} to 2.86 kg ha^{-1} mm^{-1}) as compared to the original model. The modified model was subsequently applied to several hypothetical irrigation management strategies, indicating that reducing weekly vegetative stage water applications from 20 mm to 2.5 mm can increase simulated water productivity by over 15%. While these synthetic water production functions may not be feasible in a production field with natural climate variability, the modified ET model indicates promise for limited irrigation management increasing water productivity.

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1. Introduction

Water availability issues, combined with population growth and the uncertainty of climate change have created significant water resource challenges (Anderson-Wilk, 2008). English et al. (2002) argued that a fundamental paradigm shift in agroecosystem irrigation management is inevitable as water supplies become more limited where farmers will manage irrigation to maximize net benefits instead of simply the biological objective of maximizing yields. Limited water resources and increasing pumping costs have recently caused farmers in Colorado, USA to consider limited irrigation as an alternative to full irrigation practices. Obviously, yield potential is very important in regard to the economic optimization required for such management, but crop evapotranspiration (ET) also must be considered and quantified as the potential for Colorado water rights transfer depends on “consumptive use” or ET (Smith et al., 1996). Alternatively, farmers may consider either a reduction in planted or irrigated area, or schedule irrigation events so that plants do not encounter stress during sensitive growth stages. Thus, in many irrigated areas such as the Colorado Front Range, studies are increasingly exploring benefits of limited or deficit irrigation of water-intensive crops such as corn (DeJonge et al., 2011).

Water deficit stress, often referred to as simply water stress, is a physiological condition where plants have less than full turgor because the transpiration demand exceeds root water

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Table 1
Experimental management data in Northern Colorado field experiment (2006–2010). Management was applied equally to both treatments unless indicated otherwise.

	2006	2007	2008	2009	2010
Hybrid	Garst 8827	Garst 8827	Pioneer 38P	Pioneer P9512XR	Producers Hybrids 5004VT3
Planting date	May 10	May 10[a] May 8[b]	April 30	May 13	May 4
Planting population (seeds m^{-2})	5.93[a] 7.91[b]	5.93[a] 7.98[b]	7.91	7.91	7.91
N applications (date, kg ha^{-1})	June 29 (67)[a] June 29 (157)[b]	June 27 (67)[a] June 27 (157)[b]	April 30 (52) June 23 (157)[a] Jun 23 (191)[b]	May 13 (56) June 29 (168)	May 10 (90) June 21 (168)
Anthesis date	Not collected	August 3[a] July 27[b]	July 30	August 2[a] August 6[b]	July 23
Harvest date	November 4	November 14	November 19	November 13	October 16

[a] Limited irrigation treatment only.
[b] Full irrigation treatment only.

uptake, and typically limits productivity (Saseendran et al., 2008a). Limited irrigation practices incorporate water management under restricted water application, and minimize water stress during critical crop growth stages in order to maximize yields (Schneekloth et al., 2009). Numerous field studies have addressed corn (*Zea mays* L.) response to growth stage-timed irrigation (Barrett and Skogerboe, 1978; Doorenbos and Kassam, 1979; Gilley et al., 1980; Klocke et al., 2004, 2007; Payero et al., 2006, 2009; Igbadun et al., 2008; Farre and Faci, 2009; Ko and Piccinni, 2009; Mansouri-Far et al., 2010).

Crop simulation models, such as the CERES-Maize model found in the DSSAT v4.5 system, have been widely used to assess cropping and management strategies for corn (both rainfed and irrigated) for well over two decades (Jones and Kiniry, 1986; Ritchie et al., 1998; Jones et al., 2003; Hoogenboom et al., 2010). Several studies have utilized the model in the context of crop water stress (Nouna et al., 2000; Xie et al., 2001; Mastrorilli et al., 2003; Saseendran et al., 2008b), yet cropping system models could certainly benefit from improved mechanistic representation of transpiration, photosynthesis, carbon allocation, canopy temperature, and water use efficiency or productivity (Ahuja et al., 2006). Recently, DeJonge et al. (2011) provided a detailed statistical comparison of CERES-Maize yield and ET output responses with field experimental data from 2006 to 2008 consisting of full and limited irrigation treatments in northern Colorado, USA, finding that CERES-Maize estimated yield adequately but slightly underestimated ET for full irrigation and overestimated ET for limited irrigation. These two observations contradict each other, as lower leaf area under limited irrigation should cause decreased photosynthesis and therefore decreased ET, instead of increased ET as the model predicted. This indicates that CERES-Maize simulations under stress may need improvement, especially in the form of a linkage between leaf area and ET since simulation of plant transpiration is not directly coupled with energy balance or stomatal behavior (Saseendran et al., 2008b).

In the context of crop water production functions, it is imperative that the model adequately simulate both yield and ET in terms of limited irrigation management. The overall objective of this study is to identify, evaluate, and improve CERES-Maize crop model processes that affect crop yield, ET, and LAI prediction under both non-stressed and stressed conditions. Specifically, this study explores CERES-Maize v4.0 crop simulations of full and limited irrigation treatments by: (1) evaluating local sensitivity of inputs for the maximum crop coefficient and the partitioning of potential soil evaporation and transpiration in terms of yield, cumulative ET, and maximum LAI output responses often used in model calibration; (2) creating and statistically evaluating a new function that calculates a dynamic crop coefficient for potential ET based on LAI, therefore determining ET demand as a function of vegetative growth; and (3) using the modified model with the new dynamic crop coefficient to predict water production functions (WPFs), or the relationship between yield and ET, using various forms of limited irrigation management in terms of application amount, scheduling, etc.

2. Methods

2.1. Field experiment

In a prior study, the CERES-Maize crop growth model was calibrated and validated using data from a multi-replicate field research experiment near Fort Collins, Colorado (40°39′19″N, 104°59′52″W) from 2006 to 2008. Complete experimental details can be found in DeJonge et al. (2011), where 2007 was used for model calibration and 2006/2008 were used for validation. Two irrigation treatments of continuous corn were studied during the 2006–2010 growing seasons (2006–2008 data as documented in DeJonge et al. (2011) plus the additional 2009–2010 experiment years): full irrigation (ET requirement met by irrigation throughout the season) and limited irrigation (no irrigation before the V12 growth stage unless necessary for emergence, then full irrigation afterwards). In all years, early irrigations of less than 38 mm were required by all treatments to encourage germination and avoid total loss of crop. Irrigations were applied by 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), and supported by potential ET estimates from the onsite weather station. An on-site weather station (station FTC03; 40°39′09″N, 105°00′00″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. Field observations of soil water were generally made on a weekly basis using neutron attenuation in 30 cm intervals to a depth of 180 cm, and were used in a water balance to determine seasonal ET. Yield samples were collected upon maturity each season. Field management and irrigation schedules for 2006–2010 are found in Tables 1 and 2, respectively. The soil at the study site is a Fort Collins Loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalf), with water holding and textural properties shown in Table 3.

2.2. CERES-Maize model overview

CERES-Maize is a process-oriented corn growth model that requires various inputs for soil (texture, field capacity, permanent wilting point, saturation, saturated hydraulic conductivity, bulk density, soil root growth factor), daily weather (minimum and

Table 2
Irrigation schedule and amount for both full and limited irrigation treatments and seasonal rainfall (May 1–October 31) in Northern Colorado field experiment (2006–2010).

