Revised FAO Procedures for Calculating Evapotranspiration – Irrigation and Drainage Paper No. 56 with Testing in Idaho

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Abstract

In 1998, the Food and Agriculture Organization of the United Nations (FAO) published FAO Irrigation and Drainage Paper No. 56, a revision of the earlier and widely used Paper No. 24 for calculating evapotranspiration (ET) and crop water requirements. The revision uses a single method, the FAO Penman-Monteith equation, for calculating reference evapotranspiration (ET_o). In addition to the "mean" crop coefficient (K_c) values of FAO-24, FAO-56 provides tables of "basal" crop coefficients that represent ET under conditions having a dry soil surface. Associated equations for predicting evaporation from bare soil associated with crop transpiration are based on a water balance of the soil surface layer.

Comparisons of daily ET from three agricultural crops are made between lysimeter measured ET and the basal K_c method of FAO-56 and the time-based basal K_c procedure of Wright (1982). Standard errors of estimate and accuracies were similar between the two methods and averaged about 0.77 mm/day or 15%.

Key Words:
FAO-56, Crop Evapotranspiration, basal crop coefficient, crop water requirements

Introduction

A commonly used approach for predicting consumptive use of water by irrigated crops is the crop coefficient - reference evapotranspiration (K_c ET_o) procedure. Reference evapotranspiration (ET_o) is computed for a grass or alfalfa reference crop and is then multiplied by an empirical crop coefficient (K_c) to produce an estimate of crop evapotranspiration (ET_c).

The FAO-56 procedure

The FAO Penman-Monteith equation. The FAO-56 Penman-Monteith equation for predicting ET_o, where it is applied on 24-hour calculation timesteps, has the form:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T + 273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad (1)$$

where ET_o is reference evapotranspiration [mm day^{-1}], R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapour pressure [kPa], e_a is actual vapour pressure [kPa], e_s-e_a is the saturation vapour pressure deficit [kPa], Δ is the slope of the vapour pressure curve [kPa $°C^{-1}$], and γ is the psychrometric constant [kPa $°C^{-1}$]. In applications having 24-hour calculation time steps, G is presumed to be 0 and e_s is computed as $(e^o(T_{max}) + e^o(T_{min}))/2$ where $e^o()$ is the saturation vapor function and T_{max} and T_{min} are daily maximum and minimum air temperature. For hourly time-steps, the "900" value in Eq. 1 changes to "37" for ET_o in [mm hour^{-1}], R_n and G in [MJ m^{-2} hour^{-1}], where T is mean hourly air temperature [°C] and e_s is computed using mean hourly air temperature. In hourly calculation timesteps, G for the grass reference surface is predicted as $G = 0.1\ R_n$ during daylight and $G = 0.5\ R_n$ during nighttime hours.

The FAO Penman-Monteith equation predicts ET from a hypothetical grass reference surface that is 0.12 m in height having a surface resistance of 70 s m^{-1} and albedo of 0.23. Standardized equations for computing all parameters in Eq. 1 are given in FAO-56 (Allen et al., 1998) as well as in Smith et al. (1991) and Allen et al. (1994).

The crop coefficient. The crop coefficient, K_c, is basically the ratio of ET_c to the reference ET_o, and it represents an integration of the effects of major characteristics that distinguish the crop from the reference. These characteristics are crop height, crop-soil surface resistance, and albedo of the crop-soil surface. K_c is defined for pristine conditions having no water or other ET reducing stresses. Actual ET_c, denoted as $ET_{c\ act}$, is calculated as:

$$ET_{c\ act} = K_{c\ act}\ ET_o \tag{2}$$

where $ET_{c\ act}$ is the actual ET realized and $K_{c\ act}$ is the actual crop coefficient.

