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Fitting measured evapotranspiration data to the FAO56 dual crop coefficient method

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Abstract. The FAO-56 publication of the UN Food and Agriculture Organization contains guidelines on constructing and applying a 'dual crop coefficient' method to characterize the behavior of evapotranspiration (ET) on a day to day basis. The dual crop coefficient (K_c) method substantially improves the ability to fit simulated with measured data, as compared to the 'single' K_c method, by partitioning evaporation from soil (Es) from transpiration from vegetation. This permits the separate estimation of Es when there are known wetting events from precipitation and irrigation and assists in explaining behavior of measured data. The application of the dual K_c method is relatively straight forward, especially when applied using the straight-line segment method for the basal K_c curve, K_{cb}. Illustrations are given on fitting the dual K_c method and K_{cb} curve to daily ET data for irrigated and rainfed corn crops near Mead, Nebraska measured by eddy covariance and sensitivity to various soil and root zone parameters. Assessment of transferring K_{cb} curve parameters to other fields and years indicates that soil and root zone parameters are relatively transferrable with little modification, whereas lengths of the four crop growth stages do vary from year to year due to differences in cultivar type and possibly differences in weather.

Keywords. *Evapotranspiration, Consumptive Use, Irrigation water requirement, evaporation, reference evapotranspiration, crop coefficient.*

Introduction

The crop coefficient x reference ET method has proven to be a successful and practical method for estimating daily evapotranspiration (ET) for irrigated and rainfed crops. The crop coefficient (K_c) having a basis of reference crop ET_{ref} was clarified in 1968 (Jensen 1968) and was first used in a computerized irrigation scheduling program (Jensen 1969; Jensen et al. 1970; Jensen et al. 1971). Numerous publications over the past decades have focused on measuring ET and calculating associated crop coefficients. Various ET measurement methods have been used, including eddy covariance, Bowen ratio, lysimeters and remote sensing. The primary factor causing an increase in the crop coefficient is an increase in plant cover or leaf-area per unit area (LAI) as the crop develops, resulting in a decrease in bulk surface resistance. Most publications on crop coefficient 'curves' have presented the K_c as a function of some form of absolute or scaled time-basis.

When applying the standardized reference ET equation under humid conditions, where a majority of energy for the ET process is from net radiation, the K_c for large expanses of similar vegetation does not usually exceed about 1.0 to 1.1 relative to the alfalfa reference and about 1.2 relative to the grass reference. In dry climates, where additional advection of warm dry air can occur to increase ET from irrigated surfaces, the K_c still does not exceed about 1.0 to 1.1 relative to the alfalfa reference but can reach maximum values of about 1.3 to 1.4 relative to the grass reference. The reason for the near constant 1.0 to 1.1 crop coefficients for the alfalfa reference is that the alfalfa reference crop has about the same albedo, leaf-area-index (*LAI*) and roughness as most agricultural crops at full cover and therefore converts similar amounts of radiant energy and sensible heat to vapor transfer. An expanse of reference crop (especially alfalfa) will approach the maximum conversion of available energy into latent heat, λE, so that the ratio of λE for any other tall, leafy crop to alfalfa λE will be near 1.0. This observation is born out in viewing the maximum values for K_c reported by Wright (1982), where none of Wright's K_c's, based on the alfalfa reference, exceed 1.05 when averaged over weekly or longer periods. In the case of the grass reference, where the vegetation is shorter and *LAI* may be less, values for K_c may approach 1.3 for tall, dense crops under arid and semiarid conditions (Doorenbos and Pruitt 1977; Allen et al. 1998).

The dual K_c method (Wright 1982, Allen et al., 1998) parses the K_c into a basal K_{cb} value that represents primarily the transpiration component of ET plus a small evaporation component from soil that is visually dry at the surface and a soil evaporation value, K_e,that represents primarily evaporation from exposed soil. The application of the dual K_c procedure requires adjustment for wet soil effects after rain or irrigation, but results in more accurate estimates of ET_c on a daily basis for use in soil water modeling and irrigation scheduling than using mean coefficients in which the effects of local rainfall or irrigation frequencies must be implicitly included. The total crop coefficient, K_c is computed from K_{cb} as:

$$K_c = K_s K_{cb} + K_e \qquad (1)$$

where K_s is a dimensionless coefficient dependent on available soil water and K_e is a coefficient to adjust for increased evaporation from wet soil immediately after rain or irrigation. The value for K_s is 1 unless available soil water limits transpiration, in which case it has a value less than 1. Potential ET_c is estimated as $ET_c = K_c\ ET_{ref}$ when K_s in eq. 1

equals 1. The values for K_e represent the "spikes" shown in fig. 1. Estimation of K_e for bare soil conditions is described in Allen et al., (1998, 2005) and Allen (2011) via the FAO-56 K_e model:

$$
\begin{aligned}
&K_e = K_r\,(K_{c\max} - K_s K_{cb}) \\
&such\ that \\
&K_e \le f_{ew}\ K_{c\max}
\end{aligned}
\qquad (2)
$$

where K_e is the soil evaporation coefficient, K_{cb} is the basal crop coefficient, $K_{c\ max}$ is the maximum value of K_c following rain or irrigation, K_s is a reduction coefficient to account for reduced transpiration under soil water shortage, K_r is a dimensionless evaporation reduction coefficient [0-1] and K_s is a dimensionless soil water stress factor [0-1]. f_{ew} is the fraction of soil wetted by an irrigation or precipitation event [0-1]. During the falling rate stage, where $D_e > REW$, the evaporation rate is estimated in proportion to the amount of water remaining in the surface soil layer, and K_r is calculated as:

$$
K_r = F_{stage1} + \left(1 - F_{stage1}\right)\max\left(\min\left[\frac{TEW - D_{e(i-1)}}{TEW - REW}, 1.0\right], 0.0\right) \qquad (3)
$$

where $D_{e(i-1)}$ is the cumulative depth of evaporation at the end of timestep (i – 1), representing the previous timestep and $F_{stage\ 1}$ is the fraction of the time step (day or hour) that resides in stage 1 evaporation. 1- $F_{stage\ 1}$ of the timestep resides in stage 2. The use of $F_{stage\ 1}$ is an extension to the original FAO-56 model (Allen et al. 2011) to provide better definition of the transition from stage 1 to stage 2 drying during a timestep and provides a more accurate, averaged value for K_r during that transition timestep. TEW is total evaporable water, mm, from the top soil 'slab' and REW is readily evaporable water, mm from the same slab, as defined in Allen et al., (1998) and Allen (2011).

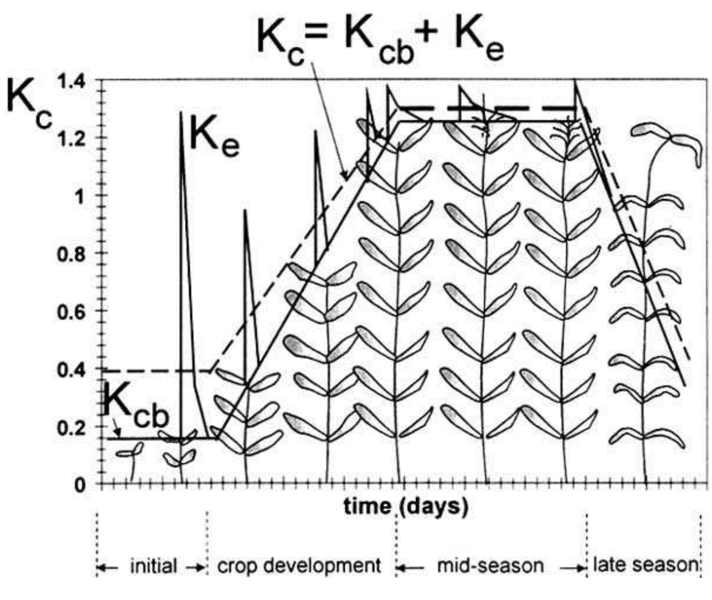


Figure 1. Schematic of the FAO-56 style dual K_c procedure showing the basal K_{cb} curve, evaporation (K_e) spikes over time.

$K_{c\ max}$ is used in eq. 2 to estimate the maximum value for K_c following rain or irrigation, under conditions of either bare soil or some degree of vegetation cover. The value for $K_{c\ max}$ is governed by the amount of energy available for evaporation of water, which is largely encapsulated by reference ET_{ref}. Because K_c is the ratio of ET to ET_{ref}, the value for $K_{c\ max}$ is not expected to exceed 1.0 to 1.3. $K_{c\ max}$ for the tall reference ET_r is estimated as (Allen et al., 2011):

$$K_{c\ max\ r} = \max\left(K_{c\ max\ bare}, \{K_{cbr} + 0.05\}\right) \tag{4}$$

where K_{cbr} denotes a basal K_{cb} used with the tall reference, ET_r. and $K_{c\ max\ bare}$ is the maximum K_c expected for bare, wet soil. That value is often set to 1.0 for use with the tall reference. Eq. 4 requires that $K_{c\ max}$ is greater than or equal to the sum K_{cb} + 0.05, suggesting that wet soil increases the K_c value over K_{cb} by about 0.05 following complete wetting of the soil surface, even during periods of full ground cover. In the analyses of this paper, the value for $K_{c\ max\ bare}$ was varied to evaluate sensitivity.

The purpose of this paper is threefold: 1) Illustrate the capability of the dual K_c method to simulate measured daily ET for corn crops in eastern Nebraska in a relatively consistent, accurate and straight forward manner; 2) illustrate the process of fitting basal K_{cb} curves and soil parameters relevant to the dual K_c procedure to measured data and the relative sensitivity of estimates to these parameters; 3) recommend dual K_c settings for midwestern corn crops based on the ASCE Penman-Monteith tall reference crop.

Materials and Methods

Daily ET measurements were obtained for three field sites near Mead, Nebraska operated by the University of Nebraska as part of long term ET, energy balance and carbon sequestration studies (Suyker and Verma 2008). The fields are located within 1.6 km of one another at the University of Nebraska Agricultural Research and Development Center and are instrumented with eddy covariance systems and other support equipment (Suyker and Verma 2008). Two 64 ha fields (sites 1 and 2) are irrigated with center pivot systems and the third 64 ha field (site 3) relies on rainfall, only. The fields employ minimum tillage operations, where a disking was done in 2001 to homogenize the top 0.1 m of soil, incorporate P and K fertilizers and previously accumulated surface residues. Between 2001 and 2005, the sites were under no-till management (Suyker and Verma 2008). Additional tillage was conducted in 2005 to incorporate excess organic mulch. The crops in the fields are under a corn and soybean rotation for two sites and a continuous corn rotation for a third field. Years 2003, 2005 and 2007 had corn grown in all three fields, and were therefore selected for analysis.

The soil type of the area is a deep silty clay loam comprised of Yutan (fine-silty), Tomek (fine), Filbert (fine) and Filmore (fine) (http://ameriflux.ornl.gov/fullsiteinfo.php?sid=74). The fields have gentle slopes, with general location of 41.18º N, 96.44º W, and elevation of 360 m. The area is relatively windy during April and May, with wind speed at 3 m averaging 3-5 m s^{-1}, and is relatively calm during June – August with wind speeds averaging 2 m s^{-1} or less.

Eddy covariance systems were used to determine measurements of latent heat (LE), sensible heat (H), and momentum fluxes using an omnidirectional three dimensional sonic anemometer (Model R3: Gill Instruments Ltd., Lymington, UK) and an open-path infrared CO2/H2O gas analyzing system (Model LI7500: Li-Cor Inc., Lincoln, NE) (Suyker and Verma 2008). The eddy covariance sensors were mounted 3 m above the ground when the crop canopy was shorter than 1 m, and later moved to a height of 6 m until harvest when over maize taller than 1 m. Soil heat flux was measured using REBS HFT3 plates buried at 0.06 m, with measurements adjusted to the surface. Fluxes were corrected for inadequate sensor frequency response (Moore, 1986; Massman, 1991; Suyker and Verma, 1993) in conjunction with cospectra. Fluxes were adjusted for the variation in air density due to the transfer of water vapor and sensible heat (e.g., Webb et al., 1980). More details of the measurements and calculations are given in Suyker et al., (2003). Suyker and Verma (2008) described the filling of missing data gaps, primarily using regression of H and LE against available energy.

Prior to use, eddy covariance data were assessed for closure of the energy balance by computing ratios of $(\lambda E + H)$ to $(R_n - G)$ on a 24-hour timestep, where H is sensible heat flux determined from the EC system, R_n is net radiation and G is soil heat flux density. λE was then adjusted by multiplying by $(R_n - G) / (\lambda E + H)$ for each day. The adjustments averaged about 10 to 18% upward adjustment for all three sites and years, similar to that found by Suyker and Verma (2008).

In 2003, maize Pioneer variety 33B51 was planted May 13, 14, 15 on sites 1, 2 and 3, and harvested October 27, 23 and October 13 for sites 1, 2 and 3. Planting populations were 77,000, 78,000 and 58,000 plants ha^{-1} for sites 1, 2 and 3 and nitrogen applications were 233, 169 and 90 kg N ha^{-1}. Grain yields were 12, 14 and 8 MG ha^{-1} (Suyker and Verma 2008). Measured leaf area index, LAI, reached 3 $m^2 m^{-2}$ on about June 30, 2003, and reached 5 on about July 7, with a peak of 5.5 for the two irrigated sites. LAI began declining about August 20 and declined to 1 on about October 5, 2003. Maximum LAI was 4.3 for the rainfed site. Planting dates and densities were similar in 2005 and 2007. In 2005, LAI reached a maximum of about 5 for the two irrigated sites and 4.3 for the rainfed site. Planting dates in 2005 were May 4, May 2 and April 26 for sites 1, 2 and 3. Harvests were October 12, 17 and 17. Planting dates in 2007 were May 1, 2 and 2.

Eddy covariance data from the three Mead sites were downloaded from the Mead Ameriflux sites maintained by the University of Nebraska in conjunction with the Oak Ridge National Labs and Ameriflux system, for example, ftp://cdiac.ornl.gov//pub/ameriflux/data/Level1/Sites_ByName//Mead_Irrigated_Rotation/. Daily weather data for computing reference ET were downloaded from the Univ. Nebraska High Plains Regional Climate Center (HPRCC). Those data were quality assessed using standard screening procedures of ASCE (2005) and daily solar radiation, R_s, was adjusted using a theoretical clear sky curve as a basis. Adjustments to R_s required as much as 10% upward adjustment, which impacted calculations for ET_r. Reference ET_r was calculated using daily timesteps using the ASCE Penman-Monteith method for a tall reference crop (alfalfa). Because the HPRCC does not report daily mean vapor pressure or dewpoint temperature, but rather daily mean relative humidity, daily mean vapor pressure was computed from hourly weather data from the HPRCC and was entered into the ET_r calculations.

The Crop Coefficient Spreadsheet and Procedure

A spreadsheet published in 1998 with FAO-56 and available at web site http://extension.uidaho.edu/kimberly/2013/04/spreadsheets-supporting-fao-56-example-calculations/ was utilized in this study, with the following modifications:

1. The K_c basis was converted to an alfalfa (tall reference) basis rather than the original grass reference basis.
2. The spreadsheet was modified to link to daily ET data based on the Mead eddy covariance measurements
3. Graphical summaries were updated.

Figure 2 shows a screenshot of the spreadsheet where colored areas are primary places where parameters are specified regarding the lengths and magnitude of the linear K_{cb} curve and parameters describing soil and rooting properties.

Procedure for fitting daily simulated K_c to measured values.

The procedure for fitting the simulated K_c to measured values was as follows:

1. Linking of data columns to daily reference ET, precipitation, ET measurements and documented irrigation dates.
2. Calculating 'measured K_c' by dividing measured ET, following adjustment for energy balance closure, by daily reference ET.
3. For a presumed midseason K_{cb} of 1.05 and beginning and ending K_{cb} values of 0.15, fitting the K_{cb} curve to the measured K_c data for the two irrigated sites by adjusting the four "L" stage length values.
4. Adjustment of the K_{cb} value for midseason based on measured K_c.

   Data from irrigated sites were used to determine best stage lengths and value for the midseason K_{cb} since there was generally little or no stress for the irrigated fields. The rainfed data exhibited substantial stress and therefore could not be used as a consistent target.

The spreadsheet simulated total ET using the $K_c = K_s K_{cb} + K_e$ procedure and automatically updated with changes in parameters, with values for K_c reflecting documented irrigation and precipitation depths.

Following establishment of stage lengths of K_{cb} that tended to reproduce measured K_c, K_c was simulated for actual $K_c = K_s K_{cb} + K_e$ for the rainfed EC treatment using a similar value for K_{cb} and stage lengths fitted to the irrigated treatment. In addition, values for beginning and ending rooting depths, initiation of root development and attainment of maximum values and values for management allowable depletion for the initial period and other periods were established through a trial-and-error process that noted the visual fit of daily K_c vs. measured K_c as well as error statistics between simulated and measured. The value for available water (AW) was calculated from field capacity and wilting point based on the general soil and estimated to be 170 mm m^{-1}. A simple, linear root growth rate was used in the simulations, with the start of effective growth and duration of that growth being the two parameters required. Prior to start of effective root growth, a minimum specified rooting depth was applied.