2006			2007			2008			2009			2010		
Date	Irrigation amount (mm)		Date	Irrigation amount (mm)		Date	Irrigation amount (mm)		Date	Irrigation amount (mm)		Date	Irrigation amount (mm)	
	Limited	Full		Limited	Full		Limited	Full		Limited	Full		Limited	Full
18 May		38	25 May	38	38	11 May	38	38	20 May	13	13	11 June		25
1 June	38		20 June	44	44	4 June	38	38	1 July	25	25	24 June		25
15 June		38	28 June		51	12 June		25	8 July		13	1 July		25
22 June		38	11 July		51	18 June		25	16 July		38	8 July		25
3 July		76	19 July	51	51	26 June		38	23 July		38	17 July	38	38
13 July		51	25 July	38	38	3 July		38	30 July		13	22 July	38	38
21 July	51	51	16 August	38	38	10 July		38	6 August	38	38	29 July	38	38
27 July	56	56	23 August		25	17 July		38	13 August	38	38	5 August	32	32
3 August	38	38	29 August		25	24 July	38	38	20 August	38	38	12 August	38	38
10 August		38				31 July	38	38	27 August	38	38	19 August		32
18 August	38	38				7 August	25	25				26 August		32
24 August	38	38				15 August	25	25				2 September	25	25
												16 September		25
Total irrigation (mm)	259	500		210	362		203	406		191	292		210	400
Seasonal rainfall (mm)	83			201			241			202			152	

maximum temperature, solar radiation, dew point temperature, wind run, rainfall), management (planting date, N applications, irrigation, planting population), initial conditions (volumetric soil water content, N content), and phenological growth parameters specific to the hybrid or cultivar used (Jones and Kiniry, 1986). The model simulates the following: biomass accumulation based on light interception; partitioning of accumulated biomass to leaves, stems, roots, and grain; environmental stresses; soil water balance; soil N transformations and uptake; and crop growth and development including phenological states, biomass production, and yield. CERES-Maize crop development rates are calculated based only on temperature and photoperiod (Ritchie et al., 1998). Final LAI is calculated from the canopy leaf area balance available each day as a function of plant population, and the model does not simulate crop height (Ma et al., 2002). In terms of crop yield, number of grains per plant is a function of the potential number of kernels per plant and the average crop growth rate (g plant^{-1}) from silking to the beginning of grain filling. CERES-Maize assumes one ear of corn per plant, however if the number of kernels per plant is significantly smaller than the potential number of kernels, the model creates some barren plants. Ear growth rate (g ear^{-1} day^{-1}) is influenced by temperature but can be decreased by water or N stress. The effective grain filling period is based on the thermal time from silking to maturity, and during this period leaf senescence increases, whereas ears, stalks, and roots are the only active growing tissues. Daily grain growth rate is a function of temperature, grains per plant, potential kernel growth rate, and soil moisture effect on growth (Ritchie et al., 1998).

2.3. *CERES-Maize ET and water balance*

The daily soil–water balance in all DSSAT models, including CERES-Maize, uses the Ritchie (1985) and Ritchie et al. (1998) one-dimensional "tipping bucket" approach, which simulates soil water flow and root water uptake for each individual user-defined soil layer (maximum of ten layers). For each layer it is required to know soil water contents (on a volumetric basis) for initial soil water content (typically found by observed values at planting), wilting point, field capacity, and field saturation. Ritchie (1985) recommends that wilting point and field capacity be determined in the field instead of from lab measurements based on disturbed samples. The root weighting factor also is required for each layer, where a maximum value of 1 indicates a soil most hospitable to root growth and a minimum value of 0 indicates the soil is inhospitable to root growth. Low values for the root weighting factor can be used to simulate restricted root growth in layers with poor physical or chemical properties. Key soil properties for the Fort Collins limited irrigation experimental site are given in Table 3; however, all values used in this study for initial soil water, wilting point, field capacity, saturation, and root weighting factor can be found in DeJonge et al. (2011). Infiltration is assumed to be rainfall plus irrigation minus runoff, calculated by the curve number method (SCS, 1972). Soil water redistribution within the soil is described in more detail in Ritchie et al. (1998), and is a function of the water contents in neighboring layers and the distance between layers. Additional information regarding simulation of water balance and water stress components can be found both in Saseendran et al. (2008a) and ICASA (2008).

For CERES-Maize as implemented in DSSAT v4.5, the overall logic of ET and water stress calculation is shown in Fig. 1. Reference evapotranspiration (ET$_o$) was calculated in earlier versions of the model using the Priestley–Taylor method (Priestley and Taylor, 1972) whose inputs are solar radiation and minimum and maximum temperature. Current versions of the DSSAT CSM can also use

Table 3
Soil properties at the Fort Collins limited irrigation experimental site.

Depth from surface (mm)	Wilting point ($mm^3\ mm^{-3}$)	Field capacity ($mm^3\ mm^{-3}$)	Sand (%)	Clay (%)
0–150	0.100	0.320	37.4	31.0
150–300	0.150	0.280	37.4	31.0
300–450	0.150	0.325	36.0	31.0
450–600	0.179	0.262	34.2	31.2
600–900	0.169	0.400	40.3	31.7
900–1200	0.160	0.420	48.6	27.1
1200–1500	0.180	0.400	46.4	29.2
1500–1780	0.180	0.420	44.4	30.4

the FAO-56 Penman–Monteith method which requires additional wind and humidity data (Allen et al., 1998):

$$\mathrm{ET}_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right) U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is the hypothetical reference crop ET rate ($\mathrm{mm\,d^{-1}}$), R_n the net radiation flux density at the surface ($\mathrm{MJ\,m^{-2}\,d^{-1}}$), G the sensible heat flux density from the surface to the soil ($\mathrm{MJ\,m^{-2}\,d^{-1}}$), γ the psychrometric constant ($\mathrm{kPa\,^\circ C^{-1}}$), T is mean air temperature (°C), U_2 is wind speed ($\mathrm{m\,s^{-1}}$) at 2 m above the ground (relative humidity and dew point are also assumed to be measured at this height), e_s is mean saturated vapor pressure (kPa) computed as the mean vapor pressure as calculated at the daily minimum and maximum temperature, e_a is the actual vapor pressure of the air (kPa), and Δ is the slope of the saturation vapor pressure versus temperature curve ($\mathrm{kPa\,^\circ C^{-1}}$).

Potential crop ET ($E0$) is calculated from:

$$E0 = K_{CS} \times \mathrm{ET}_o \quad (2)$$

where K_{CS} is the static CERES-Maize crop coefficient. In the context of this study, it is important to understand that K_{CS} is not necessarily the same as a crop coefficient in the traditional sense (K_c) as described by Allen et al. (1998). While it is true that the crop coefficient K_c is multiplied by a reference ET, the resulting value denotes ET *demand* and not necessarily actual ET. CERES-Maize model code employs the following formula for calculation of K_{CS}:

$$K_{CS} = 1.0 + (K_{c\,\mathrm{max}} - 1.0) \times \frac{\mathrm{LAI}}{6.0} \quad (3)$$

where LAI is leaf area index and $K_{c\mathrm{max}}$ is defined as the maximum K_{CS} at LAI = 6.0 (Sau et al., 2004). This formula ensures that K_{CS} varies daily between 1.0 and $K_{c\mathrm{max}}$. Values of $K_{c\mathrm{max}}$ less than 1 should not be used, as this would actually decrease the ET based on increased