The linearized form used for K_c curves in FAO-56 was introduced in FAO-24 (Doorenbos and Pruitt, 1977). In FAO-56, two forms for K_c are presented: the "singular" K_c form of FAO-24 and the "dual" K_{cb} and K_e form introduced in FAO-56. In the dual form, the basal crop coefficient K_{cb} represents the ratio of ET_c to ET_o under conditions when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. Additional evaporation due to wetting of the soil surface by precipitation or irrigation is represented in an evaporation coefficient K_e. The total, actual $K_{c\ act}$ is the sum of K_{cb} and K_e reduced by any occurrence of soil water stress:

$$K_{c\ act} = K_s\ K_{cb} + K_e \tag{3}$$

where K_{cb} is the basal crop coefficient [0 - ~1.4], and K_e is a soil water evaporation coefficient [0 - ~1.4]. The stress reduction coefficient K_s [0 - 1], reduces the value of K_{cb} when the average soil water content of the root zone is not adequate to sustain full plant transpiration and is described later. K_e represents the evaporation component from wet soil that occurs in addition to the ET represented in K_{cb}. The sum of K_{cb} and K_e can not exceed some maximum value for a crop, based on energy limitations. The form and principle of Eq. 3 was first developed by Jensen et al., (1971) and Wright (1981, 1982).

In FAO-56, the K_{cb} curve is divided into four growth stage periods: the initial, the development, the midseason and the late season. The initial and midseason periods are characterized by horizontal line segments and the development and late season periods are characterized by rising and falling line segments (shown later as part of the "basal Kcb" lines of Fig. 1). Three point values for K_{cb} are required to generate the K_{cb} curve, namely the K_{cb} during the initial period, $K_{cb\ ini}$, the K_{cb} during the midseason, $K_{cb\ mid}$, and the K_{cb} at the time of harvest or dormancy, $K_{cb\ end}$.

FAO-24 (Doorenbos and Pruitt, 1977) presented four values for K_c for the midseason (i.e., $K_{c\ mid}$) and four values for K_c at the end of the season ($K_{c\ end}$) for each crop. The four values represented ratios of ET_c to ET_o under four different climatic cases (of wind and humidity). In contrast, FAO-56 includes only single entries for $K_{cb\ mid}$ and for $K_{cb\ end}$ for each crop. The single entries correspond to K_c values expected in a subhumid climate having average daytime minimum relative humidity (RH_{min}) of about 45 % and having calm to moderate wind speeds of 1 - 3 m s^{-1}, averaging 2 m s^{-1}. K_c and K_{cb} values are listed for about 80 crops in FAO-56. These can be accessed on the FAO web site at www.fao.org.

For climates where mean RH_{min} is different from 45 % or where wind speed at 2 m (u_2) is different from 2.0 m s^{-1}, $K_{cb\ mid}$ values from FAO-56 are adjusted as:

$$K_{cb\ mid} = K_{cb\ mid\ (table)} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \quad (4)$$

where $K_{c\ mid\ (table)}$ is the value for $K_{cb\ mid}$ from Table 17 of FAO-56, u_2 is mean daily wind speed at 2 m height [m s^{-1}], RH_{min} is mean daily minimum relative humidity [%] during the midseason period, and h is the mean plant height during the midseason period [m]. The adjustment in Eq. 4 accounts for impacts of differences in aerodynamic roughness between crops and the grass reference with climate. Justification is given in Allen et al. (1998). A similar adjustment is made to $K_{cb\ end}$.

Evaporation from soil. Evaporation from soil beneath a canopy or in between plants is predicted by estimating the amount of energy available at the soil surface. This energy is what remains following consumption of energy by transpiration. Transpiration plus baseline diffusive evaporation is approximated as $K_{cb}\ ET_o$. When the soil is wet, evaporation is presumed to occur at some maximum rate and the sum $K_c = K_{cb} + K_e$ is set equal to some maximum value $K_{c\ max}$ (defined in Eq. 6).

When the surface soil layer dries, a reduction in evaporation occurs:

$$K_e = K_r\ (K_{c\ max} - K_{cb}) \leq f_{ew}\ K_{c\ max} \quad (5)$$

where $K_{c\ max}$ is the maximum value of K_c following rain or irrigation, K_r is a dimensionless evaporation reduction coefficient (defined in Eq. 8) and is dependent on the cumulative depth of water depleted (evaporated), and f_{ew} is the fraction of the soil that is both exposed to solar radiation and that is wetted. Evaporation is restricted by the energy available at the exposed soil fraction, i.e., K_e cannot exceed $f_{ew}\ K_{c\ max}$. $K_{c\ max}$ represents an upper limit on evaporation and transpiration from the cropped surface and is introduced to reflect the natural constraints placed on available energy. $K_{c\ max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_o:

$$K_{c\ max} = \max\left(\left\{1.2 + \left[0.04(u_2 - 2) - 0.004\ (RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right\},\ \left\{K_{cb} + 0.05\right\}\right) \quad (6)$$

where h is the mean maximum plant height during the period of calculation (initial, development, mid-season, or late-season) [m], and max ( ) indicates the selection of the maximum value within the braces { }. Equation 6 ensures that $K_{c\ max}$ is always greater or equal to the sum $K_{cb} + 0.05$, suggesting that wet soil always increases the value for K_{cb} by 0.05 following complete wetting of the soil surface, even during periods of full ground cover. The value 1.2 represents the impact of reduced albedo of wet soil and the contribution of heat stored in dry soil prior to wetting events that are separated by more than 3 or 4 days.

It is presumed that the soil can dry to a soil water content that is halfway between wilting point, θ_{WP}, and oven dry (no water left). The amount of water that can be removed by evaporation during a complete drying cycle is hence estimated as:

$$\text{TEW} = 1000\ (\theta_{FC} - 0.5\,\theta_{WP})\ Z_e \tag{7}$$

where TEW (total evaporable water) is the maximum depth of water that can be evaporated from the surface soil layer when the layer has been initially completely wetted [mm]. Field capacity, θ_{FC}, and θ_{WP} are expressed in [$m^3\ m^{-3}$] and Z_e is the depth of the surface soil subject to drying by way of evaporation [0.10-0.15 m]. Typical values for θ_{FC}, θ_{WP} and TEW are given in FAO-56 for various soil types.

Evaporation from the exposed soil is presumed to take place in two stages: an energy limiting stage (stage 1), and a falling rate stage (stage 2). During stage 1, the soil surface remains wet and evaporation is assumed to occur at the maximum rate limited only by energy availability at the soil surface and therefore, $K_r = 1$. Stage 1 holds until the cumulative depth of evaporation, D_e, is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to near the soil surface at a rate to supply the demand. At the end of stage 1 drying, D_e is equal to REW (readily evaporable water). REW normally ranges from 5 to 12 mm and is highest for medium and fine textured soils.

In stage 2, evaporation decreases in proportion to the amount of water remaining in the surface soil layer:

$$K_r = \frac{\text{TEW} - D_{e,\,i\text{-}1}}{\text{TEW} - \text{REW}} \tag{8}$$

where $D_{e,i-1}$ is cumulative depletion from the soil surface layer at the end of day i-1 (the previous day) [mm], and TEW and REW are in mm (REW < TEW).

It is recognized that both the location and the fraction of the soil surface exposed to sunlight change to some degree with the time of day and depend on row orientation. The procedure presented here predicts a general, averaged fraction of the soil surface from which the majority of evaporation occurs. Evaporation from the soil beneath the crop canopy is included in the basal K_{cb} coefficient. Where the complete soil surface is wetted, as by precipitation or sprinkler, then the fraction of soil surface from which most evaporation occurs, f_{ew}, is defined as $(1-f_c)$, where f_c is the average fraction of soil surface covered by vegetation and $(1-f_c)$ is the approximate fraction of soil surface that is exposed. For irrigation systems where only a fraction of the ground surface is wetted, f_{ew} is limited to the fraction of the soil surface wetted by irrigation:

$$f_{ew} = \min\left(1 - f_c \, , \, f_w\right) \tag{9}$$

where $1\text{-}f_c$ has limits of [0.01 - 1] and f_w is the average fraction of soil surface wetted by irrigation or precipitation [0.01 - 1]. The limitation imposed by Eq. 9 presumes that the fraction of soil wetted by irrigation occurs within the fraction of soil exposed to sunlight and ventilation. This is generally the case, except perhaps with drip irrigation, when Eq. 9 is modified following Allen et al. (1998).