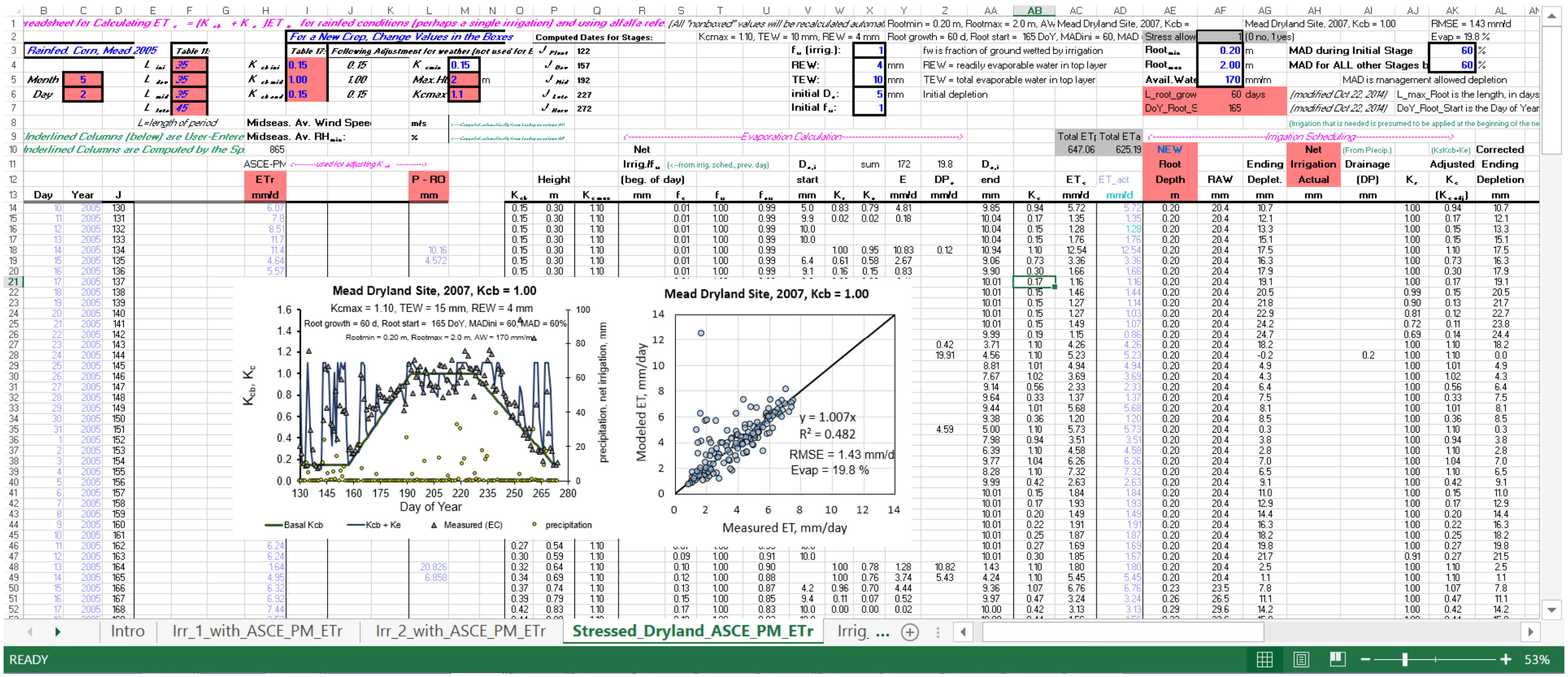


Figure 2. Screen shot of the daily dual K_c spreadsheet used to fit the dual FAO-56 K_c procedure to measured ET data based on an alfalfa reference basis. The two figures in the spreadsheet are repeated later in this paper with larger scale.

Sensitivity analyses were conducted on what are considered to be the more uncertain, but important parameters in the dual K_c application to gain familiarity with the response of the simulations to their values and to assess to what degree the values specified for parameters helped to reproduce ET measurements. These parameters included the K_{cb} for midseason, K_{cmax}, TEW, REW, maximum rooting depth, time to develop maximum rooting depth, MAD and available water holding capacity of the soil. As one might expect, with the eight parameters having varying values, there were a number of combinations that produced similar outcomes. However, the analyses helped to identify what can be considered to be central values for the best performing parameters.

Parameters having the most impact on simulations and fit to measurements for the irrigated fields were a) lengths of growing periods and b) TEW and REW. For the dryland treatments, results were substantially impacted by values for rooting depth, MAD, and dates for start and end of root growth. These three parameters impact the timing and magnitude of the soil water reservoir available to the crop. Values for rooting depth and MAD had little effect on simulations for the irrigated treatments since those treatments held water above MAD levels. The value for K_{cb} during midseason did not generally impact simulation results, especially for the irrigated treatments since an increase or decrease in $K_{cb\ mid}$, given a constant value for Kc max, typically changed the partitioning of E and T with little change in total ET. This occurred since the irrigations by center pivot were frequent enough to keep soil surface water contents at relatively high levels and therefore, values for K_e near maximum. This phenomenon makes it difficult to establish a basal K_{cb} value for the midseason period and the sensitivity analyses reinforced this, as well as reinforcing the value of using the dual K_c approach to simultaneously parse measured ET into E and T while determining best parameters for the simulations.

For background, FAO-56 tables for K_{cb} for corn are 1.15 for the midseason for a grass based reference, example growth stage lengths are 30/40/50/50 days for a northern, temperate climate and maximum rooting depth is estimated as 1.0 to 1.7 m, with MAD = 55%. Wright (1982) suggested a maximum K_{cb} value for corn of 0.96, when converted to the ASCE Penman-Monteith basis for the tall (alfalfa) reference.

Results and Comments on Results

A large number of sensitivity analyses were done and are expressed in the form of side-by-side graphics showing, on the left, the day by day simulation (blue line) and measured K_c values (tan triangles), and on the right, a scatter plot of daily ET from the simulation vs. daily measured ET by eddy covariance. The scatter plots also contain slope of regression through the origin, R^2, root mean square error (RMSE), and an estimate of the fraction of total ET that occurred in the form of evaporation. The latter was calculated by taking the ratio of $K_e\ ET_r$ to $K_c\ ET_r$ when summed over the growing season. A standard period length of May 10 to September 21 was used in computing statistics during the growing season, for consistency.

Because of the large number of sensitivity runs, the resulting graphics are presented in a sequence of figures showing clusters of simulation results, and with comments preceding each figure. The large number of graphics are presented to illustrate the relative sensitivities of the simulations to various parameter values.

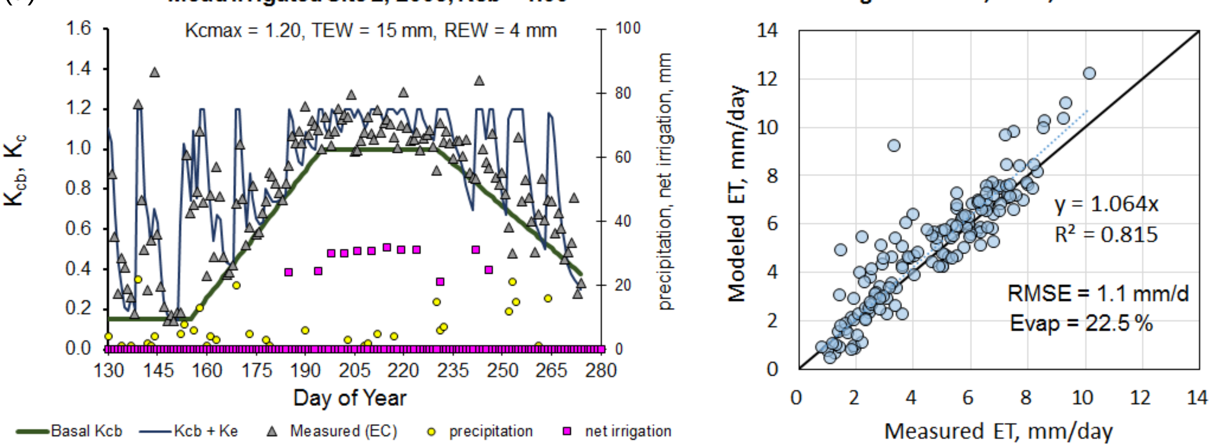
The following sequence of results begins with year 2003 and site 2, which is an irrigated site, and using ASCE PM-based alfalfa reference ET following adjustment of solar radiation based on QAQC analyses as recommended in ASCE (2005). The value for K_{cmax} was initially set to 1.20, which is a relatively high value, and stronger than generally recommended in practice. The 1.20 value was selected to cause simulated K_c on 'wet' days to reach many of the 'measured' K_c values during midseason. Values for TEW and REW were set to 15 mm and 4 mm to reflect the impact of organic mulch on the surface in reducing total evaporable depths during stage 1 and stage 2. Sensitivity analyses were performed on these parameters during later steps.

Values for growth stage lengths were visually fitted so that the linear K_{cb} segments just bounded the lower measured K_c values. Values for the four stages, in days are:

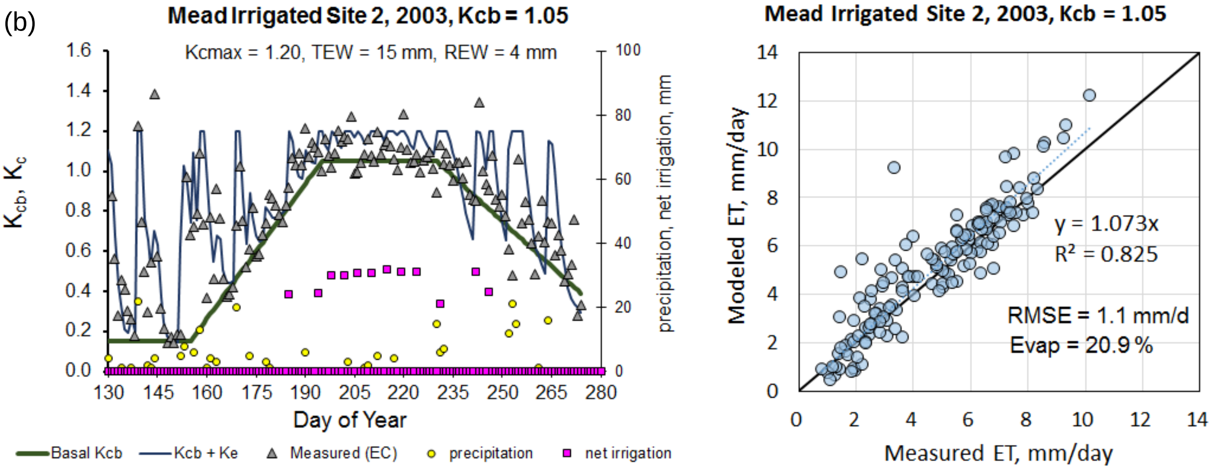
L_{ini}	***30***
L_{dev}	***35***
L_{mid}	***35***
L_{late}	***50***

Figure 3a-e show results for a progression of $K_{cb\ mid}$ values of 1.00, 1.05, 1.10 and 1.15 as well as 0.95. As noted previously, the change in K_{cb} had little impact on statistics, due to the tendency of the K_{cmax} value of 1.20 to absorb the change in K_{cb} when the simulation indicated water in the evaporation layer due to rain or irrigation. Increases in $K_{cb\ mid}$ resulted in reductions in K_e and reductions in percentages of estimated evaporation. This essentially ‘transferred’ evaporation during the partitioning of ET into transpiration. Visually, the $K_{cb\ mid}$ = 1.0 tended to undergird the measured K_c values, whereas, $K_{cb\ mid}$ = 1.05 allowed some measured K_c values to lie below the K_{cb} curve, but within the range of likely error in measurements. $K_{cb\ mid}$ = 0.95 (Figure 3e) left some ‘space’ between the K_{cb} curve and the lowest measured K_c’s during midseason.

(a)



(b)



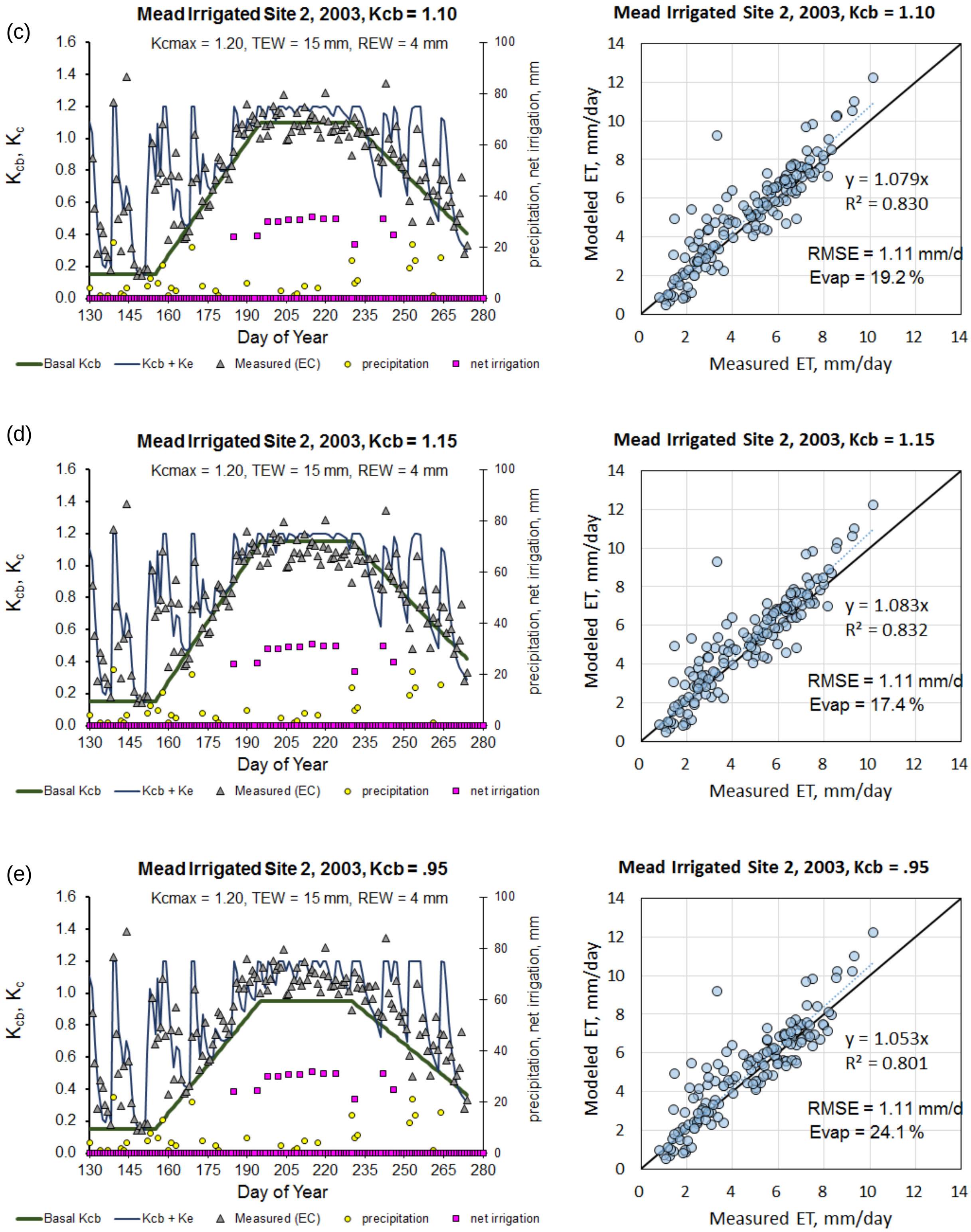


Figure 3. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 2 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for (a) K_{cb} = 1.00, (b) K_{cb} = 1.05, (c) K_{cb} = 1.10, (d) K_{cb} = 1.15 and (e) K_{cb} = 0.95.

Figure 4 shows three sets of graphics that illustrate impacts of reducing the value for K_{cmax} from 1.20 to 1.10 and 1.15, for values of K_{cb} of 1.00 and 1.05. The reduction of K_{cmax} from 1.20 to 1.10 reduced the slope of the scatter plot by about 5% due to lowering of midseason maximum values for simulated K_c. RMSE was reduced to below 1 mm/day.