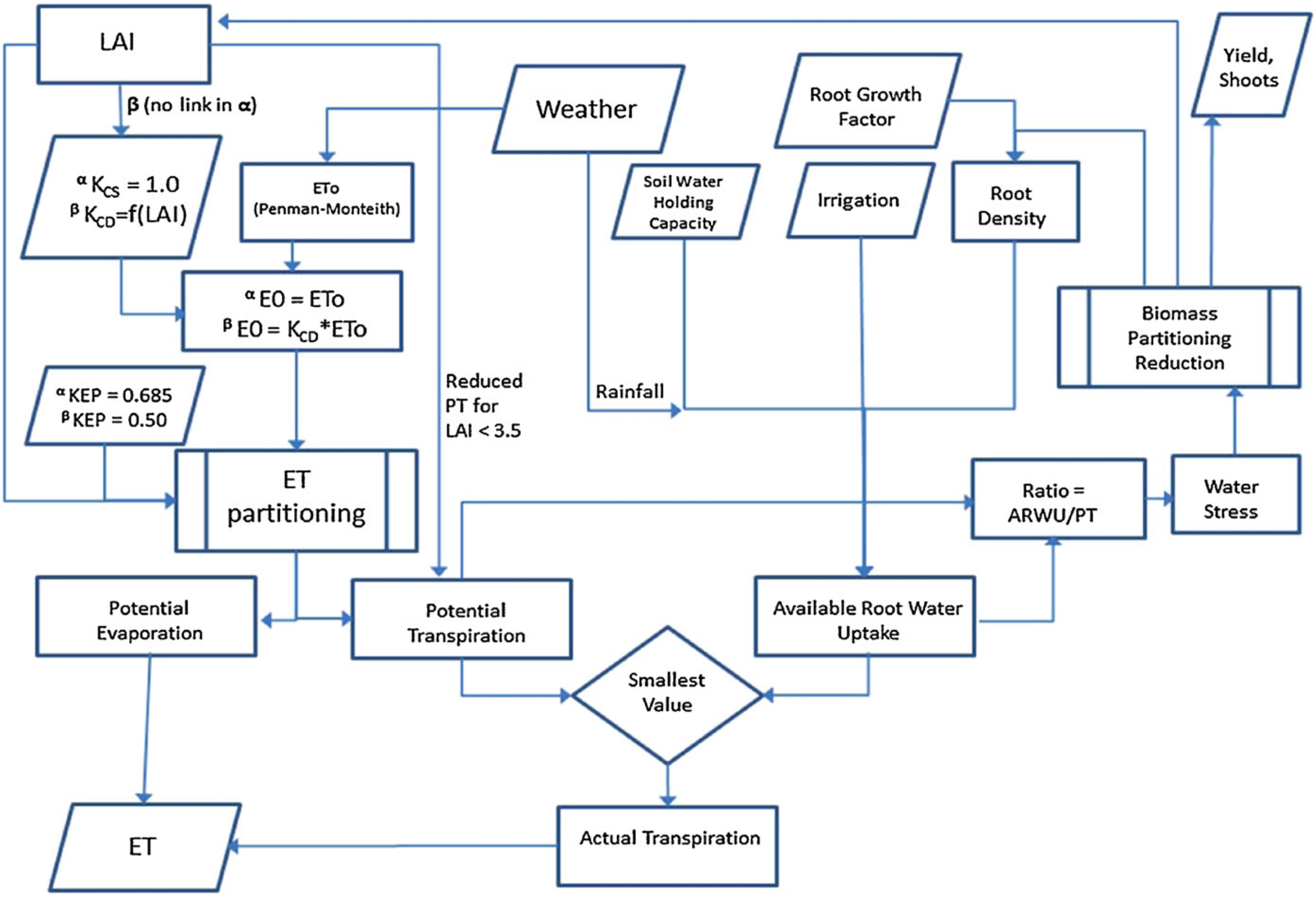

Fig. 1. Logic of evapotranspiration (ET) calculation and basic crop growth in the CERES-Maize model (Hoogenboom et al., 2010). In instances where modifications were made by this study, original model is indicated by α and modified model indicated by β. LAI = leaf area index, ET_o = reference ET, K_{CS} = static CERES-Maize crop coefficient, K_{CD} = dynamic crop coefficient, $E0$ = potential model ET, KEP = partitioning coefficient for evaporation and transpiration.

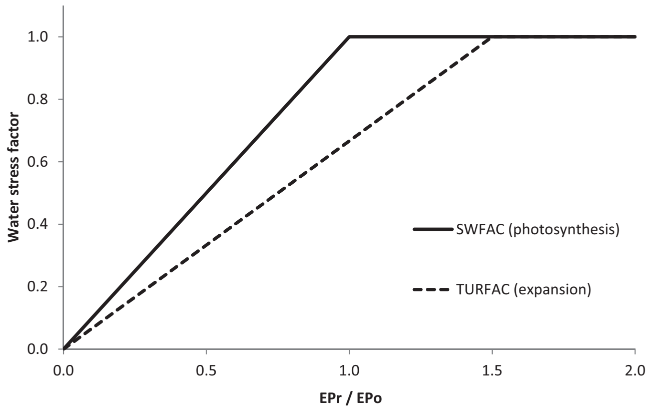

Fig. 2. Water stress factors SWFAC (photosynthesis) and TURFAC (expansion) used in DSSAT models as a function of the ratio of potential water uptake (EP_r) to potential transpiration (EP_o) (Ritchie et al., 1998 via Saseendran et al., 2008b). Values of 1 indicate that no stress is imposed on photosynthesis or expansion processes; values between 0 and 1 will impose stresses on the crop, with lower values indicating more stress.

LAI. The current version of CERES-Maize sets the value of $K_{c\max}$ equal to 1, ensuring that K_{CS} remains at 1.0 for the entire simulation and is thus static. Allen et al. (1998) noted that closely spaced plants with tall canopy heights may have mid-season ET greater than the reference ET, and suggested a K_c of up to 1.2 for a non-stressed maize crop. This option has been evaluated in previous studies with mixed results. For example, López-Cedrón et al. (2008) used the FAO-56 option with $K_{c\max}$ (maximum K_{CS}) of 1.0 and 1.1 (in addition to the Priestley–Taylor method) to simulate rainfed and irrigated maize biomass and yield, finding that $K_{c\max}$ greater than 1.0 proved to be too stressful on rainfed biomass and yield.

$E0$ is partitioned into potential plant transpiration (EP_o) and potential soil evaporation (ES_o), where

$$EP_o = E0 \times (1 - \exp(-\mathrm{KEP} \times \mathrm{LAI})) \quad (4)$$

$$ES_o = E0 - EP_o \quad (5)$$

where KEP (default value of 0.685) is defined as an energy extinction coefficient of the canopy for total solar irradiance used for partitioning $E0$ to EP_o and ES_o.

Soil-limited root water uptake (EP_r) is calculated based on the effective root zone of the crop and the available water within that root zone (Ritchie, 1998). The actual plant water uptake (EP) is found as the smaller of EP_r and EP_o. In other words, if the potential plant evaporation (transpiration) can be supplied by the soil water, then this demand is fully met. It is important to remember that in the current version of CERES-Maize, EP_o is based on a non-stressed full canopy crop, even when the crop itself may be in the vegetative growth stage with less actual ET demand. Cases where ET demand may not be met include the beginning growth stages (where the root water uptake will be minimal) and also the prolonged water shortage. Two stress factors are calculated in CERES-Maize based on the ratio of EP_r to EP_o. Under well-watered conditions, potential root water uptake is greater than potential transpiration and this ratio is greater than one. As soil dries because of root water uptake, EP_r is reduced, and eventually a threshold is reached where the turgor stress factor (TURFAC, Fig. 2) is triggered, limiting expansive growth which is considered more sensitive to drought stress than other growth and development processes (Saseendran et al., 2008a). In the current version of the model, this is calculated as:

$$\mathrm{TURFAC} = \frac{EP_r}{\mathrm{RWUEP1} \times EP_o} \quad (6)$$

where RWUEP1 is a species-specific parameter that is currently set to 1.5 for all DSSAT crops. When potential transpiration demand exceeds the potential root water uptake, a second stress factor affecting photosynthesis (SWFAC, Fig. 2) is activated and is calculated as:

$$\mathrm{SWFAC} = \frac{EP_r}{EP_o} \quad (7)$$

Both stress factors are bounded by values of 0 and 1. Values of 1 indicate that no stress is imposed on photosynthesis or expansion processes; values between 0 and 1 will impose stresses on the crop, with lower values indicating more stress.

2.4. Local sensitivity of K_{cmax} and KEP

The two main model parameters and processes initially explored in this study are the maximum K_c for FAO-56 Penman–Monteith potential ET ($E0$) and the KEP value partitioning EP_o and EP_r based on LAI. In an earlier study, a global sensitivity analysis was performed on CERES-Maize using the same northern Colorado, USA datasets (i.e., 2006–2010), and verified that the limited irrigation treatment was very sensitive to inputs affecting the soil's available water capacity, whereas the full irrigation treatment showed minimal sensitivity (DeJonge et al., 2012). In this manuscript, a local sensitivity analysis (SA) of $K_{c\max}$ and KEP was performed by manually changing the baseline (default) parameter values through input files and code manipulation. Five years of management data (2006–2010) were used with the two irrigation treatments (separated in the SA) to simulate CERES-Maize output variability. Model output responses evaluated included yield at maturity (kg ha^{-1}), maximum seasonal LAI, and cumulative ET (mm). Mean and standard deviation of the output responses for each treatment were calculated, as well as the overall change (%) from the mean values using the baseline run.