When f_c is not measured, f_c is estimated as:

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5h)} \tag{10}$$

where f_c is limited to [0-0.99] and $K_{c\ min}$ is the minimum K_c for dry bare soil with no ground cover. When possible, Eq. 10 is validated from field observations. $K_{c\ min}$ ordinarily has the same value as $K_{cb\ ini}$ used for annual crops under nearly bare soil conditions (i.e., $K_{c\ min} \sim 0.15$). The difference K_{cb} - $K_{c\ min}$ is limited to ≥ 0.01 for numerical stability. f_c decreases during the late season period in proportion to K_{cb} to account for local transport of sensible heat from senescing leaves to the soil surface.

The estimation of K_e requires a daily water balance computation for the exposed and wetted fraction of the surface soil layer to determine D_e:

$$D_{e,i} = D_{e,\,i\text{-}1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + T_{ew,i} + DP_{e,i} \tag{11}$$

where $D_{e,i-1}$ and $D_{e,i}$ are cumulative depletion depth at the ends of days i-1 and i [mm], P_i and RO_i are precipitation and precipitation runoff from the soil surface on day i [mm], I_i is the irrigation depth on day i that infiltrates the soil [mm], E_i is evaporation on day i (i.e., $E_i = K_e\ ET_o$) [mm], $T_{ew,\ i}$ is the depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i [mm], and $DP_{e,\ i}$ is the deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity [mm]. Assuming that the topsoil is at field capacity following heavy rain or irrigation, the minimum value for $D_{e,i}$ is zero. The limits imposed on $D_{e,i}$ are consequently $0 \leq D_{e,i} \leq TEW$. RO_i can be computed using the USDA curve number procedure. The irrigation depth is divided by f_w to approximate the infiltration depth to the f_w portion of the soil surface. Similarly, E_i is divided by f_{ew} since it is assumed that all E_i (besides a small amount of evaporation that is implicit to the K_{cb} coefficient) is taken from the f_{ew} fraction of the surface layer.

Except for shallow rooted crops (i.e., where the depth of the maximum rooting zone is < 0.5 to 0.6 m), the amount of transpiration from the evaporating soil layer is small and can be ignored (i.e., $T_{ew} = 0$). In this application, T_{ew} was estimated according to the fraction of the root zone that was in the surface soil layer, assuming a 40, 30, 20, and 10% extraction percentage for the top to bottom quarters of the root zone following procedures in FAO-56.

Downward drainage (percolation) of water from the topsoil layer is calculated as:

$$DP_{e,i} = (P_i - RO_i) + \frac{I_i}{f_w} - D_{e,\,i\text{-}1} \qquad \geq 0 \qquad (12)$$

As long as the soil water content in the evaporation layer is below field capacity (i.e., $D_{e,\,i} > 0$), the soil is assumed to not drain and $DP_{e,\,i} = 0$.

Water stress. The effects of soil water stress on crop ET are accounted for by multiplying K_{cb} by the water stress coefficient, K_s. Mean water content of the root zone is expressed by root zone depletion, D_r, i.e., water shortage relative to field capacity. At field capacity, $D_r = 0$. Stress is presumed to be induced when D_r equals RAW, the depth of readily available water in the root zone. For $D_r > RAW$, K_s is:

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)\ TAW} \qquad (13)$$

where K_s is a dimensionless transpiration reduction factor dependent on available soil water [0 - 1], D_r is root zone depletion [mm], TAW is total available soil water in the root zone [mm], and p is the fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r \leq RAW$, $K_s = 1$.

The total available water in the root zone is estimated as the difference between the water content at field capacity and wilting point:

$$TAW = 1000\,(\theta_{FC} - \theta_{WP})\,Z_r \qquad (14)$$

where Z_r is the effective rooting depth [m]. RAW is estimated as:

$$RAW = p\ TAW \qquad (15)$$

where RAW has units of TAW (mm). RAW and TAW represent readily and total available water in the root zone (Z_r), whereas REW and TEW represent readily and total water that can be evaporated from the soil surface layer (Z_e).

Model Application

An example application of the FAO-56 procedure is made for three crops at Kimberly, Idaho using precision lysimeter measurements by Wright (1982). The time-based basal K_c procedure of Wright (1982), which is based on alfalfa reference ET, is also applied to provide a comparison. The Wright (1982) procedure is described in that publication and it represents the current state-of-the-practice for much of the industry. The FAO-56 procedures represent perhaps a more universal application for a range of climates and soils. However, in this application, FAO-56 soil-related parameters and lengths of growth stages were fit to the Kimberly data as were those by Wright (1982).