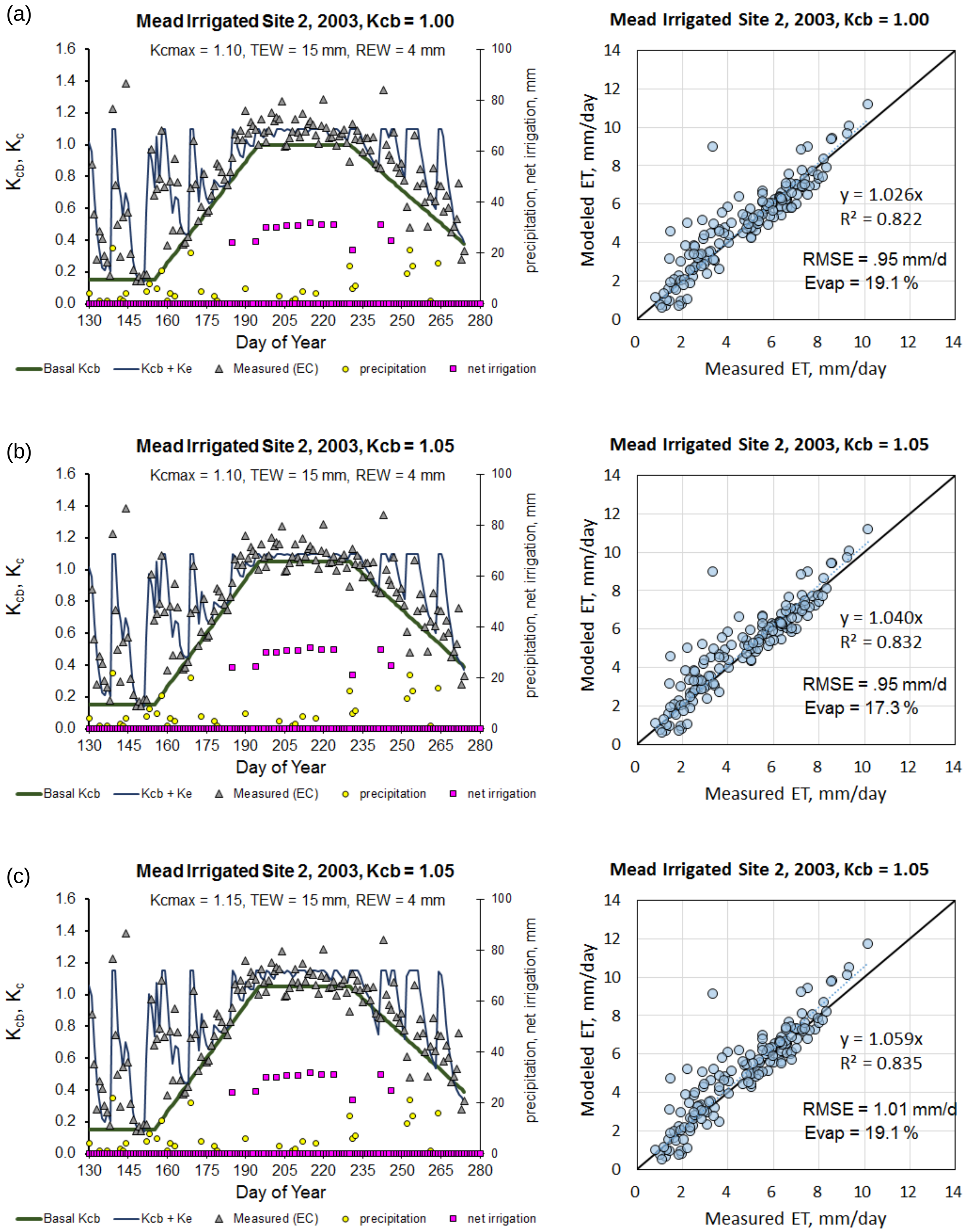
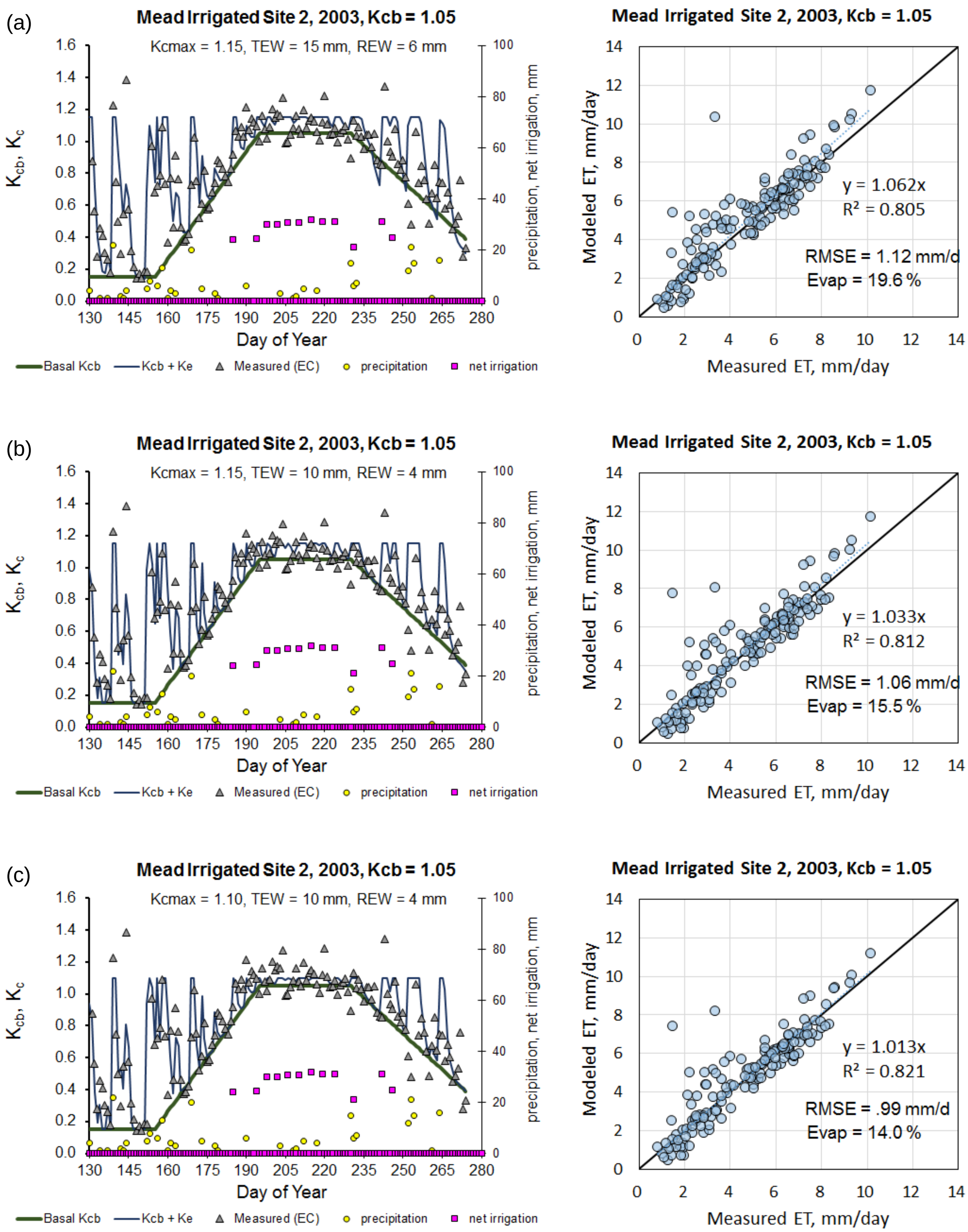


Figure 4. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 2 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for (a) K_{cmax} = 1.10 and K_{cb} = 1.00, (b) K_{cmax} = 1.10 and K_{cb} = 1.05, and (c) K_{cmax} = 1.15 and K_{cb} = 1.05.

The set of 6 graphs in Figure 5 illustrates sensitivity analyses on values for TEW and REW, for values of K_{emax} = 1.15 and 1.10, and TEW and REW set to 10 mm and 6 mm, respectively, in various combinations and for $K_{cb\ mid}$ = 1.00 and 1.05.

Overall, simulation error tended to be smallest with TEW = 15 mm, REW = 4 mm and K_{emax} = 1.00 and $K_{cb\ mid}$ = 1.0, even though the K_{cmax} = 1.00 tended to cause simulated K_c during midseason to underestimate some measurements. Those EC measurements, however, contain some random error components, so that some underestimation relative to up to one-half of all measurements should be expected, in proportion to the expected magnitude of random measurement error. Equation 2 for K_e adds 0.05 to K_{emax}, which causes the total K_c to exceed K_{emax}, even when K_{emax} is set to 1.0. This tended to cause the total simulated K_c to follow measured K_c more closely on some of the higher K_c days.



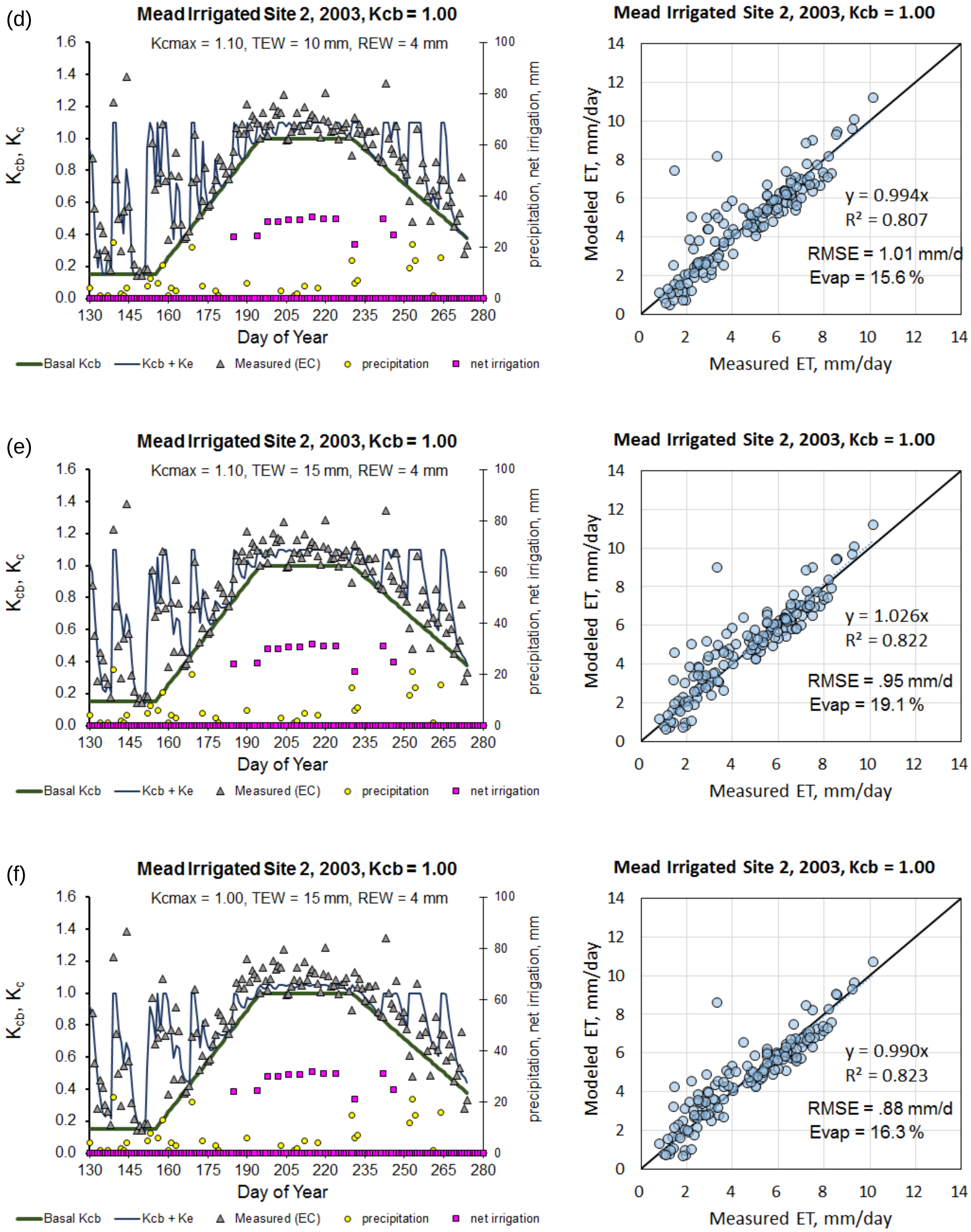
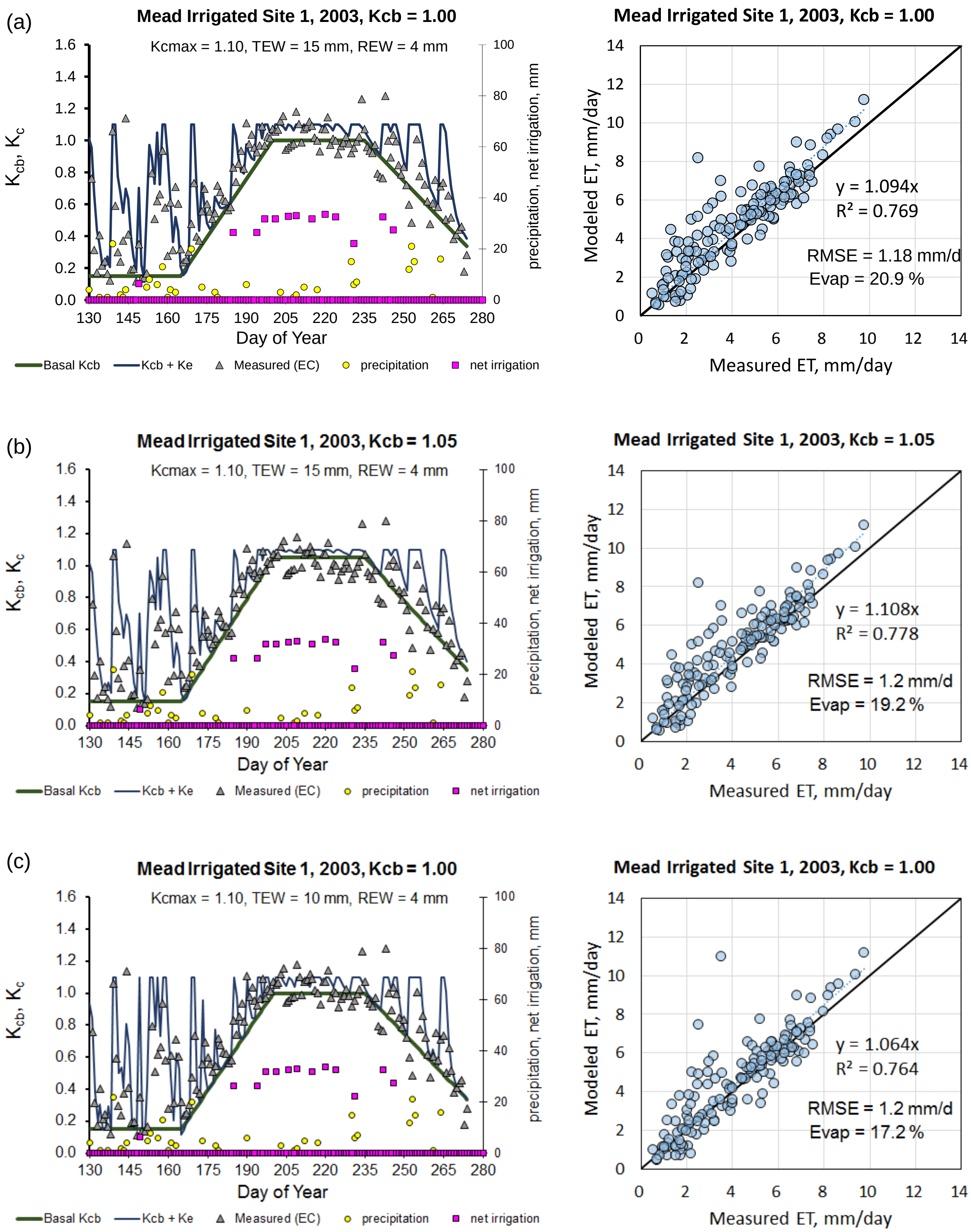


Figure 5. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 2 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of K_{emax} = 1.15 and 1.10 and (a) TEW = 15 mm and REW = 6 mm and (b) TEW = 10 mm and REW = 4 mm, (c) with TEW = 10 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.05, (d) with TEW = 10 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.00, (e) with TEW = 15 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.00, and (f) with TEW = 15 mm, REW = 4 mm, K_{cmax} = 1.00 and K_{cb} = 1.00.

Simulations for the Mead irrigated site 1, which was one field over from site 2, were similar as for site 2, but with not quite as good of fit in early season or late season, as indicated in Figure 6 for similar combinations of K_{cmax}, K_{cb}, TEW and REW as were applied to site 2. In general, for site 1, K_{cmax} = 1.00, TEW = 10 mm, REW = 4 mm and $K_{cb\ mid}$ = 1.00 tended to produce the best results, visually.



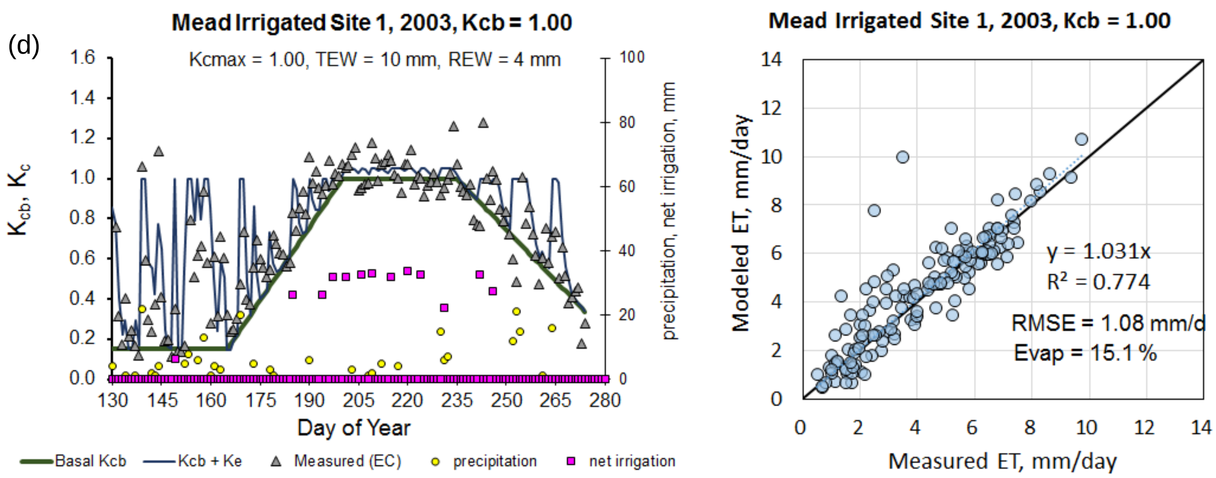


Figure 6. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 1 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of (a) TEW = 15 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.00, (b) TEW = 15 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.05, (c) TEW = 10 mm, REW = 4 mm, K_{cmax} = 1.10 and K_{cb} = 1.00, and (d) TEW = 10 mm, REW = 4 mm, K_{cmax} = 1.00 and K_{cb} = 1.00.