As suggested by Allen et al. (1998), the crop coefficient (K_c) can be as high as 1.2 for midseason corn. The DSSAT code was modified to remove the hard-coded K_{CS} value (currently set to 1.0) and thus allow a maximum K_{CS} value (as set by $K_{c\max}$, Eq. (3)) to be initialized in the maize species input file. $K_{c\max}$ values of 1.1, 1.2, and 1.3 were compared with the baseline value K_c of 1.0. While $K_{c\max}$ of 1.3 may give higher than expected K_{CS} values, maximum observed LAI in Colorado, USA is typically not much higher than 5.0 (DeJonge et al., 2011), which using Eq. (3) would give a K_c of 1.25.

Values of KEP were changed to evaluate the effects of varying partitioning to potential transpiration and potential soil evaporation based on LAI (Eq. (4)). Different KEP values have been investigated in previous studies, for example, Sau et al. (2004) used a KEP value of 0.85 with DSSAT v3.5 and López-Cedrón et al. (2008) used a value of 0.685 with DSSAT v4.0. Both authors recommended lowering the KEP value to 0.5 for better simulation of biomass and yield and López-Cedrón et al. (2008) evaluated a KEP of 0.5 in rainfed maize. However, no analysis of the direct effect of changing these values on ET or LAI was made in either study. For the purposes of this study, KEP was evaluated using the CERES-Maize default value (0.685) and three other values (0.605, 0.524, and 0.444).

2.5. Dynamic K_{CD} calculation

In order to potentially improve the simulation of ET in CERES-Maize, it is desirable to replace Eq. (3) with a new estimation of K_{CS} that more reasonably estimates the ET demand as a function of LAI. A few past studies (e.g., Al-Kaisi et al., 1989; Kang et al., 2003; Duchemin et al., 2006) show a direct relationship between the traditional crop coefficient (K_c) and LAI (Fig. 3). All of the studies used lysimeters to determine ET and all were for corn with the exception of Duchemin et al. (2006) which was for wheat, and is shown for comparison purposes. Although this study focuses on corn, there are limited examples in the literature that directly compare K_c and

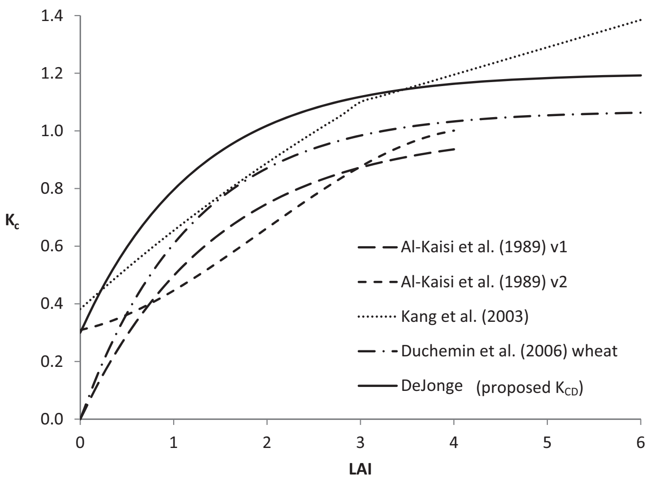

Fig. 3. Crop coefficient (K_c) versus leaf area index (LAI) relationships found in literature, and newly proposed dynamic crop coefficient function (K_{CD}) for this study: $K_{CD} = 0.3 + 0.9 \times (1 - \exp(-0.8 \times \text{LAI}))$.

LAI, and wheat has similar crop coefficient characteristics to corn (Allen et al., 1998). The K_c versus LAI relationships generally had R^2 between 0.72 and 0.86, and the first leg of the Kang et al. (2003) relationship (i.e., up to an LAI of 3) had an R^2 of 0.95. The graphs in Fig. 3 all share commonalities, for example the graphs typically start with K_c between 0 and 0.4 for LAI = 0, and increase in a linear or exponential limit fashion until approximately an LAI of 3, where K_c is between 0.8 and 1.1. At this point the relationships level off with small increases in K_c for any increase in LAI. Several of the studies showed that ET demand does not significantly increase as LAI increases above 3 since this LAI level is near the maximum intercepted net radiation. It is worth noting that the curves predicted by Al-Kaisi et al. (1989) and Duchemin et al. (2006) are debatable at low values of LAI (e.g., at LAI = 0 there is no canopy yet there would still be soil surface evaporation, thus $K_c > 0$).

For the purposes of improving the CERES-Maize crop growth model, it is desirable to link the factors governing interception of solar radiation (i.e., LAI) with those governing ET demand (i.e., K_{CS}) to provide for a more mechanistic representation of the ET process. Based on production functions used in previous studies (Fig. 3), the following dynamic exponential decay function K_{CD} is proposed and evaluated to replace K_{CS} as determined in Eq. (3):

$$K_{CD} = K_{c\,\min} + (K_{c\,\max} - K_{c\,\min})(1 - \exp(-SK_c \times \text{LAI})) \tag{8}$$

where $K_{c\min}$ is the minimum crop coefficient or K_{CD} at LAI = 0, $K_{c\max}$ 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. The three unknown terms (other than LAI) in this function were added to the model code as parameters in a new input file. Based on several examples of $K_{c\min}$ and $K_{c\max}$ for various crops in FAO-56 (Allen et al., 1998), suggested values for these parameters for corn are $0 < K_{c\min} \leq 0.4$ and $0.9 \leq K_{c\max} \leq 1.2$. Because SK_c is a new parameter introduced in this manuscript, the authors suggest $0.5 \leq SK_c \leq 1.0$ as a typical range to match the general shape and scale of other experiments as shown in Fig. 3.

Both irrigation treatments were evaluated using 2006–2010 data after replacing Eq. (3) with Eq. (8). Values for $K_{c\min}$ and $K_{c\max}$ were set at 0.3 and 1.2, respectively, based on typical values expected for corn (Allen et al., 1998). This ensured an early season K_{CD} near 0.3 before significant canopy growth, as well as K_{CD} well above 1 with higher LAI. Additionally, SK_c was set to 0.8 to resemble trends found in previous studies (Fig. 3) and KEP was set to 0.5 to follow recommendations by Sau et al. (2004). Model changes are indicated by β in Fig. 1.

2.6. Synthetic water production functions

To evaluate the irrigation scenarios described above, the new K_{CD} function was analyzed using the irrigation treatments from the northern Colorado, USA field experiment (full and limited irrigation), along with three other theoretical treatments (Table 4). Five years of historical weather data were used (2001–2005), using the onsite CoAgMet weather database for weather inputs (FTC03, any missing data were replaced by the nearby FTC01 Fort Collins, Colorado, USA station). All scenarios were run using field observed 2006–2010 input data, except that the theoretical irrigation schedules and amounts were modifications of the observed irrigation data. In the new irrigation treatments irrigation timing was based on the full and limited irrigation treatments in that irrigation occurred only on the same dates as for the observed treatments; however, the irrigation quantities varied toward a specific objective. In order to further evaluate the effectiveness of the limited irrigation management treatments as applied in these studies, and to test CERES-Maize using climate scenarios outside of those used in the model parameterization, an additional comparison was made using synthetic limited irrigation experiments created with varying levels of water stress during the vegetative growth stage. All precipitation data were deleted and replaced with a weekly artificial water application in an effort to create a synthetic water production function. During the vegetative growth stage, effects of five application rates (2.5, 5, 7.5, 10, and 20 mm week^{-1}) were simulated. During the reproductive and maturity stages, these weekly water applications were set at 50 mm to ensure a full water profile. In order to ensure that the differences in outputs only occur as a result of treatment or weather variability, all other initial conditions and management inputs were taken from the original simulations of the 2008 full irrigation treatment, including planting day of year, nitrogen applications, initial water conditions, etc.