The three crops grown at Kimberly were snap beans grown for seed, sugar beets and sweet corn harvested as silage in years 1974, 1975 and 1976. Dates for planting and harvest and for precipitation and irrigation were based on field observations for both K_c procedures. Values for K_{cb} were taken from FAO-56 and from Wright (1982) except for K_{cb} for sugar beets which was updated for the Wright procedure by Wright (1995). The date for full cover for sweet corn for the Wright (1982) procedure was based on that publication, with the date for sugar beets taken from Wright (1995) and the date for full cover for beans selected to fit the lysimeter data. Dates for beginning of development, midseason and late season periods for the FAO-56 procedure were selected to fit the lysimeter data. Weather data were assembled from a grassed weather station located about 1 km north of the lysimeter site. The resolution of the lysimeter system was about 0.05 mm.

In the FAO-56 application at Kimberly, the depth of the evaporation layer, Z_e, was set equal to 0.10 m and REW was set equal to 10 mm. The values for f_w were set equal to 0.5, 1.0, and 0.6 for beans, sugar beets and sweet corn for both the FAO and Wright methods to reflect the surface irrigation practices for each crop. $K_{c\ max}$ for the FAO method was computed using Eq. 6 and K_1, the equivalent of $K_{c\ max}$ for the Wright (1982) method, was fixed at 1.0.

Results

K_{cb} and $K_{c\ act}$ curves generated for the growing periods for the three crops are shown in Figure 1 for both the FAO-56 and Wright (1982) methods. Overlain on the curves are values for K_c based on lysimeter measurements. These values were obtained by dividing lysimeter measurements of $ET_{c\ act}$ by reference ET after correction for effects of precipitation or irrigation (Wright, 1982). Reference ET for the FAO-56 procedure was grass ET_o based on Eq. 1 whereas reference ET for Wright (1982) was alfalfa reference based on the 1982 Kimberly Penman equation.

Figure 2 shows comparisons between $ET_{c\ act}$ from Eq. 2 against lysimeter measurements for FAO-56 and Wright (1982) methods. Also shown are the unadjusted standard errors of estimate (SEE) between the estimates and lysimeter and the seasonal ratio of predicted ET to measured ET. In all cases, the seasonal ratios were nearly 1.0 and values for SEE averaged about 0.77 mm/day for both methods. This SEE is equivalent to about 15% of average daily $ET_{c\ act}$ indicating predictive accuracy for any single day of about +/- 15% about 70% of the time. Accuracy for a series of days would be better than 15% due to canceling of random errors.

Evaporation Estimates

The dual K_c approaches used by Wright (1982) and FAO-56 provide predictions of evaporation from the soil surface. This is useful for studies that desire to optimize crop production by reducing the soil evaporation fraction of ET. Total seasonal evaporation as percentages of total seasonal ET are listed in Figure 1. Percentages for the FAO-56 method ranged from 13% for beans to 24% for sweet corn. Percentages for the Wright (1982) method ranged from 7% for beans to 13% for sweet corn. Estimates by the FAO-56 were almost double those from Wright (1982).

Unfortunately, the lysimeter measurements provided only integrated values of ET, so that the predictions of evaporation could not be evaluated for accuracy.

Both prediction methods followed the evaporation "spikes" in the K_c caused by soil wetting (Figure 1), but the spikes for the FAO method were somewhat wider than for Wright (1982). Estimates of soil evaporation from both methods do not include the evaporation from soil that occurs as a diffusive component of K_{cb} over time. Therefore, the percentages shown on Figure 1 do not represent all evaporation that took place from the soil surface during the season. The diffusive components may have added an additional 5 to 10% to the values shown.

Summary and Conclusions

Both the Wright (1982) and FAO-56 methods provide good estimates of ET following periods of wetting by precipitation and irrigation. Each method predicted with relatively equal accuracy for the three crops at Kimberly, with the FAO-56 predicting about twice as much soil evaporation as the Wright (1982) method. More testing is needed for systems where separate measurements of evaporation and transpiration have been made.