Impact of QAQC on Solar Radiation

Proper and accurate simulation of ET via the reference ET x crop coefficient method and accurate determination of values for K_c require accurate estimates of reference ET that serves as the basis for K_c. Reference ET is, of course, impacted by error in weather data inputs, and can develop a systematically high or low error bias when such a bias occurs in the weather data. The following three graphics show simulation results for site 2 during 2003 when using reference ET calculated using original R_s measurements without QAQC analyses. Table 1 shows ratios of measured R_s on clear days to the theoretical clear sky curve values (R_{so}) for intervals of 60 days during 2003, and their impact on ET_r:, where ET_{r_adj} is the tall reference ET estimate following correction of R_s data. R_s data were by dividing by adjustment ratios recomputed for clear days each 60 day period. That adjustment was done using the University of Idaho QAQC software that is distributed with the REF-ET software (http://extension.uidaho.edu/kimberly/2013/04/ref-et-reference-evapotranspiration-calculator/).

Table 1. Ratios of measured R_s on clear days to the theoretical clear sky curve values (R_{so}) for intervals of 60 days during 2003, and their impact on ET_r

’60 day period	R_{s_clear}/R_{so}	ET_{r_adj}/ET_{r_orig}
2003.001~2003.060	0.98	1.001
2003.061~2003.120	0.94	1.012
2003.121~2003.180	0.91	1.029
2003.181~2003.240	0.90	1.035
2003.241~2003.300	0.96	1.021
2003.301~2003.365	0.96	1.030

The use of original, undermeasured R_s caused ET_r to be understated and consequently ‘measured’ K_c that was determined using ET_r as a basis, to be higher in value. The use of undermeasured R_s did have the effect of bringing the scatter plot of modeled to measured ET closer to a slope of 1.00 and reducing RMSE, as shown in Figure 7 below. These figures can be compared with figures 4a and 4b previously used that were based on corrected R_s.

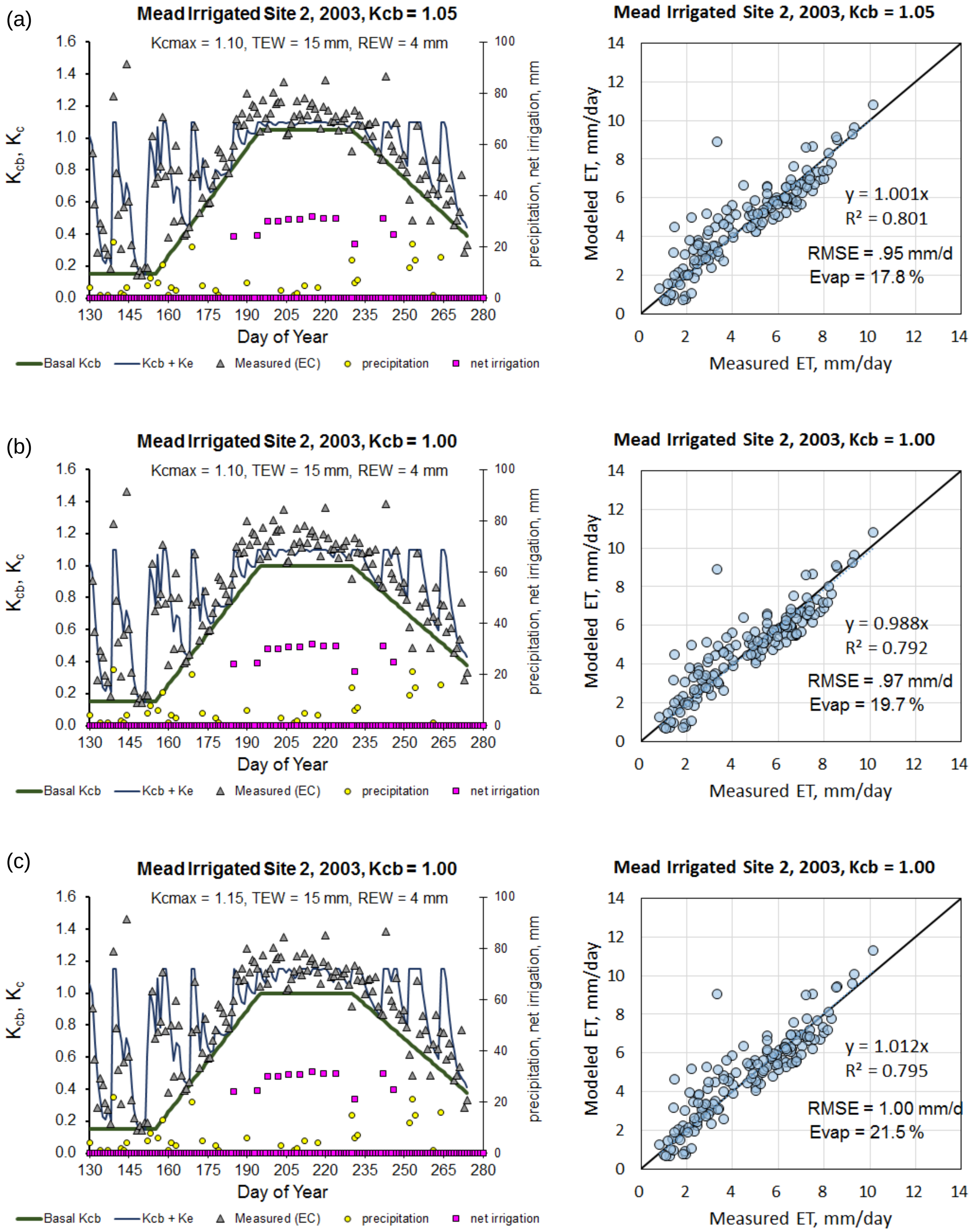


Figure 7. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 2 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) prior to correcting measured solar radiation for undermeasurement for values of TEW = 15 mm, REW = 4 mm and (a) K_{cmax} = 1.10 and K_{cb} = 1.05, (b) K_{cmax} = 1.10 and K_{cb} = 1.00, and (c) K_{cmax} = 1.15 and K_{cb} = 1.00.

The Dryland site 3

The dryland site 3 exhibited substantial stress during 2003 as illustrated in the following graphics. Because of the stress effects, it is not possible to establish the best values for $K_{cb\ mid}$. Therefore, the strategy was followed, where the value for K_{cmid} (listed as "K_{cb}" on the figure) was based on the analysis of irrigated site 2, and applied to the dryland condition. Different values for growth stage lengths were explored for site 3, even though the cultivar was the same as for irrigated sites. Different lengths could be caused by early season stresses and the more sparse planting density for the rainfed site. Figure 8 shows results for the following growth stage lengths. The stage lengths suggested in FAO-56 for maize in Idaho are 30, 40, 50 and 50 days for the four periods.

L_{ini}	*25*
L_{dev}	*40*
L_{mid}	*35*
L_{late}	*60*

The simulation of reduction in K_c due to water stress was quite sensitive to the values used for maximum rooting depth, available water, and MAD level, as expected, and on the time length specified for root development. The values determined for Rootmax, MAD and root development were a combination of values that caused the simulated K_c to best follow measured values over time. The MAD of 60% is higher than the value of 50% recommended in FAO-56, suggesting that the particular corn hybrid had better tolerance to low soil water content than traditional varieties.

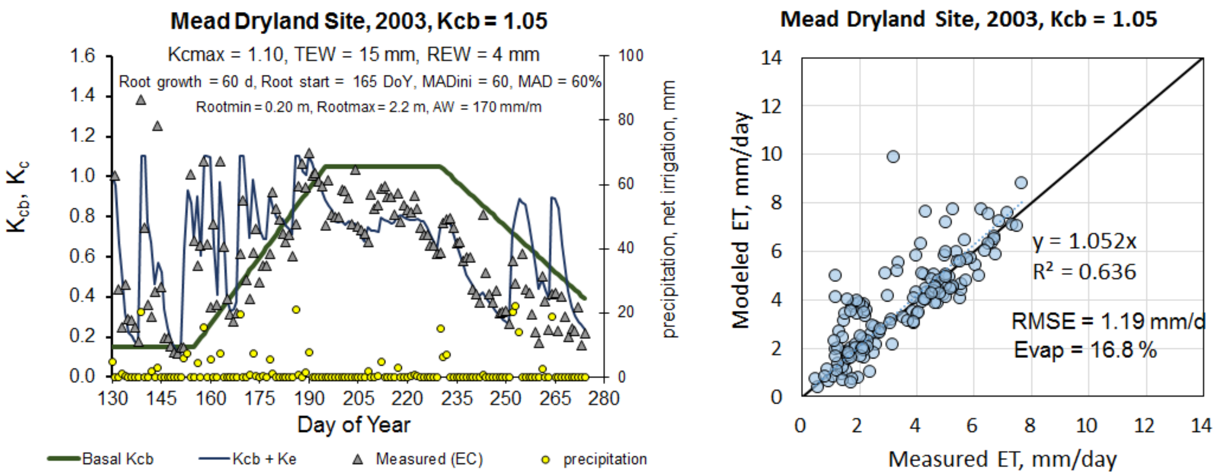


Figure 8. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for best performing values of parameters as shown on the graphic.

Figure 9 shows simulations when the length of the first growth stage (initial period) was extended by five days and the end period shortened by 10 days. This alternation of stage lengths substantially improved the fit of the K_{cb} curve during the development period. The longer period for development may be a reflection of the corn cultivar grown on the rainfed field as compared to the irrigated fields. The period lengths are also more in line with those of FAO-56 noted earlier with the exception of the shorter midseason period which may have been caused by the water stress or may be an artifact of growing a shorter season variety for drought mitigation.

L_{ini}	30
L_{dev}	40
L_{mid}	35
L_{late}	50

The two graphs in Figure 9 show results for $K_{cb\ mid}$ = 1.05 and $K_{cb\ mid}$ = 1.00 for a maximum rooting depth of 2.2 m. That depth was required to cause the simulated K_c to most closely follow the measured K_c during the midseason when stress was large. The simulated K_c from Eq. 1 did a good job of simulating measurements during all periods except during the last 30 days of the season. Both K_{cb} = 1.00 and 1.05 performed equally well with K_{cmax} = 1.1. The value for K_{cmax} had little effect since measured K_c only approached K_{cmax} during the initial and development periods.

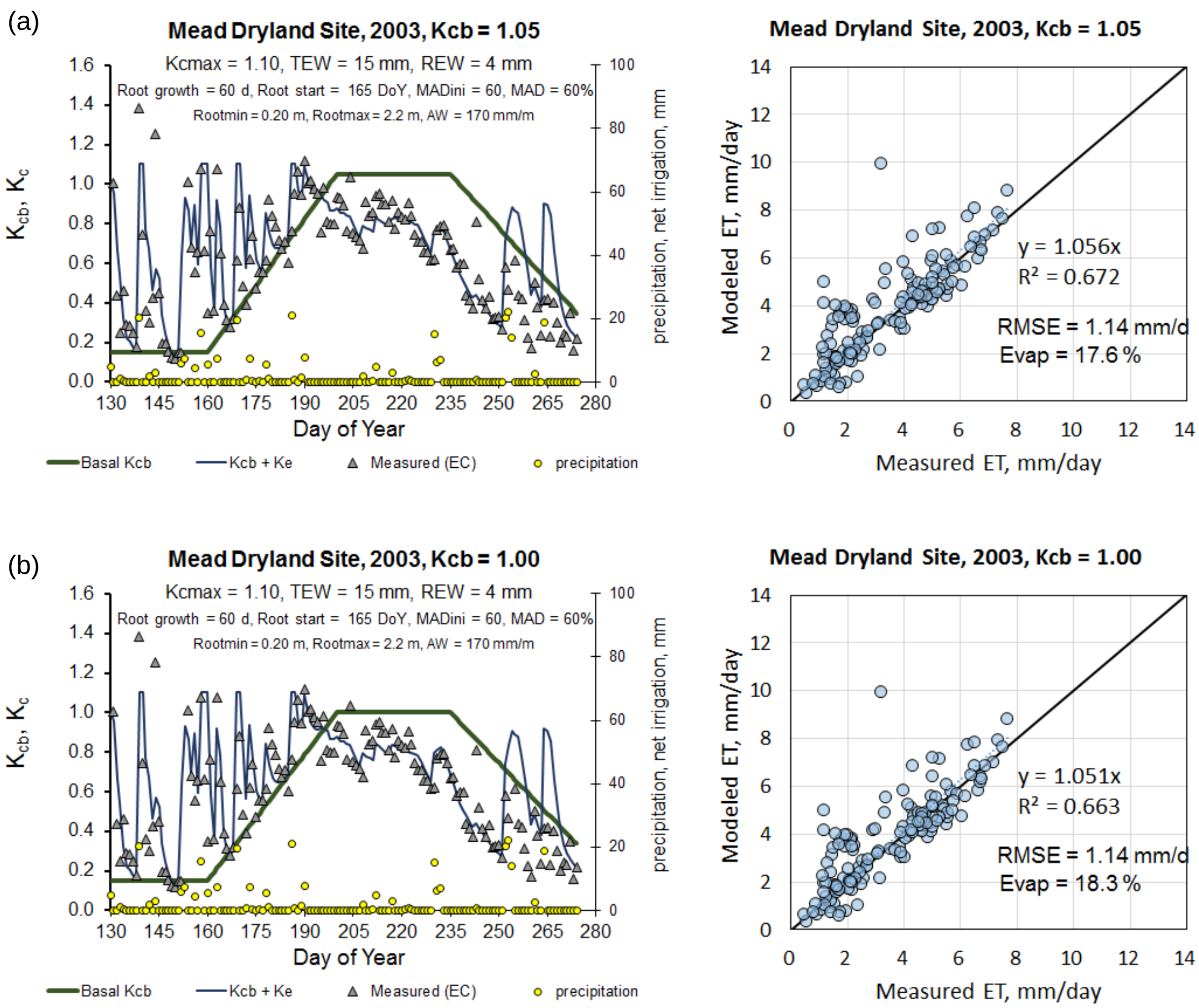


Figure 9. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for best performing values of parameters as shown on the graphic, for $K_{cb\ mid}$ = 1.05 (a) and $K_{cb\ mid}$ = 1.00 (b) and where of the first growth stage (initial period) was extended by five days and the end period shortened by 10 days as compared to Figure 8.

The next sequence explored the impact of reducing maximum rooting depth to 1.5 and 2.0 m, which are more in line with other publications, for example, FAO-56 that suggests a maximum rooting depth range of 1.0 to 1.7 m for maize. University of Nebraska NebGuide 1850 (http://www.ianrpubs.unl.edu/pages/publicationD.jsp?publicationId=1004) suggests a maximum rooting depth for corn of 5 to 6 feet which is equivalent to 1.5 to 1.8 m.

The use of 1.5 m in Figure 10 suggests that this depth does not provide sufficient moisture reservoir to support the observed ET. This assumes that the value for available water (AW) of 170 mm/m was appropriate. Therefore, a 2.0 to 2.2 m root zone depth appears to be more appropriate to use with the particular rainfed corn cultivar grown.

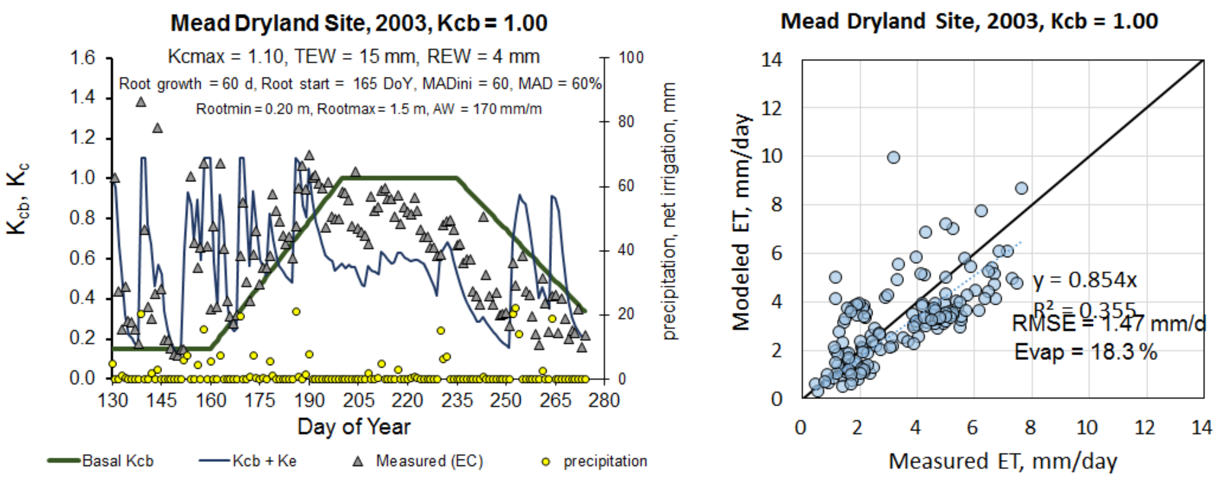


Figure 10. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 1.5 m, for $K_{cb\ mid}$ = 1.00.