2.7. Statistical evaluation

CERES-Maize simulations for yield, cumulative ET, and water productivity (WP, yield divided by cumulative ET) were performed using both the original (static K_{CS} value) and modified (dynamic K_{CD} function) models. Model output responses were compared with experimentally observed values using the root mean square deviation (RMSD), normalized objective function (NOF), and relative error (RE) statistical evaluation criteria:

$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{9}$$

$$\text{NOF} = \frac{\text{RMSD}}{\bar{O}} \tag{10}$$

$$\text{RE} = \frac{(\bar{P} - \bar{O})}{\bar{O}} \times 100 \tag{11}$$

where O_i is the observed value, P_i is the CERES-Maize predicted value, n is the total number of observations, $\bar{P}$ is the mean of all predicted values, and $\bar{O}$ is the mean of all observed values. Smaller values of RMSD among the same data type indicate better performance of the model. The NOF should be interpreted as a relative value to compare model performance of simulating different data sets. RMSD or NOF = 0 indicate perfect fit between experimental data and simulated results; NOF < 1 may be interpreted as a simulation error of less than one standard deviation around the experimental mean. RE is a measure of the average tendency of the simulated values to be larger or smaller than the observed values. The optimal RE value is 0.0; a positive value indicates a model bias toward overestimation, whereas a negative value indicates a model bias toward underestimation.

Table 4
Observed and hypothetical irrigation treatments explored with the modified model.

Treatment	Description	Goal
Full (observed)	Irrigation applied to meet ET demand throughout the growing season	Achieve maximum yield, zero stress throughout growing season
Limited (observed)	During vegetative stage, irrigations only applied to establish stand. Full irrigation during reproductive stage	Intentionally stress crop during vegetative stage but minimize stress after reproductive stage
50% full (hypothetical)	Irrigation events on same days as full irrigation, but 50% of full	Reduced irrigation amount with no change in irrigation timing
Full anthesis only (hypothetical)	Same as 50% full treatment, but full irrigation amounts are within a week of anthesis date	Reduced irrigation amount with no stress during sensitive reproductive stage
Stress anthesis only (hypothetical)	Same as full irrigation treatment, but zero irrigation is applied within a week of anthesis date	Maximum stress during sensitive reproductive stage with no irrigation reduction otherwise

3. Results and discussion

3.1. Linear sensitivity of K_{cmax} and KEP

As expected, increasing K_{cmax} (Eq. (3)) increased cumulative ET for the full irrigation treatment (Fig. 4). Cumulative ET was increased 4.6% by changing K_{cmax} to 1.1 and increased 8.0% by changing K_{cmax} to 1.2. Increasing K_{cmax} to 1.3 produced a smaller incremental change in cumulative ET (10.1% higher than baseline). Because ET increased for this treatment, the water in the soil profile was less than in the baseline treatment, so a small amount of water stress was introduced that slightly decreased yield (e.g., 1.9% decrease in yield with K_{cmax} of 1.2) but had an even smaller effect on LAI (only a 0.8% reduction with K_{cmax} of 1.3). DeJonge et al. (2011) showed that cumulative ET under full irrigation was generally underpredicted, with a relative error of −7.2% for the three years (2006–2008) evaluated. Allen et al. (1998) noted that a maximum K_c (K_{cmax}) value of 1.2 for unstressed, full canopy corn is typical; therefore, it is conceivable that this value would improve simulations of ET for fully irrigated corn.

As the limited irrigation treatment was not expected to reach full ET throughout the season, changes in K_{cmax} did not have a significant impact on ET, with only a 0.7% increase in cumulative ET for K_{cmax} of 1.3 (Fig. 4). Root water uptake and subsequent transpiration is limited by the smallest of ET demand and available root water (Fig. 1), which in the limited irrigation treatment is often

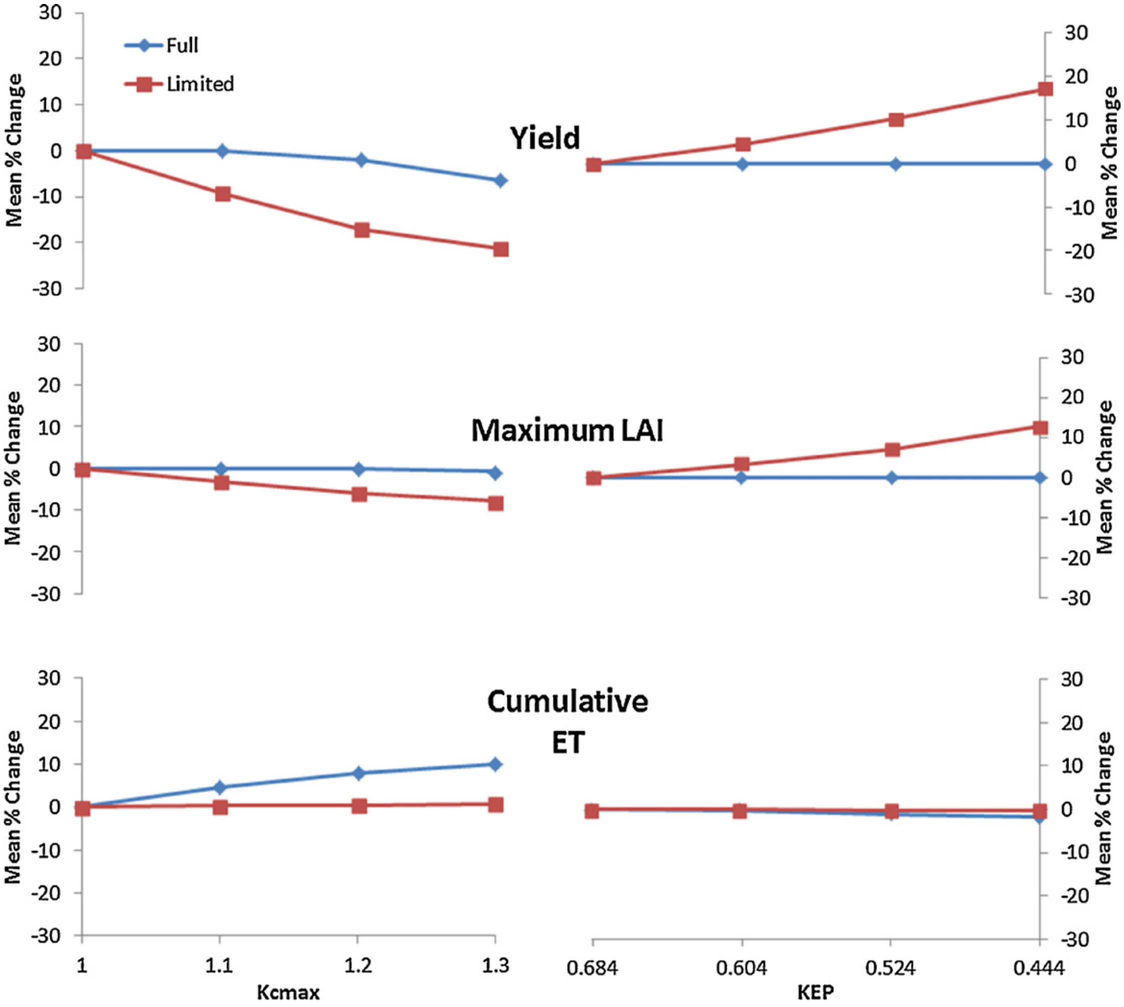

Fig. 4. Local sensitivity of yield, maximum leaf area index (LAI), and cumulative evapotranspiration (ET) to changes in K_{cmax} and KEP for full and limited irrigation treatments. Vertical axis indicates change in output (%) from baseline (K_{cmax} = 1.0, KEP = 0.685) averaged over the five years simulated.

the latter, regardless if the ET demand is increased as in this sensitivity analysis. However, due to the processes used to partition ET and calculate water stress, increases in K_{cmax} introduced significant decreases in both yield and LAI. For example, with K_{cmax} of 1.2, yield decreased 17.2% and LAI decreased 5.8%. By allowing for a higher K_c, Eq. (2) calculates a higher $E0$ (ET demand or potential ET). When $E0$ is partitioned based on Eqs. (4) and (5), this in turn produces a higher potential transpiration (EP_o). Although the overall ET rate changes little, more of ET is partitioned into crop water needs so Eqs. (6) and (7) will introduce more stress into the model, thus decreasing yield and leaf expansion. By definition, Eq. (3) limits the K_c to values greater than 1, which in turn simulates excessive demand for a crop with less than full canopy. Eq. (8) with the dynamic K_{CD} is an attempt to remedy this issue.