The use of maximum rooting depth of 2.0 m shown in Figure 11, did not perform as well as the use of 2.2 m. It is possible that the deep silty clay loam exhibited the capability of upward movement of water from below the actual rooting depth and therefore produced a deeper effective rooting zone value. In addition, the particular cultivar may have been bred for deep rooting.

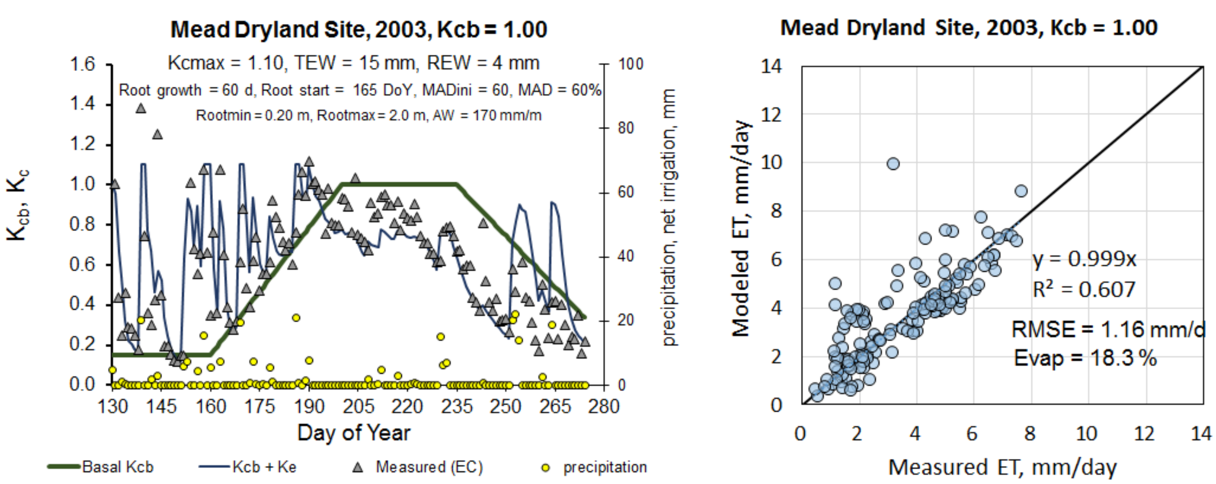


Figure 11. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.0 m, for $K_{cb\ mid}$ = 1.00.

Use of a maximum rooting depth of 2.5 m overstated water reservoir capacity and did not allow initiation of stress until later than observed as shown in Figure 12 below.

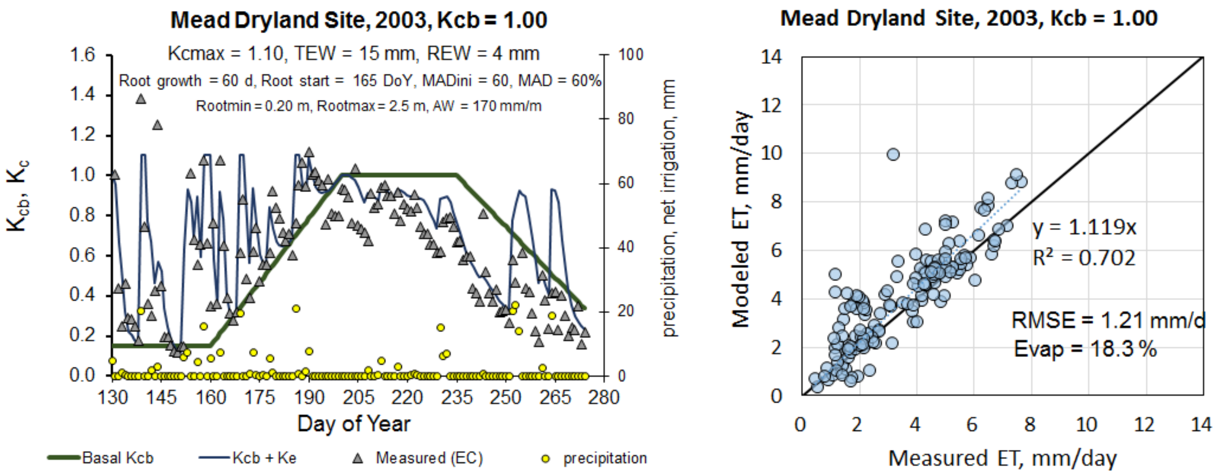


Figure 12. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.5 m, for $K_{cb\ mid}$ = 1.00.

Changing the MAD value during midseason from 60% to 50% had a similar effect as making the root zone more shallow, as shown in Figure 13, where initiation of stress appears to be overstated for some days around DOY 200. However, the stress effect did tend to capture all of the lower bound of measured K_c during the midseason period. The cause of the day-to-day fluctuation in measured values during that period is unclear.

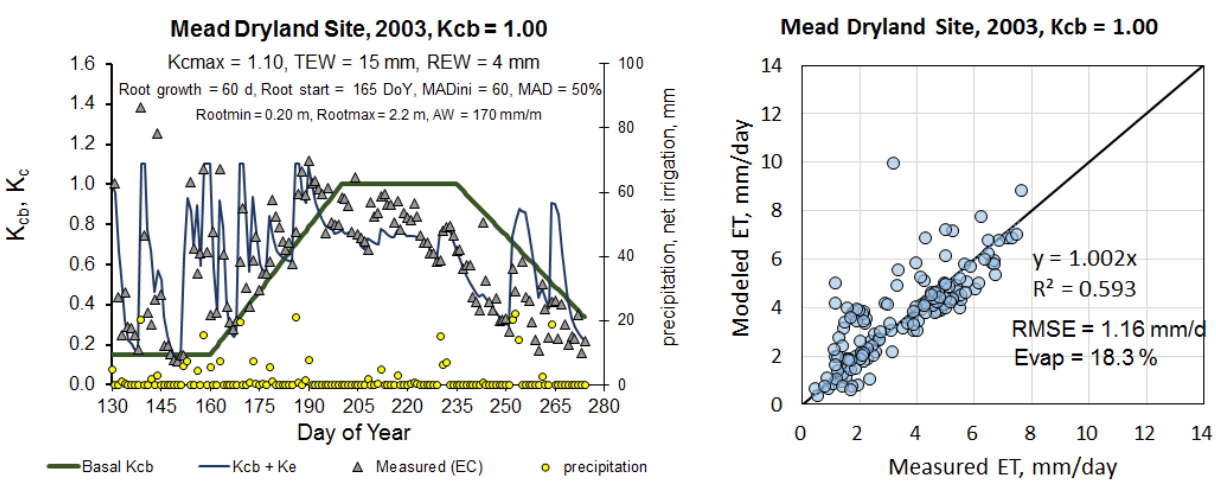


Figure 13. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 50%, for $K_{cb\ mid}$ = 1.00.

Increasing MAD to 70% delayed initiation of stress during the late vegetative development period and early midseason period, resulting in departure from most observed values during midseason as shown in Figure 14.

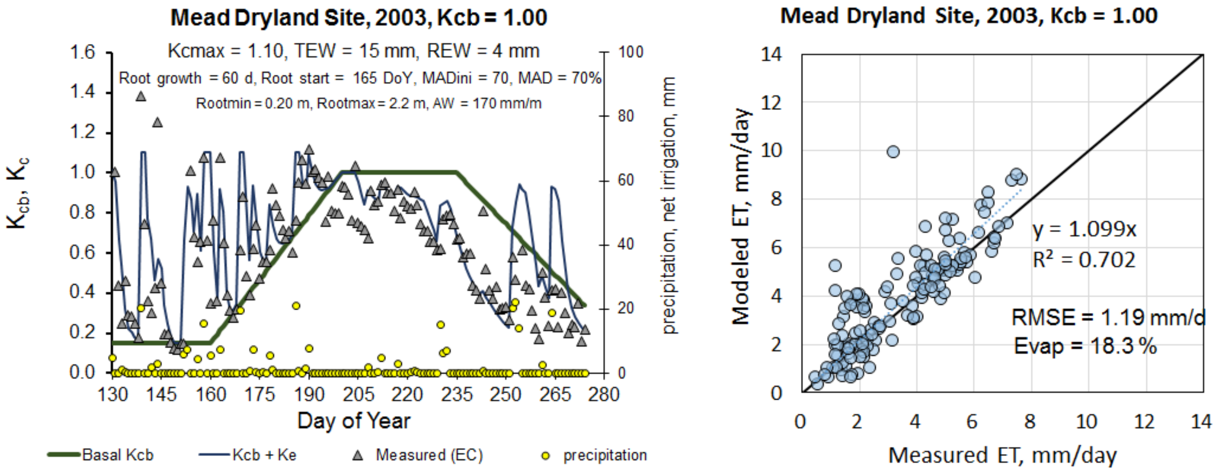


Figure 14. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for initial and midseason of 70%, for $K_{cb\ mid}$ = 1.00.

The reduction of AW to 150 mm/m had similar effect, as expected, to reducing MAD or reducing root zone depth (Figure 15):

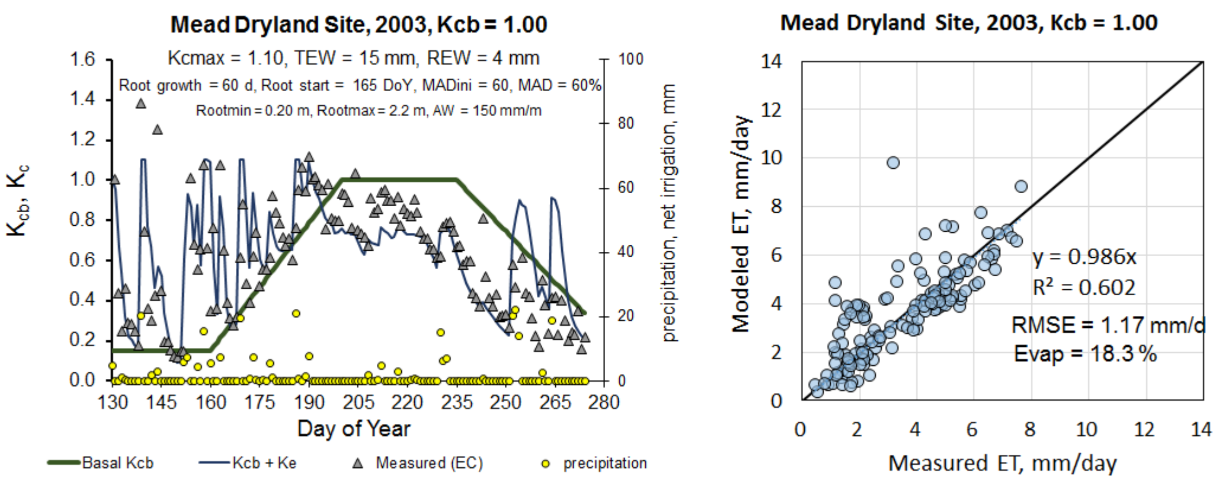


Figure 15. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 150 mm/m, and $K_{cb\ mid}$ = 1.00.

Increasing AW resulted in a delay of initiation of stress, similar to using a higher value for MAD as shown in Figure 16:

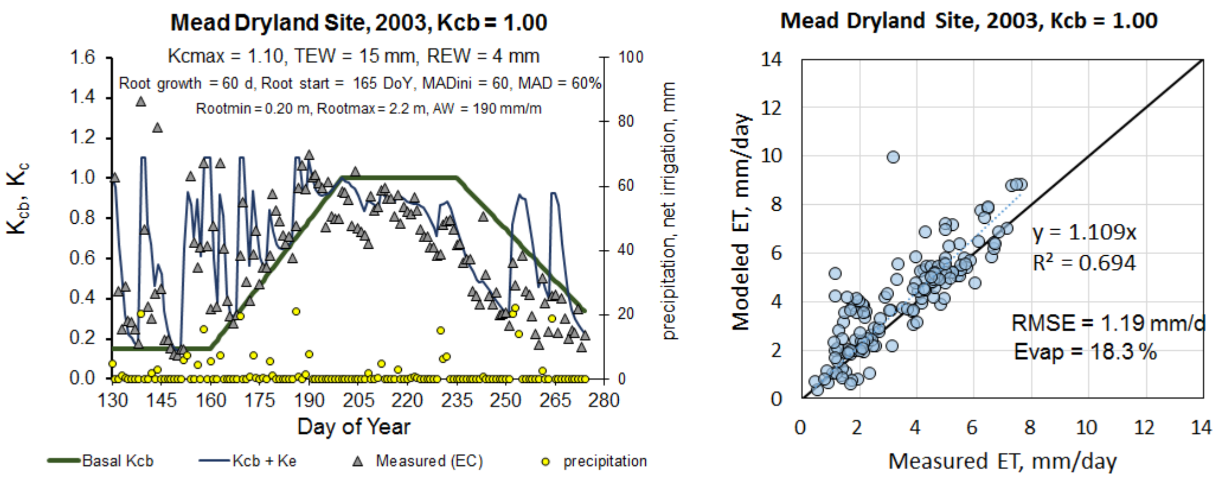


Figure 16. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 190 mm/m, and $K_{cb\ mid}$ = 1.00.

Shortening the time for root growth from 60 days to 50 days caused more rapid expansion of the root zone and effectively delayed the onset of water stress during the first part of the midseason period, as shown in Figure 17. This result indicates the substantial sensitivity of the simulation of stress to the dynamics of root growth. Those dynamics are often uncertain and poorly modeled in many applications. The impact can be reduced accuracy in yield estimation in models that utilize severity of stress during specific crop stages to estimate reductions in yield.

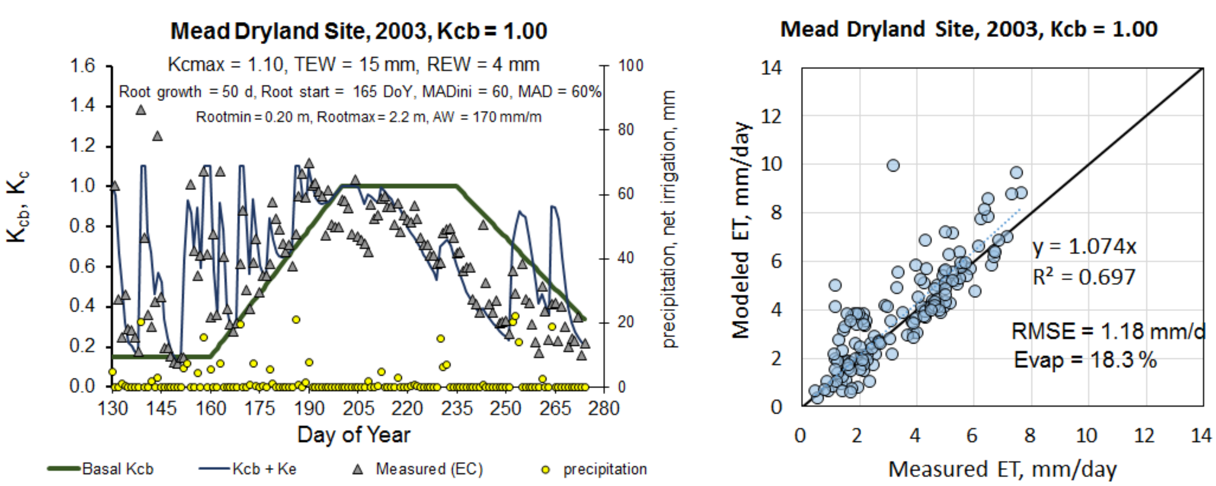


Figure 17. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, $K_{cb\ mid}$ = 1.00, and a 50 day period for root zone development.

Lengthening the time for root growth retarded the growth rate for the root zone and accelerated the onset of stress as shownin Figure 18.

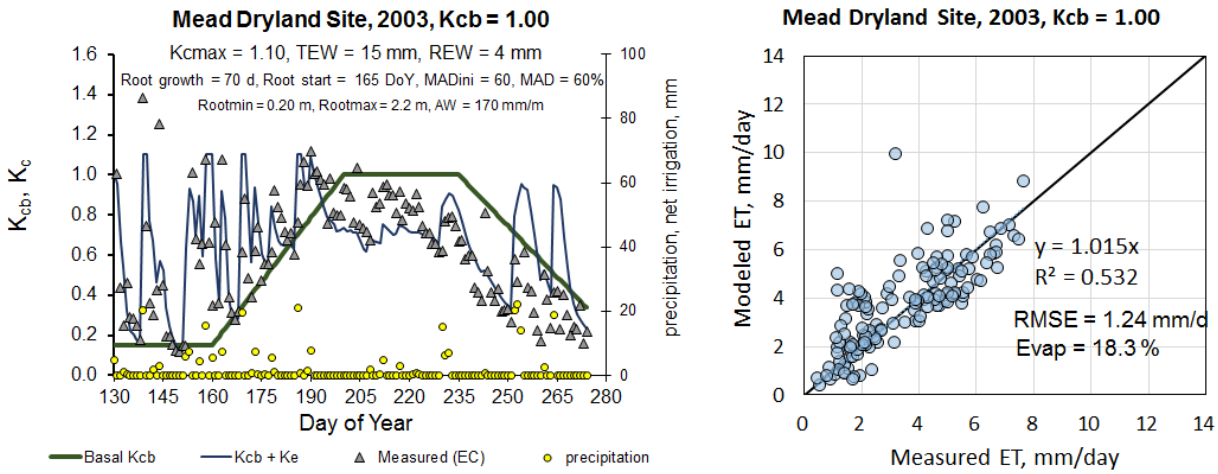


Figure 18. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, $K_{cb\ mid}$ = 1.00, and a 70 day period for root zone development.

Advancing the date of the start of rapid root growth expanded the water reservoir earlier and delayed onset of stress.

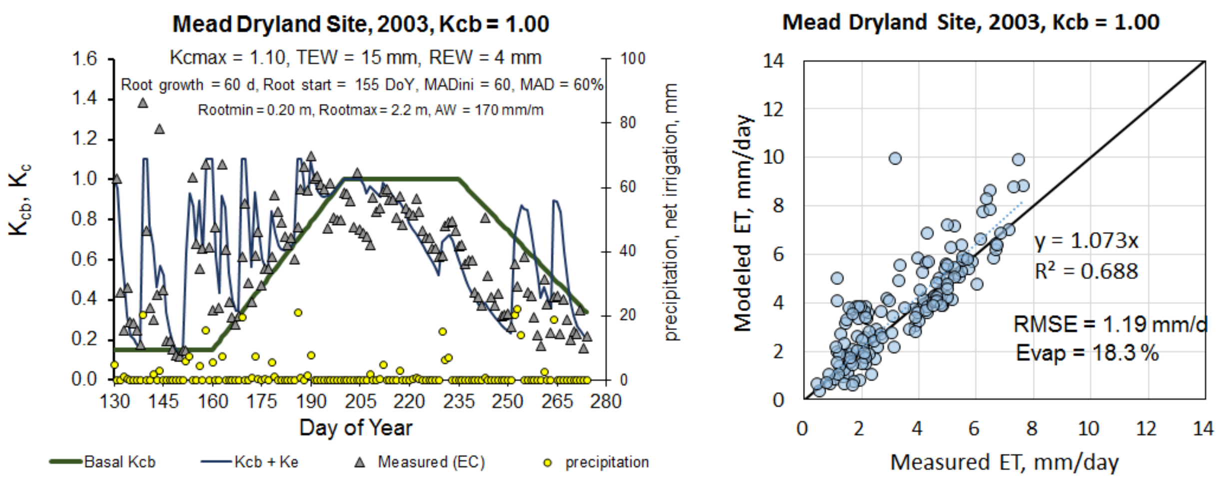


Figure 19. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, $K_{cb\ mid}$ = 1.00, a 60 day period for root zone development, and earlier start of root depth of DoY 155.

Delaying the date of the start of rapid root growth to DoY 175 moved the onset of stress forward in time and reduced the estimated stress later in the midseason as shown in Figure 20:

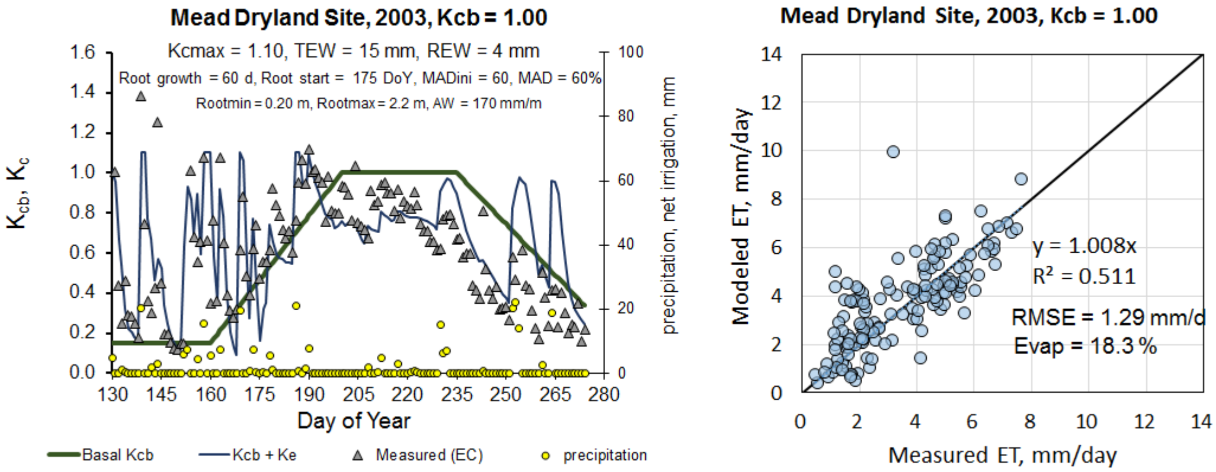


Figure 20. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of 2003 (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, $K_{cb\ mid}$ = 1.00, a 60 day period for root zone development, and later start of root depth of DoY 175.

In general, the use of maximum rooting depth of 2.2 m, coupled with MAD = 60% and AW = 170 mm m^{-1} and beginning of root growth on DoY 165 with 60 day duration tended to produce the best agreement between simulated and observed K_c during the midseason period which was entirely under stress. Those parameter settings were used in Figures 8 and 9.

The two large wetting events simulated towards the end of season (after day 250) were caused by two large precipitation events totaling 70 mm. Those events were not as pronounced in the measured K_c values as for the simulated K_c, possibly due to the influence of senesced vegetation on shading the wet soil and reducing total evaporation in reality. In contrast, the simulation assumed complete 'rebound' of the vegetation to the K_{cb} curve following rehydration of the soil.

Year 2005

Simulations for year 2005 were initially made using reference ET as calculated with what is referred to as the HPRCC Penman equation (http://www.hprcc.unl.edu/awdn/et/), which is a Penman-style equation with a linear wind function having wind and vapor pressure limits. Use of that method is explored in this section to evaluate the effect of reference method on simulated crop ET. It is noteworthy that the HPRCC Penman equation estimates very similar to the ASCE Standardized Penman-Monteith equation for the tall (alfalfa) reference.

Growth stage length of the initial period was longer for year 2005 in order to fit observations. The longer initial period may have been caused by a cooler spring with cooler soil temperature that impacted germination rate.

L_{ini}	40
L_{dev}	30
L_{mid}	35
L_{late}	45

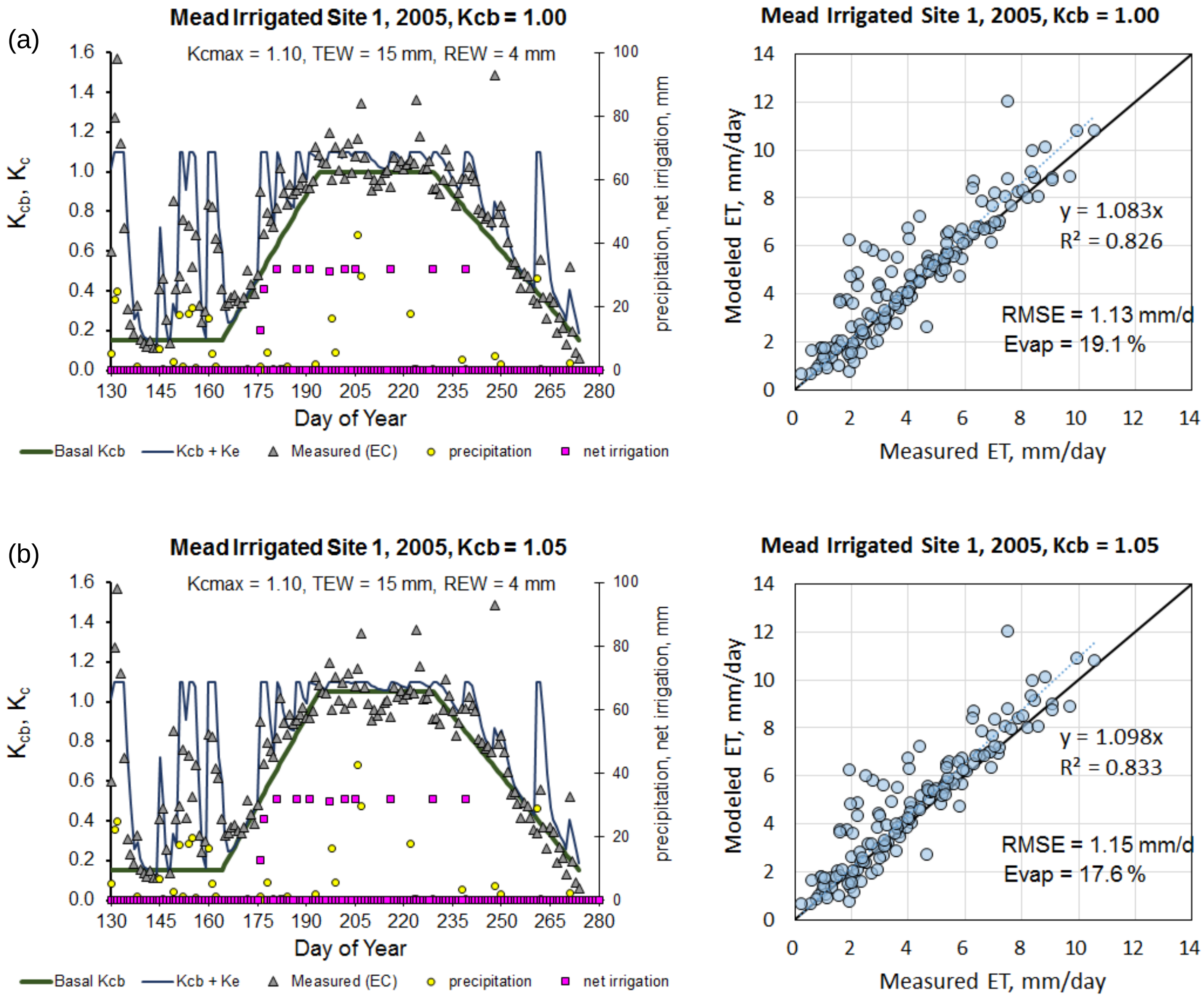


Figure 21. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 1 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) with maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, and $K_{cb\ mid}$ = 1.00 (a) and $K_{cb\ mid}$ = 1.05 (b), with reference ET calculated using the HPRCC Penman equation.

Simulation results were relatively good for year 2005 for the irrigated conditions, with R^2 of about 0.83 and RMSE of about 1.15 mm/day for $K_{cb\ mid}$ of 1.00 and 1.05. Agreement was good across the range of K_c values including for days following irrigation. A few spuriously high values for 'observed' K_c occurred due to understatement of ET_r by the HPRCC method.

Using Reference ET based on the ASCE PM equation

Solar radiation required adjustment in 2005, with measurements being about 5% low. Adjustments were made prior to calculation of the ASCE PM-based reference ET. No adjustments to solar radiation data were required for 2003.

Period during 2005 Year.DoY	Ratio of ET_r prior to adjustment to after adjustment of solar radiation
2005.001~2005.060	0.96
2005.061~2005.120	0.95
2005.121~2005.180	0.95
2005.181~2005.240	0.95
2005.241~2005.300	0.97
2005.301~2005.365	1

The use of corrected solar produced about 5% stronger estimates of reference ET, which in turn produced estimates of observed K_c, computed as $K_c = ET/ET_r$, to be reduced by about 5%.

Statistics for 2005 are similar to those obtained in 2003, which also used the ASCE PM tall reference, with R2 of about 0.76 and RMSE of about 1.2 mm/day for $K_{cb} = 1.00$ and $K_{cb} = 1.05$ (Figure 22).

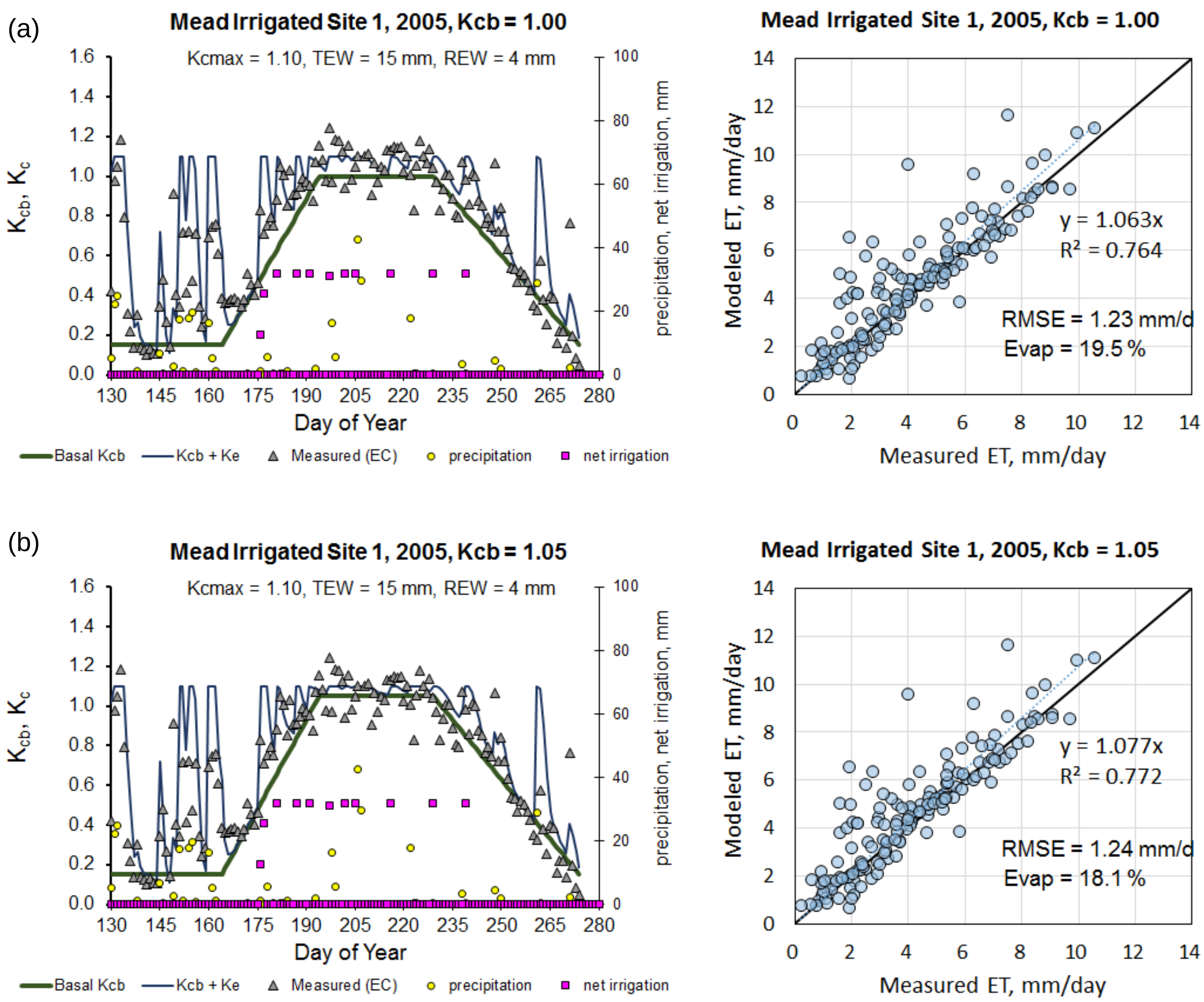


Figure 22. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 1 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) with maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, and $K_{cb\ mid} = 1.00$ (a) and $K_{cb\ mid} = 1.05$ (b), with reference ET calculated using ASCE PM equation following correction of solar radiation data.