Values of KEP, the extinction coefficient for partitioning $E0$ into EP_o and EP_r, were varied from the baseline run of 0.685 to lower values of 0.605, 0.524, and 0.444. Both Sau et al. (2004) and López-Cedrón et al. (2008) recommend lowering KEP to around 0.5. Effects on full irrigation were minimal (Fig. 4) as expected. Since full irrigation management met the ET demand of the crop, no stress was invoked resulting in no change from baseline for yield or maximum LAI. Because shifting KEP downward changes the partitioning, a smaller amount of transpiration is apportioned to ET. However, because full irrigation has such high LAI, the differences between KEP values were minimal (e.g., a 1.9% decrease by changing KEP from 0.685 to 0.444).

There was minimal response in ET (<0.5%) to changes in KEP for the limited irrigation treatment (Fig. 4). On the other hand, there were substantial increases in yield and LAI due to decreases in KEP. As KEP is reduced (Eqs. (4) and (5)), partitioning of $E0$ results in lower potential transpiration (EP_o). Because this demand is more easily met, the ratio of EP_r/EP_o will be higher and water stress functions (Eqs. (6) and (7)) will be less severe, resulting in less yield and LAI reduction. For example, changing KEP from 0.685 to 0.524 resulted in a 10.2% increase in yield and a 6.9% increase in maximum LAI.

3.2. Dynamic K_{CD} as a function of LAI

The dynamic K_{CD} was evaluated by using values of $K_{cmin} = 0.3$, $K_{cmax} = 1.2$, and $SK_c = 0.8$, as well as changing KEP from 0.685 to 0.5 (Eqs. (4) and (5)). Full irrigation treatment data from 2008 is used in Fig. 5 to show the functionality of the new equation. The previous version of CERES-Maize has the K_{CS} value hard-coded at 1.0 for the entire growing season; even by changing K_{cmax} then K_{CS} would still be greater than 1.0 at all times (Eq. (3)). Eq. (8) allow for a dynamic K_c (K_{CD}) as a function of leaf canopy. Beginning at planting, the K_{CD} for both irrigation treatments was near K_{cmin} (or 0.3) for several weeks (Fig. 5). A typical K_c curve from FAO-56 (Allen et al., 1998) is shown for comparison purposes (dashed line). It is encouraging to see that the modified K_{CD} curve for the non-stressed full irrigation treatment follows the FAO-56 K_c curve extremely closely through most of the growing season. In the full irrigation treatment, the crop is irrigated to meet ET demand, which, as can be seen in Fig. 5, meets non-stressed values proposed by FAO-56. At the end of the season, the K_{CD} curve does not drop as much as the FAO-56 curve, indicating that crop senescence may be underestimated by the model; however, the late season evaporative demand (roughly September and later) is less than the mid-season demand, so the difference in these curves would have a small effect on cumulative seasonal ET values. For comparison purposes, K_{CD} is also shown for the limited irrigation treatment, indicating the lower ET demand computed as a result of smaller LAI values.

In the context of this model and Eq. (8), K_{CD} will be mathematically limited to low values during the early season and under water stress (i.e., small or reduced canopy). This relationship essentially assumes that the soil surface is not wet and does not directly account for differences in soil evaporation when the soil is irrigated or receives rainfall, where K_c as defined by Allen et al. (1998) would in that circumstance be greater than indicated by the dashed line in Fig. 5. However, in such cases where irrigation or rainfall is added to the water balance, CERES-Maize model ET demand will be met more easily, minimizing water stress and LAI reduction, thus calculating more ET over the course of the season as had been without the rainfall.

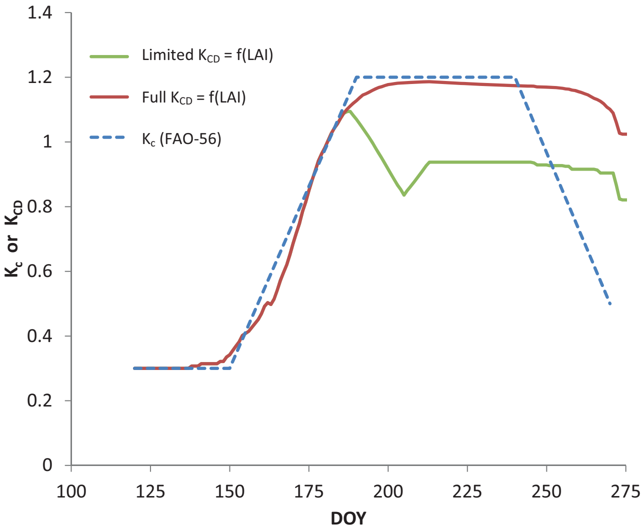

Fig. 5. Crop coefficient curve K_{CD} for potential evapotranspiration (ET) in full and limited irrigation treatments (2008) as a function of leaf area index (LAI), found by Eq. (8) using $K_{cmin} = 0.3$, $K_{cmax} = 1.2$, and $SK_c = 0.8$. For comparison purposes, a crop coefficient curve from FAO-56 is also shown (Allen et al., 1998).

While one purpose of the dynamic K_{CD} variable was to compute more accurate cumulative ET over the course of a season, it was also capable of determining more logical amounts of daily ET during certain growth stages. The 2008 dataset was used to show the daily ET simulation ratio, or the ratio of simulated ET under limited irrigation to simulated ET under full irrigation (Fig. 6). In both the original and modified CERES-Maize models, the ET ratio was near 1 toward the beginning of the season because the only difference between irrigation treatments at this point is the initial soil water which was quite similar. The beginning of the differences in irrigation treatments is more apparent when the ET simulation ratio becomes less than 1 (i.e., when the limited irrigation treatment is given less irrigation water). In both treatments, this ratio is reduced further, to around 0.2 as the water deficit under limited irrigation increases. Up until this point, the original CERES-Maize model behaves in a sensible manner. However, near late July (the beginning of the reproductive growth) both treatments received large amounts of water to meet ET demand. In the original model, the ET demand was generally the same in both irrigation treatments because K_c was always 1.0, so the ET simulation ratio was near 1 during this time of high watering. However, it is logical that a crop with reduced LAI (limited irrigation) would have less ET than a crop with greater LAI (full irrigation). With the dynamic K_{CD} improvement, the modified model simulates the ratio of limited irrigation ET to full irrigation ET at a maximum of (and often below) about 0.85 during the reproductive growth stage. This example shows how overall ET simulation in CERES-Maize under water stress is different using the dynamic K_{CD} function, especially in the reproductive growth stage.

The original and modified CERES-Maize models were run for all years (2006–2010) with both full and limited irrigation treatments. Simulated yield, cumulative ET, and WP for the modified model

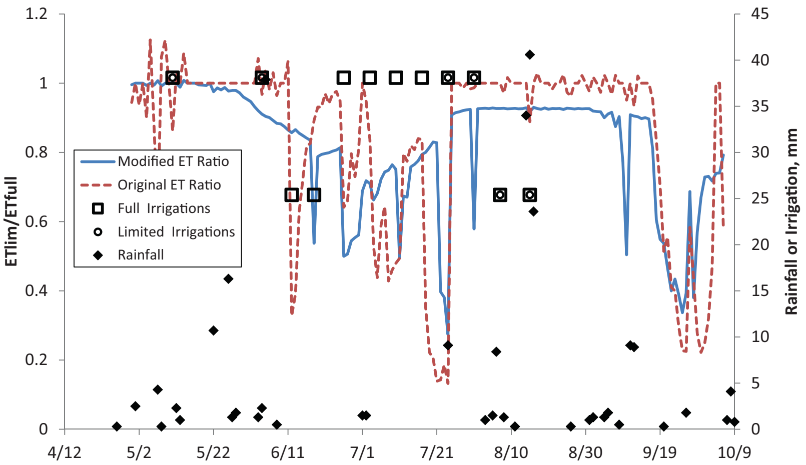

Fig. 6. Ratio of 2008 simulated evapotranspiration (ET) under limited irrigation to simulated evapotranspiration (ET) under full irrigation, for original and modified versions of model (left axis). Points mark individual irrigation and rainfall events (right axis).

Table 5
Observed and simulated results for yield, evapotranspiration (ET), and water productivity (WP) for full and limited irrigation treatments, using both original and modified versions of the model.

Treatment	Year	Yield ($kg\,ha^{-1}$)			Cumulative ET (mm)			WP ($kg\,ha^{-1}\,mm^{-1}$)		
		Observed	Original simulated	Modified simulated	Observed	Original simulated	Modified simulated	Observed	Original simulated	Modified simulated
Full	2006	11,107	11,373	11,373	553	561	556	20.1	20.3	20.5
	2007	11,670	9810	9810	556	587	526	21.0	16.7	18.7
	2008	10,863	12,733	12,727	650	679	608	16.7	18.8	20.9
	2009	10,755	8659	8659	527	596	512	20.4	14.5	16.9
	2010	12,307	12,724	12,723	651	621	582	18.9	20.5	21.9
	Mean	11,340	11,060	11,058	587	609	557	19.4	18.2	19.8
Limited	2006	8916	7851	9723	345	402	395	25.8	19.5	24.6
	2007	8484	7378	9436	386	491	454	22.0	15.0	20.8
	2008	10,451	9611	11,628	454	539	518	23.0	17.8	22.4
	2009	8301	6577	6136	481	549	455	17.3	12.0	13.5
	2010	10,129	8896	8426	441	522	465	23.0	17.0	18.1
	Mean	9256	8063	9070	421	501	457	22.2	16.3	19.9

were compared against original model values (Table 5), and statistical comparisons of both model versions were performed against observed data (Table 6). Late planting and cool seasonal weather caused the model, which advances growth stages and accumulates grain biomass based on thermal time, to predict considerably low yields in 2009 (efforts were made to alter default temperature parameters governing grain growth, but no significant changes were obtained).

Simulated yield changed little with modifications to the model under full irrigation, with the mean simulated yield over the five years differing by only 2 $kg\,ha^{-1}$ (Table 5), leading to very little statistical difference between the models (Table 6). Simulated yields under limited irrigation generally increased with the dynamic K_{CD} change, with mean yield increasing by 1007 $kg\,ha^{-1}$. Statistically, yield under limited irrigation had a slightly higher RMSD under the new model as compared with the original model. However, RE improved from −12.9 to −2.0%. Both the original and modified CERES-Maize models simulated higher limited irrigation yields in 2006–2008 while simulating slightly lower yields in 2009–2010.

There were significant improvements in ET estimation for the limited irrigation treatment, as mean simulated ET was lowered from 501 to 457 mm. This was still higher than the observed ET (421 mm) but much improved statistically (RMSD of 80.9 mm for the original model and 49.9 mm for the modified model). Furthermore, RE was reduced from 18.8% to 8.5%. Simulated ET under full irrigation was slightly overestimated for the original model (mean

Table 6
Root mean square deviation (RMSD), normalized objective function (NOF), and relative error (RE) statistical evaluation criteria for original and modified model simulations, both irrigation treatments, and outputs of yield, evapotranspiration (ET), and water productivity (WP).

Evaluation criteria	Treatment	Yield ($kg\,ha^{-1}$)		Cumulative ET (mm)		WP ($kg\,ha^{-1}\,mm^{-1}$)	
		Original simulated	Modified simulated	Original simulated	Modified simulated	Original simulated	Modified simulated
RMSD (output unit)	Full	1523	1521	38.8	39.1	3.45	2.98
	Limited	1229	1451	80.9	49.9	5.97	2.86
NOF (unitless)	Full	0.134	0.134	0.066	0.067	0.178	0.153
	Limited	0.133	0.157	0.192	0.119	0.269	0.129
RE (%)	Full	−2.47	−2.49	3.64	−5.21	−6.53	1.76
	Limited	−12.90	−2.01	18.79	8.54	−26.70	−10.46

of 587 mm observed and 609 simulated, RE = 3.6%), whereas the modified model now slightly underestimates ET (simulated mean of 557 mm, RE = –5.2%). This is likely due to the original model estimating high ET during early vegetative periods with low LAI, whereas with the modified model the ET will be reduced. Statistically, when including 2009 data, there was little difference in simulated ET under full irrigation (RMSD of 38.8 mm for the original model and 39.1 mm for the modified model).

Evett and Tolk (2009) suggest that crop models correctly simulate WP under well-watered conditions, but tend to poorly predict WP under conditions of water stress. As resolution of this issue is a main goal of this study, it is interesting to note the differences in WP averaged among the years (Table 6). Experimental observations indicated that WP under limited irrigation (22.2 kg ha^{-1} mm^{-1}) was higher than under full irrigation (19.4 kg ha^{-1} mm^{-1}). Using the modified model to predict WP under full irrigation, simulated WP value was very close to observed (19.8 kg ha^{-1} mm^{-1}). However, despite statistically improved simulation of WP under limited irrigation, the modified model failed to duplicate the observed increase in WP for this treatment, with simulated WP of 19.9 kg ha^{-1} mm^{-1} being nearly the same as under full irrigation. This was due to a combination of under-predicted yield and over-predicted cumulative ET for the limited irrigation treatment. Many studies indicate potential for higher WP under limited or deficit irrigation, for example Ge et al. (2012) found that while severe water stress can cause significant reductions in maize WP, more minimal levels of water stress can increase WP. If increased WP is physiologically possible under limited irrigation management as observations from this and other studies suggest, future efforts should be made to further improve both yield and ET simulation under limited irrigation conditions with relevant crop models.

When including 2009 data, prediction of WP was slightly improved for full irrigation (RMSD decreased from 3.45 to 2.98 kg ha^{-1} mm^{-1}, RE changed from –6.5 to 1.8%) and significantly improved for limited irrigation (RMSD decreased from 5.97 to 2.86 kg ha^{-1} mm^{-1}, RE changed from –26.7% to –10.5%). Both irrigation treatments had similar RMSD values under the modified model, an overall improvement over the original model where the RMSD was much higher for limited irrigation than for full irrigation.

The NOF statistic is convenient because it divides the RMSD by the observed mean, thus normalizing the value so it can be directly compared between model output responses, treatments, and CERES-Maize model versions. Under full irrigation, NOF statistics indicate ET was the best simulated output response (0.066 and 0.067 for respective original and modified model versions), followed by yield (0.134 for both model versions) and WP where the modified simulation improved NOF from 0.178 to 0.153. NOF statistics indicated more mixed results for the limited irrigation treatment: the original model performance was best with yield (0.133) followed by ET (0.192) and WP (0.269); the modified model performed best with ET (0.119), followed by WP (0.129) and yield (0.157).

3.3. Synthetic water production functions

The new dynamic K_{CD} function was applied to the two observed irrigation treatments, as well as three new hypothetical irrigation scenarios as described in Table 4, and yield was shown as a function of ET (Fig. 7). As discussed previously, CERES-Maize simulations poorly matched 2009 observed data for both treatments because of abnormally cold weather conditions. The 2009 data was therefore omitted from this analysis. Full irrigation, as expected, exhibited both high yield and high ET, whereas limited irrigation exhibited lower values for both yield and ET. The Full, Full Anthesis Only, Stress Anthesis Only, and 50% Full treatments (all treatments but Limited) appear to form the following linear relationship: $\text{Yield}_{\text{kg ha}^{-1}} = 38.85 \times (\text{ET}_{\text{mm}} - 273)$, $R^2 = 0.901$. However, the Limited treatment shown in Fig. 7 is distinctly different from the above linear relationship in three out of four years, indicating that the modified model predicts higher yield for given values of ET when stress occurs at the vegetative growth stage only. This relationship is similar in shape to the experimental water production functions for maize in Turkey found by Çakir (2004), but has a steeper slope (38.85 kg ha^{-1} mm^{-1} ET in the model, as compared with observed slopes of 21.33, 18.09, and 14.48 kg ha^{-1} mm^{-1} ET found by Çakir in three consecutive years). It is likely that water production functions such as these are site-specific and would change with climate, soils, maize variety, etc.