Site 2 (Figure 23) had similar results as for site 1 with higher R^2 of about 0.82 and lower RMSE of about 1.1 mm/day:

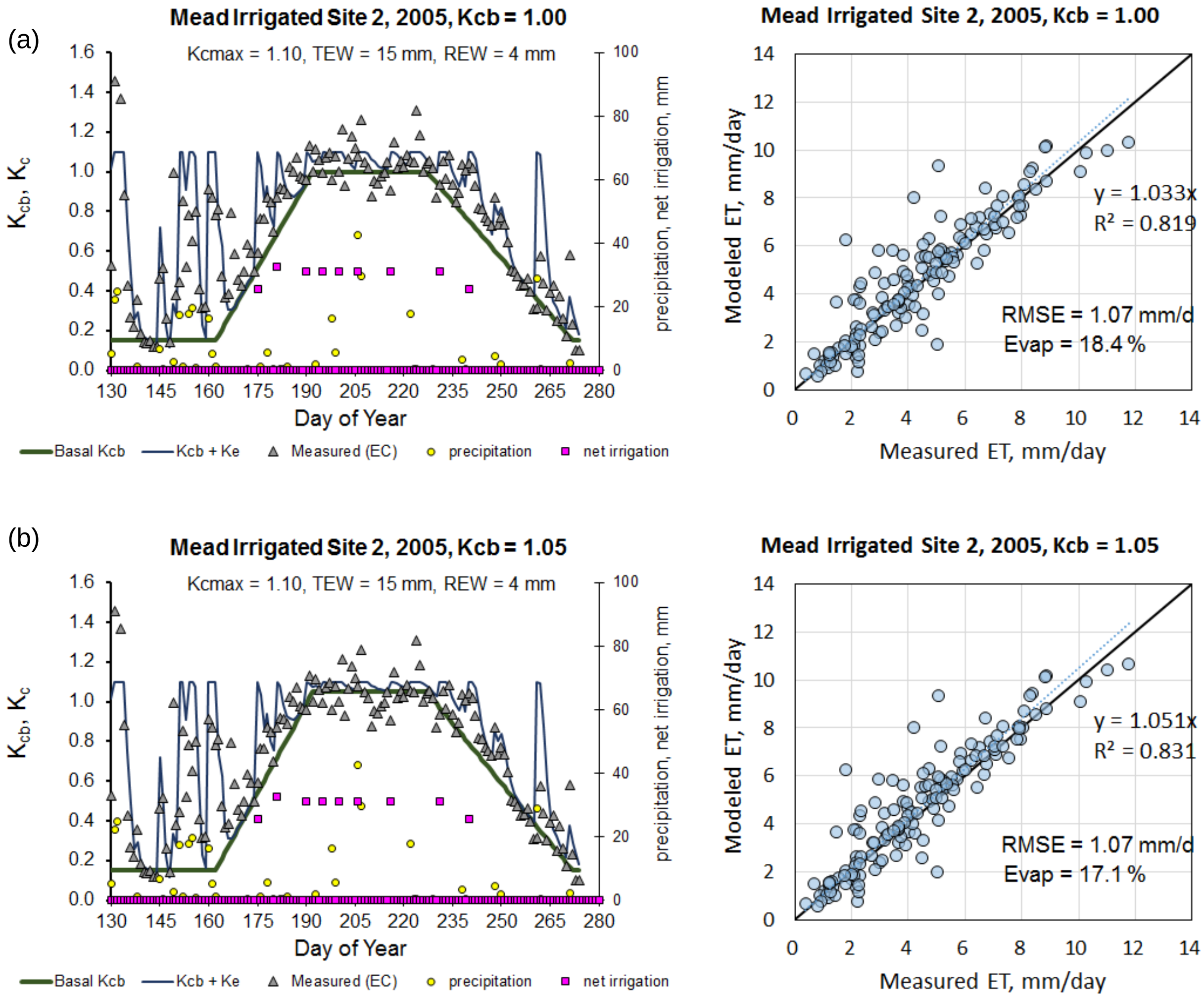


Figure 23. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Site 2 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) with maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, and $K_{cb\ mid}$ = 1.00 (a) and $K_{cb\ mid}$ = 1.05 (b), with reference ET calculated using ASCE PM equation following correction of solar radiation data.

As for 2003, K_{cb} = 1.00 or 1.05 did not impact the slope of the scatter plots significantly, nor the RMSE, since with the same K_{cmax} = 1.10, the upper bound on estimates during midseason was largely unchanged with high frequency wetting by irrigation, and K_e simulated above the K_{cb} was essentially exchanged for transpiration when K_{cb} was shifted upward. The scatter plots look very similar. Is is noted that observed K_c during the initial period generally only reached values of 1.0 following wetting events, which is a widely recommended value. Therefore the use of $K_{c\ max}$ of 1.0 would produce slightly better error statistics during that period.

Consistency of Eddy Covariance Data

The following scatter plot shows ET derived from eddy covariance at site 2 during the 2005 growing period plotted against ET derived from eddy covariance at site 1. The agreement between the two fields and systems is quite good, with R^2 of 0.95, slope of 1.04 and RMSE 0.63 mm day^{-1}. That RMSE is about ½ of the RMSE values for simulated K_c vs. EC-based

K_c. This suggests that most of the 'random error' for the simulations was likely due to random error in the simulation model or impact of parameter settings, rather than due to error in the EC measurements and handling. It is possible that the EC data exhibits some systematic error, even following the energy balance closure adjustments, which was done on a 24-hour basis by multiplying latent heat flux density LE by the ratio of (Rn – G) to (LE + H), where G is ground heat flux and H is sensible heat flux. The consistent agreement between the two EC measurements for irrigated fields representing full water supplies does indicate that both systems were operating similarly in regard to instrumentation and measurements. Both fields of corn were of the same variety and were planted within two days of one another and irrigated with similar schedules via center pivot during 2005.

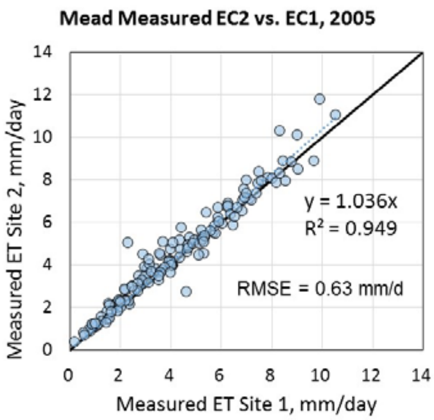


Figure 24. Daily measured ET from the Mead EC2 site vs. tha from the Mead EC1 site during the 2005 growing season.

Dryland Site 3 in year 2005

The corn crop for the dryland site 3 was planted about ten days earlier (4/26/2005) than the two irrigated sites. Year 2005 had more stress early in the midseason, with less stress late in the midseason due to several large rain events in July. The K_c simulations did a relatively good job of reproducing the observed values during a majority of the season. As with 2003, the simulations overestimated following rain events and lessoning of stress levels, possibly due to less than full rebound by the actual crop due to damaged leaves, senescence and drought conditioning. Results for the 'standard' soil parameter settings as used in earlier figures 7 and 8 are shown in Figure 25 for year 2005. The ASCE PM equation was used as the reference basis following correction of solar radiation data as noted earlier.

The following 2 sets of graphics in Figure 26 show impacts of beginning root growth five days earlier than the standard DoY = 165 as applied for Figure 25. Even a five day earlier start on root growth in either direction impacted the fit and prediction of the onset of stress.

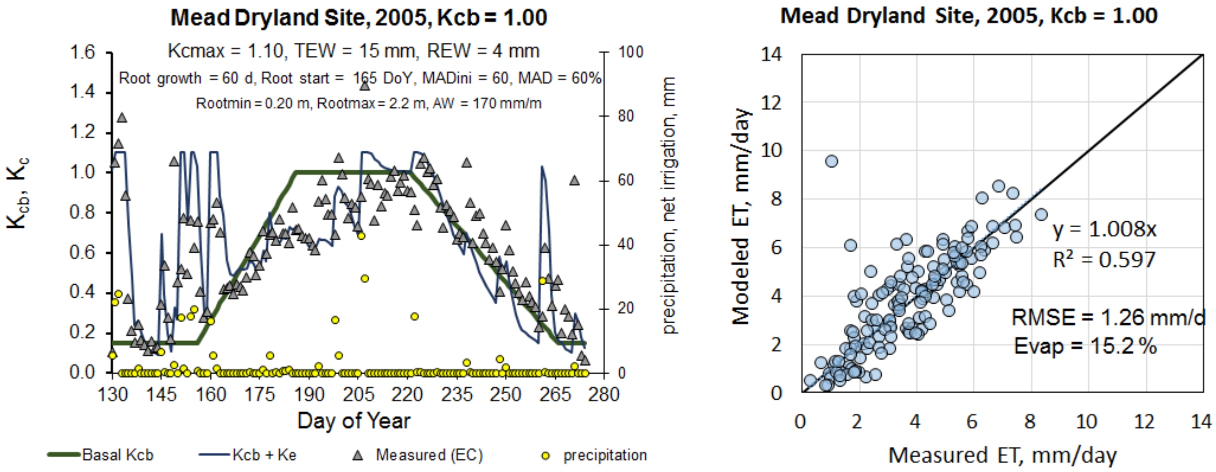


Figure 25. Daily simulated and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and start of root development of DoY = 165.

(a)

(b)

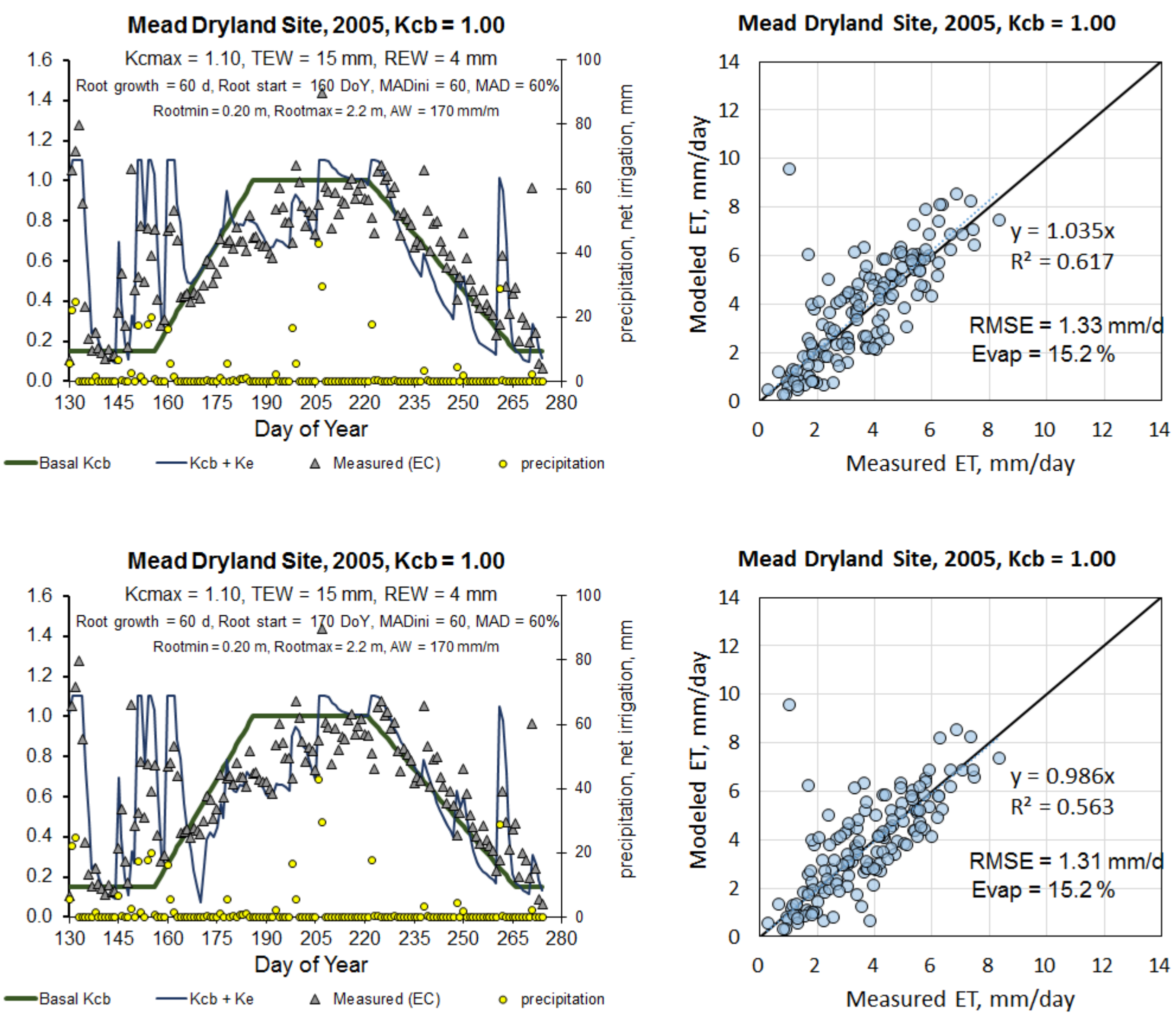


Figure 26. Daily simulated and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone develop., $K_{cb\ mid}$ = 1.00 and start of root develop. of DoY = 160 (a) and DoY = 170 (b).

Reducing rooting depth to 2 m (Figure 27) did not impact the simulation in August, since the soil was recharged to above MAD during that period by July rain events.

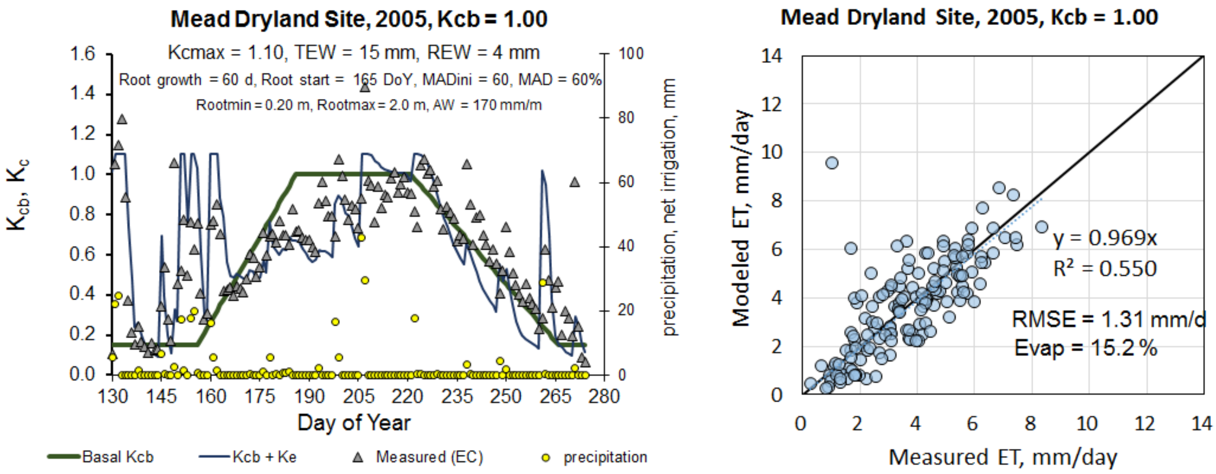


Figure 27. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2005** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.0 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and start of root development of DoY = 165.

Year 2007

Lengths of growth stages that best fit for year 2007 were similar between the irrigated and dryland sites, but with slight differences by 5 days in two stages:

Irrigated:

L_{ini}	30
L_{dev}	35
L_{mid}	40
L_{late}	45

Dryland:

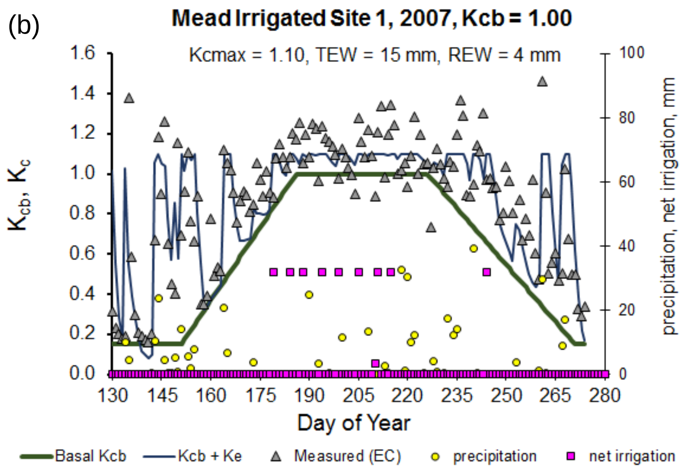
L_{ini}	35
L_{dev}	35
L_{mid}	35
L_{late}	45

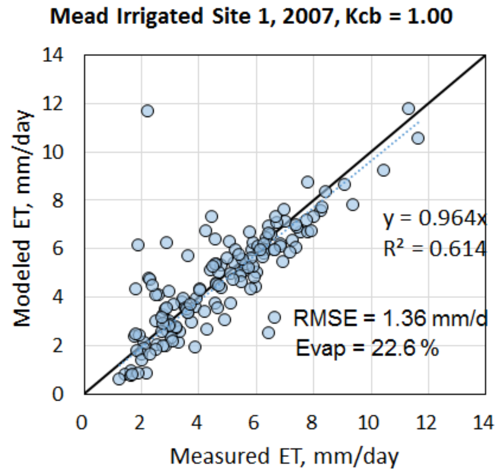
Planting dates were essentially the same among all three sites in 2007: 5/1, 5/2, and 5/2.

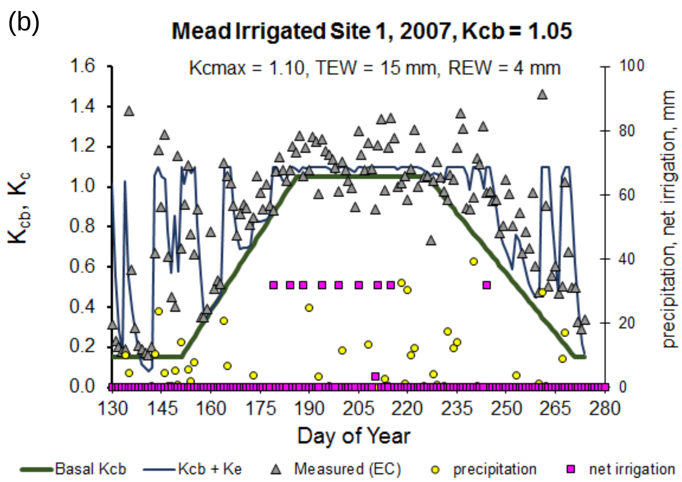
Solar radiation required 5 to 7% upward adjustment during the entire calendar year of 2007, with 11% upward adjustment during May and June:

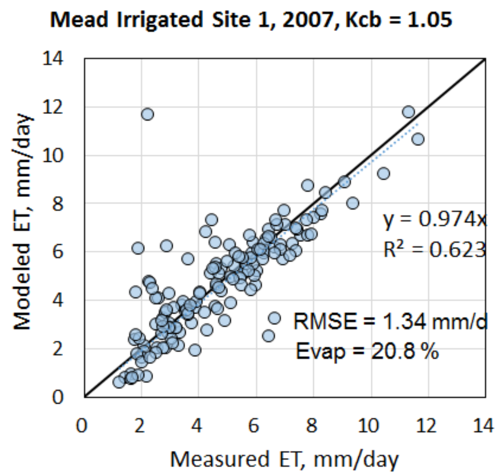
Period during 2005 Year.DoY	Ratio of ET_r prior to adjustment to after adjustment of solar radiation
2007.001~2007.060	0.95
2007.061~2007.120	0.93
2007.121~2007.180	0.89
2007.181~2007.240	0.93
2007.241~2007.300	0.97
2007.301~2007.365	0.93

Results based on the ASCE PM reference ET are shown in Figure 28 a-d for Irrigated Sites 1 and 2 during 2007 using similar variation in K_{cmid} as conducted for the years 2003 and 2007:









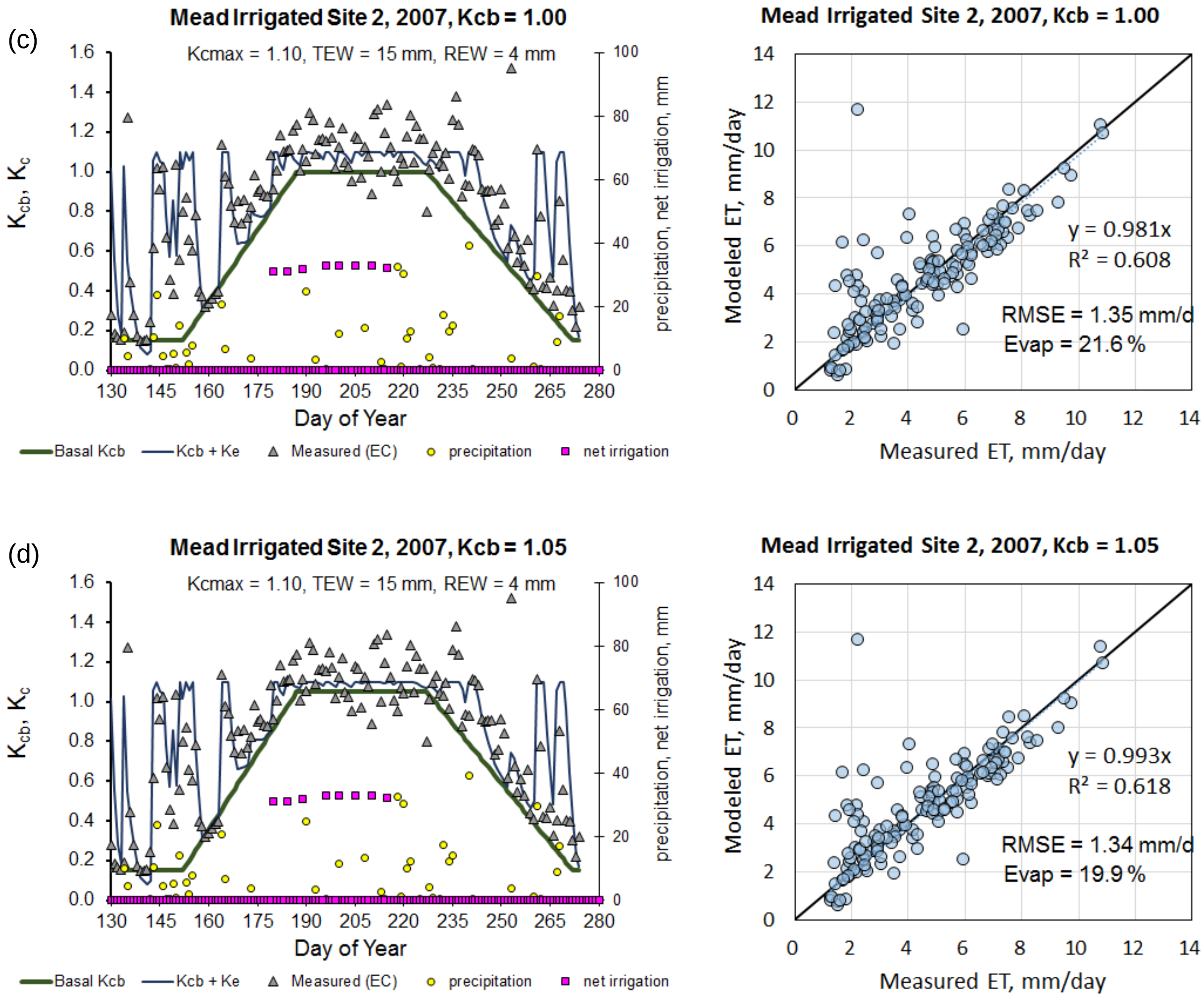


Figure 28. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Irrigated Sites 1 and 2 during the growing season of **2007** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.2 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development and start of root development of DoY = 165 for Site 1 and $K_{cb\ mid}$ = 1.00 (a), Site 1 and $K_{cb\ mid}$ = 1.05 (b), Site 2 and $K_{cb\ mid}$ = 1.00 (c) and Site 2 and $K_{cb\ mid}$ = 1.05 (d).

Values for measured K_c that lie below the K_{cb} = 1.00 and 1.05 line during midsummer in Figure 28 are not explained. As expected, fewer values lie below the K_{cb} line when K_{cb} = 1.00. Agreement between EC of the two fields suggests that these data points are valid. That they occurred for both fields might suggest either some stress occurring during irrigation events, or some impacts on EC measurements due to large-scale eddy mixing associated with regional advective conditions that can cause undermeasurement by eddy covariance (Foken et al 2010). Agreement between the EC-measured ET for the two irrigated fields was similar for 2007 as shown in Figure 29, with field two 3.5% lower than field one.

The ASCE PM was applied using Mead HPRCC daily data from the 'standard' HPRCC Mead stations using mean daily vapor pressure estimated from summed hourly vapor pressure.

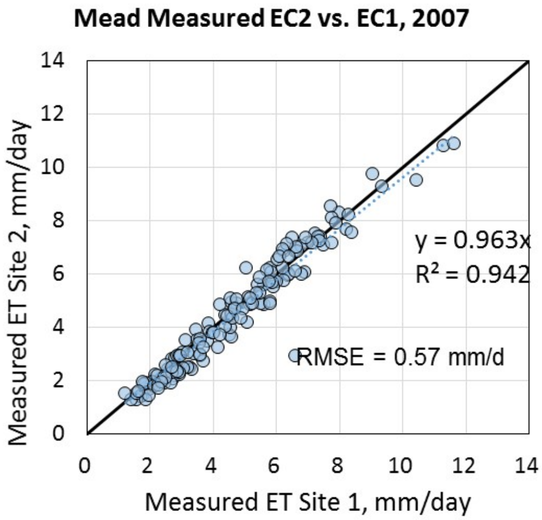


Figure 29. Daily measured ET from the Mead EC2 site vs. tha from the Mead EC1 site during the 2007 growing season.

The rainfed site had less stress in 2007 than in 2003 and 2005 due to more abundant rainfall during summer, as shown in Figure 30. The fit is good using same parameters for rooting and soil as for previous years. The only difference was adjustment to the four growth lengths for the K_{cb} curve.

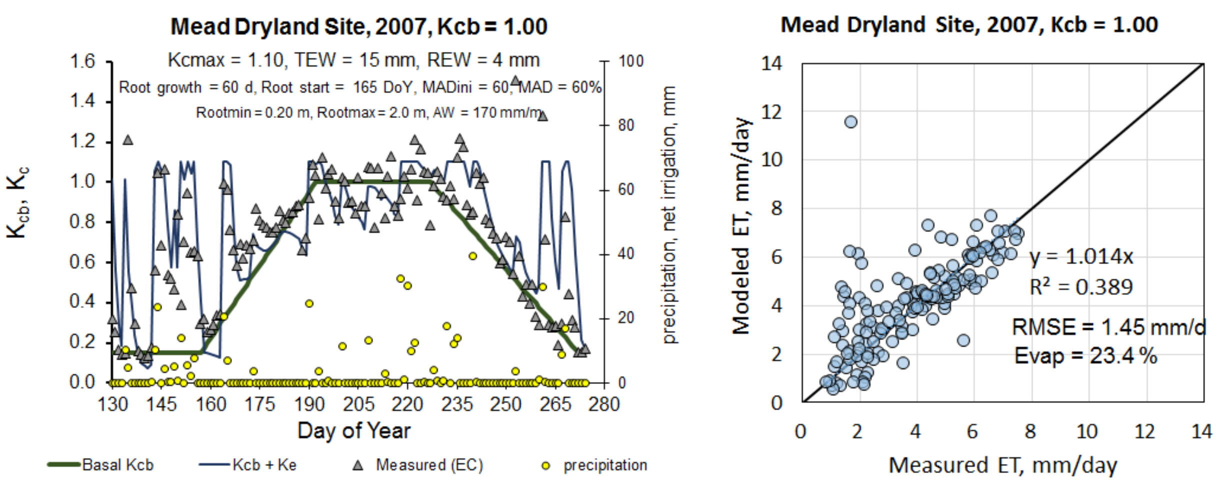


Figure 30. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2007** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.0 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and start of root development of DoY = 165.

Estimation of impact of surface mulch on evaporation losses

The evaporation percentage was estimated to be 23% of total ET, based on the dual K_c FAO-56 simulation method, which suggests some opportunity to conserve water by reducing opportunities for evaporation during early season so as to convert it into transpiration later on during the growing season. The web site at http://fluxnet.ornl.gov/site/951 describes crop residue management at the Mead sites and the objective to leave 1/3 surface covered by residue.

The settings for REW (4 mm) and TEW (15 mm) that were found to best reproduce observed ET represent some impacts of surface residue that existed on the Mead fields on reducing amounts of water available for evaporation. When more general settings for bare soil are used (REW = 8 mm; TEW = 25 mm (FAO-56), the estimated evaporation percentage increased by 6% to 30% (and with worse fit with EC data). This suggests that the surface residue did reduce total ET lost by evaporation from soil by 6% as compared to conventional (bare) tillage.

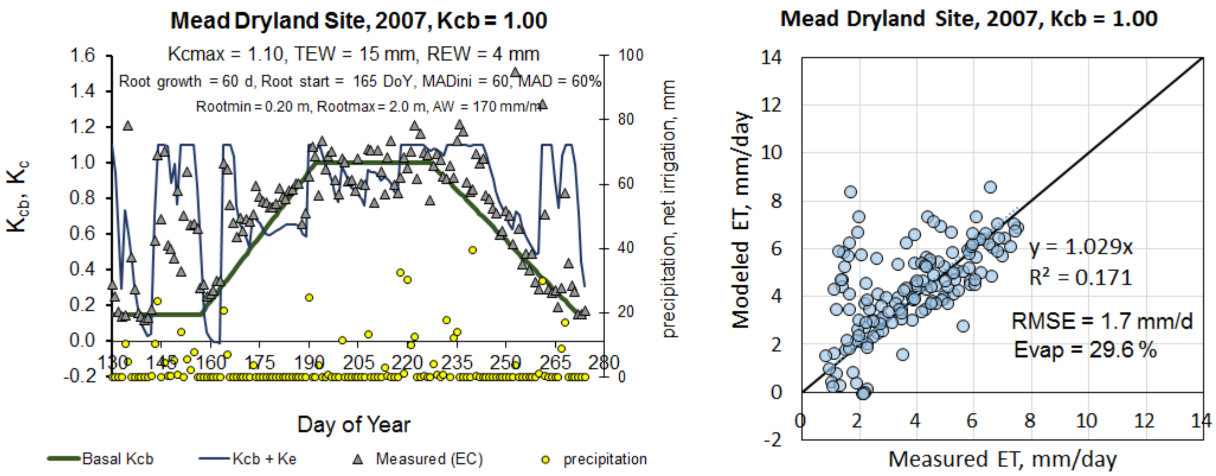


Figure 31. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2007** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.0 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and start of root development of DoY = 165, and with TEW = 25 mm and REW = 8 mm.

A reduction in TEW to 10 mm improved the fit to the 2007 dryland data, as shown in Figure 32, suggesting that surface mulching by minimum tillage does substantially reduce evaporation losses. In this case, evaporation from soil percentage was 10% less than for conventional tillage. Total ET was similar, indicating that more stored water may have been available for transpiration and yield increases because of the retention of crop residue on the surface.

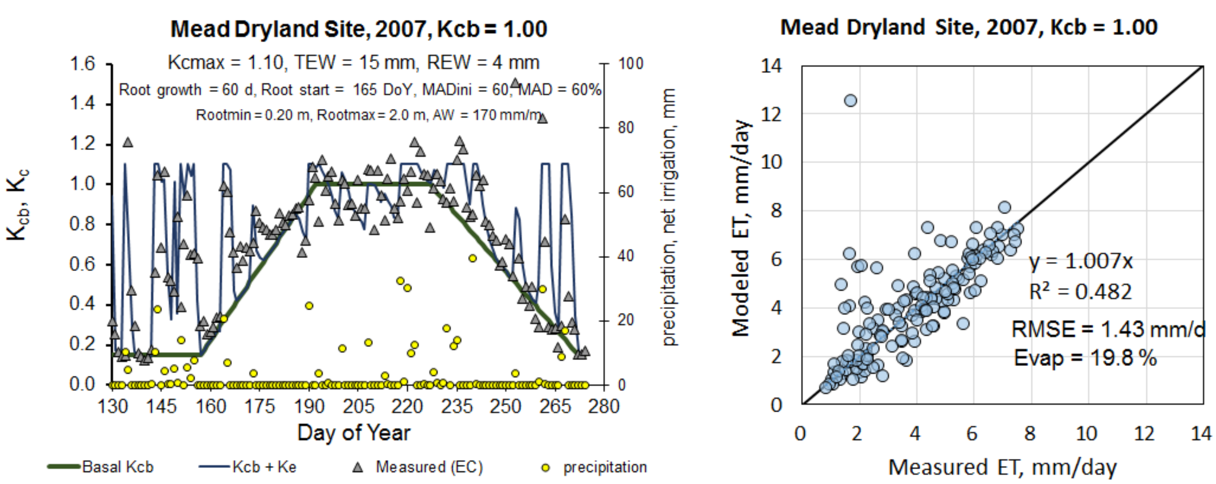


Figure 32. Daily simulated crop coefficients and measured crop coefficients vs. day of year for the Mead Dryland Site 3 during the growing season of **2007** (left) and simulated ET vs. measured ET for the same days (right) for values of parameters as shown on the graphic, including maximum rooting depth of 2.0 m and MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and start of root development of DoY = 165, and with TEW = 10 mm and REW = 4 mm.

Conclusions

The dual crop coefficient approach is an efficient and capable method for simulating effects of both vegetation growth and wetting frequency on total evapotranspiration and water consumption. The method provides a simple visual means of determining values for parameters to fit measurements. Fitted parameters tend to be consistent from field to field and from year to year. The multiplicative nature of some parameters, such as rooting depth, available water, and management allowed depletion creates a relatively broad range of combinations of those parameters in nearly equally fitting measured ET data. Examination of timing and duration of stressed reduced ET and responses to precipitation inputs can provide some indication of best combinations. Similar tradeoffs exist between the value established for the midseason basal crop coefficient, $K_{cb\ mid}$, and the maximum daily K_c, K_{cmax}. That additive tradeoff occurs from transfer of estimated energy consumption by vegetation into estimated energy consumption by evaporation from wet soil and canopy.

Root mean squared error (RMSE) averaged about 1.1 to 1.5 mm d^{-1}, which can be considered to be acceptable accuracy. RMSE of eddy covariance-determined ET from adjacent fields was 0.57 to 0.62 mm d^{-1}, indicating that consistency, and hopefully accuracy, of measurements was about twice that of day-to-day accuracy of the simulations. The application of the dual crop coefficient to the corn crops in eastern Nebraska suggests that the linear style FAO method for constructing a seasonal K_{cb} curve using four line segments provides sufficient accuracy, given the uncertainty in measurements and in other parameters such as K_{cmax}. The dual K_c method provides the means to estimate the relative fraction of consumed water that is evaporated from soil and plant surfaces. However uncertainty exists on the most correct partitioning between transpiration and evaporation according to values set for parameters. More research is needed in this area, since reduction of evaporation is a relatively straight-forward means to reduce total water consumption without substantial impact on plant transpiration and yield. It appears that using a midseason K_{cb} value of 1.00 to 1.05 and K_{cmax} of 1.00 to 1.10 best reproduced measured ET from the eddy covariance stations, based on the tall alfalfa reference crop of ASCE (2005) and following QAQC of weather data and adjustment of eddy covariance data for energy balance closure. Best combinations of model parameters tended toward maximum rooting depth of 2.0 to 2.2 m, MAD for midseason of 60%, available water of 170 mm/m, a 60 day period for root zone development, $K_{cb\ mid}$ = 1.00 and $K_{c\ max}$ = 1.0 or 1.10, start of root development of DoY = 165, REW = 4 mm and TEW = 15 mm (representing impacts of surface crop residue).

The large number of sets of results and graphics produced provide a good glimpse of both sensitivity and consistency of daily ET simulations to variation in model parameters and performance among years. The various types of variations explored for parameters can provide practitioners with ideas and insights and behavior of the FAO-style dual K_c method and ways to parameterize it to fit observed data.

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