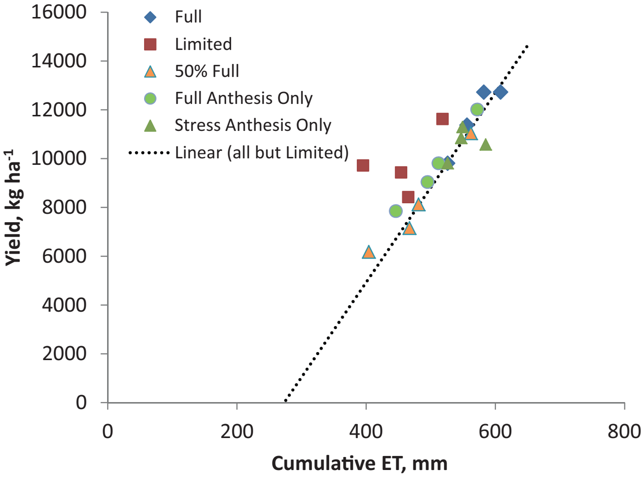

Fig. 7. Model-predicted water production function (WPF) simulations based on two observed irrigation management treatments and three hypothetical treatments, as described in Table 4.

Individual values for yield and cumulative ET were plotted for each "synthetic" limited irrigation treatment (Fig. 8), along with the best fit line from Fig. 7 that represents the linear WPF assumed for other types of management. On average, the plot of the 20 mm treatment (which essentially represents a full irrigation simulation because there is minimal resultant stress) lands very near the line of the WPF. However, under this limited irrigation management

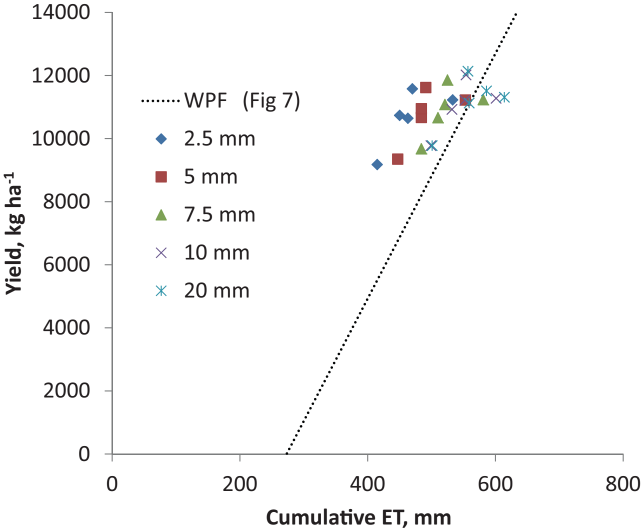

Fig. 8. Water production function (WPF) simulations using hypothetical limited irrigation treatments. Dotted line taken from WPF line defined by Fig. 7. Treatment name in legend indicates weekly irrigation amount during the vegetative stage (mm). No water stress occurred during the reproductive stage for any treatment.

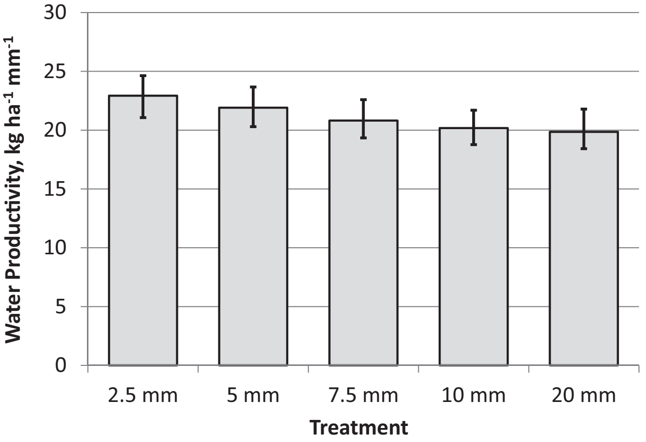

Fig. 9. Mean simulated water productivity (WP = yield/ET) for varying synthetic treatments, indicating weekly water input during the vegetative growth stage. Error bars indicate minimum and maximum values from the five years simulated.

strategy the CERES-Maize model predicts that significant savings in ET can occur with minimal losses to yield. As each treatment applies less water there is a slight drop in yield; however, ET is reduced relatively more, creating points that are above the linear water production function curve. The potential for separate ET–yield relationships can be visualized for the individual irrigation treatments (except for the 2005 year that had higher ET than the others). As less irrigation is applied to the vegetative growth stage, the potential ET–yield relationships appear to shift more to the left (i.e., there is less ET while retaining high yields). WP (Fig. 9) is also shown, indicating that treatments with less water applied during the vegetative stage have a higher WP as well. Further use of the CERES-Maize model in comparison with limited irrigation experiments is needed to verify these relationships, with rain-out shelters or greenhouse experiments suggested to maintain control of the water balance by preventing natural rainfall.

4. Conclusions

As previous efforts to use the CERES-Maize crop model ET under water stress have provided less than satisfactory results (e.g., DeJonge et al., 2011), this study evaluated and improved ET simulation under water stress while not negatively impacting other model processes. Local sensitivity results from this study showed that under full irrigation, increasing $K_{c\max}$ could increase predicted cumulative ET, but under limited irrigation increasing $K_{c\max}$ led to significantly decreased predicted yield and vegetative growth with no change in ET. We recommend changing the default value of KEP from 0.685 to 0.5, as also suggested by López-Cedrón et al. (2008) and Sau et al. (2004). Both of these studies suggest that accurate simulation of output responses (namely yield and ET) becomes an increasing complicated endeavor when water stress is introduced, and CERES-Maize water balance components may need adjustments to become more robust.

While previous methods for evaluating ET using a static crop coefficient (i.e., K_{CS}) have worked well for studies under non-stressed water conditions, few studies have emphasized ET accumulation under water stress. Because a stressed crop will usually have a smaller leaf area than a non-stressed crop, the ET demand and subsequent actual ET will often be less. Therefore, our new equation that calculates a dynamic crop coefficient (K_{CD}) as a function of LAI results in a crop coefficient relationship that very closely correlates to that suggested by FAO-56 (Allen, 1998) under full irrigation. The new dynamic K_{CD} model modification vastly improved ET estimation under limited irrigation, thereby significantly reducing WP error under limited irrigation (and full irrigation as well). New “synthetic” simulations indicate that the modified CERES-Maize crop model predicts that higher WP of corn can be obtained through limited irrigation management where the crop is water stressed during the vegetative growth stage, and where there is no stress during or following anthesis. The results further suggest that development of new hybrids with higher potential water productivity should consider separately the effects of water stress during vegetative and reproductive growth stages. As knowledge about water stress improves, especially in terms of plant physiologic responses, the dynamic K_{CD} and KEP modifications should be incorporated into new versions of DSSAT models.

While not an easy proposition, the ability of CERES-Maize and other DSSAT models to further improve crop response prediction to limited water, especially in regard to ET, could be again strengthened by working toward more physically and physiologically based model processes. Such model enhancements could be based on stomatal conductance and other parameters that are inputs to physically based ET models. Increased multidisciplinary collaboration between model programmers, field experimentalists, and plant physiologists will be necessary to carry out such an endeavor. It is likely that increases in WP as described herein may not be attainable in every year under limited irrigation management, as there is inherent variability and randomness in precipitation and other weather patterns that will ultimately dictate final yield and ET. For example, in a season with a wet spring and little potential to apply water stress during the vegetative stage, there may not be the opportunity to reduce ET during the early growth stages. It may be desirable to compare a more controlled physiological experiment to CERES-Maize using a rainout shelter and/or greenhouse tests.

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