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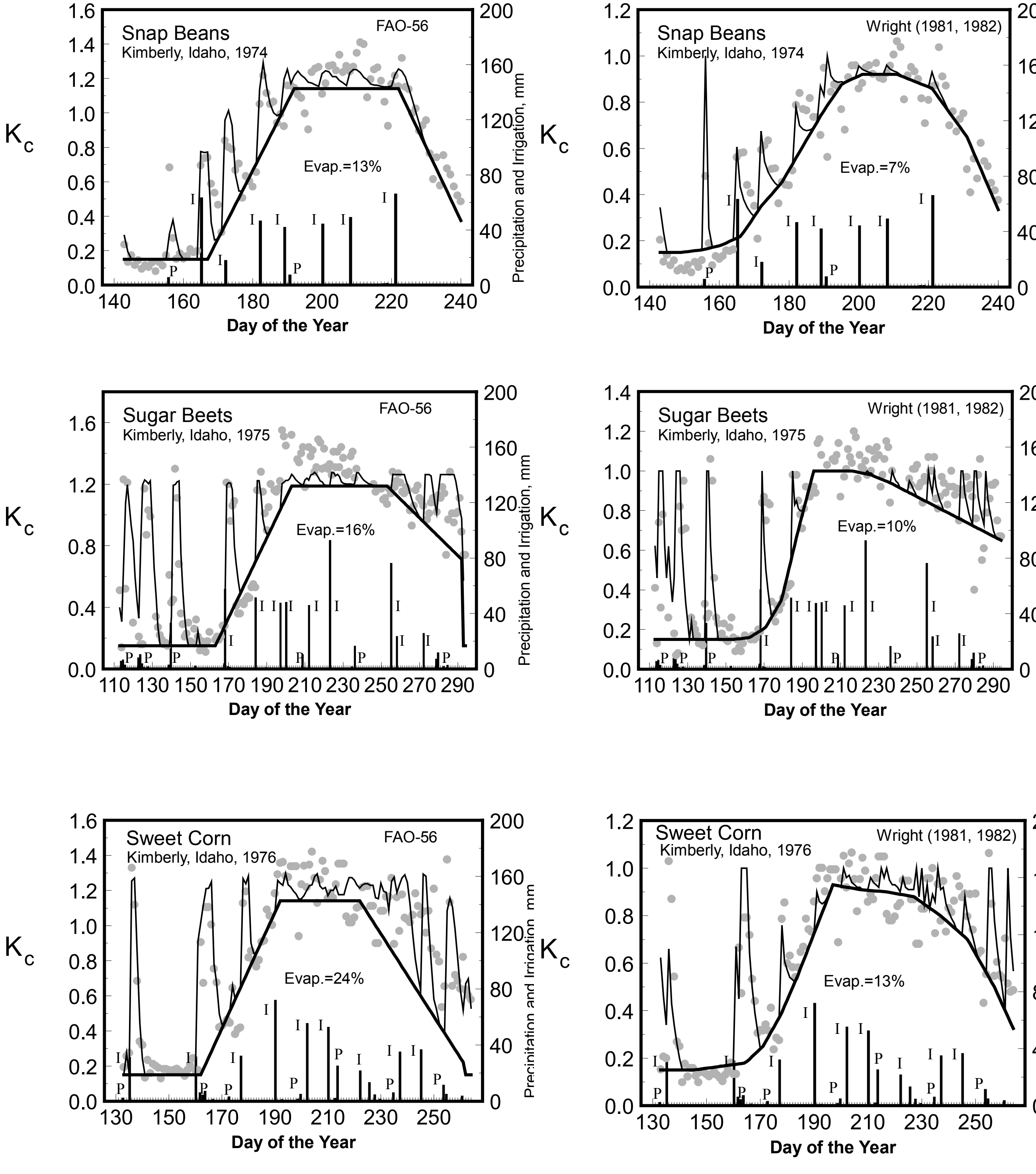

Figure 1. Daily crop coefficients based on measured ET and predicted using the basal K_c approach at Kimberly, Idaho for a) snap beans with FAO-56, b) snap beans with Wright (1981, 1982), c) sugar beets with FAO-56, d) sugar beets with Wright (1981, 1982), e) sweet corn with FAO-56, and f) sweet corn with Wright (1981, 1982). Figures run left to right and top to bottom.

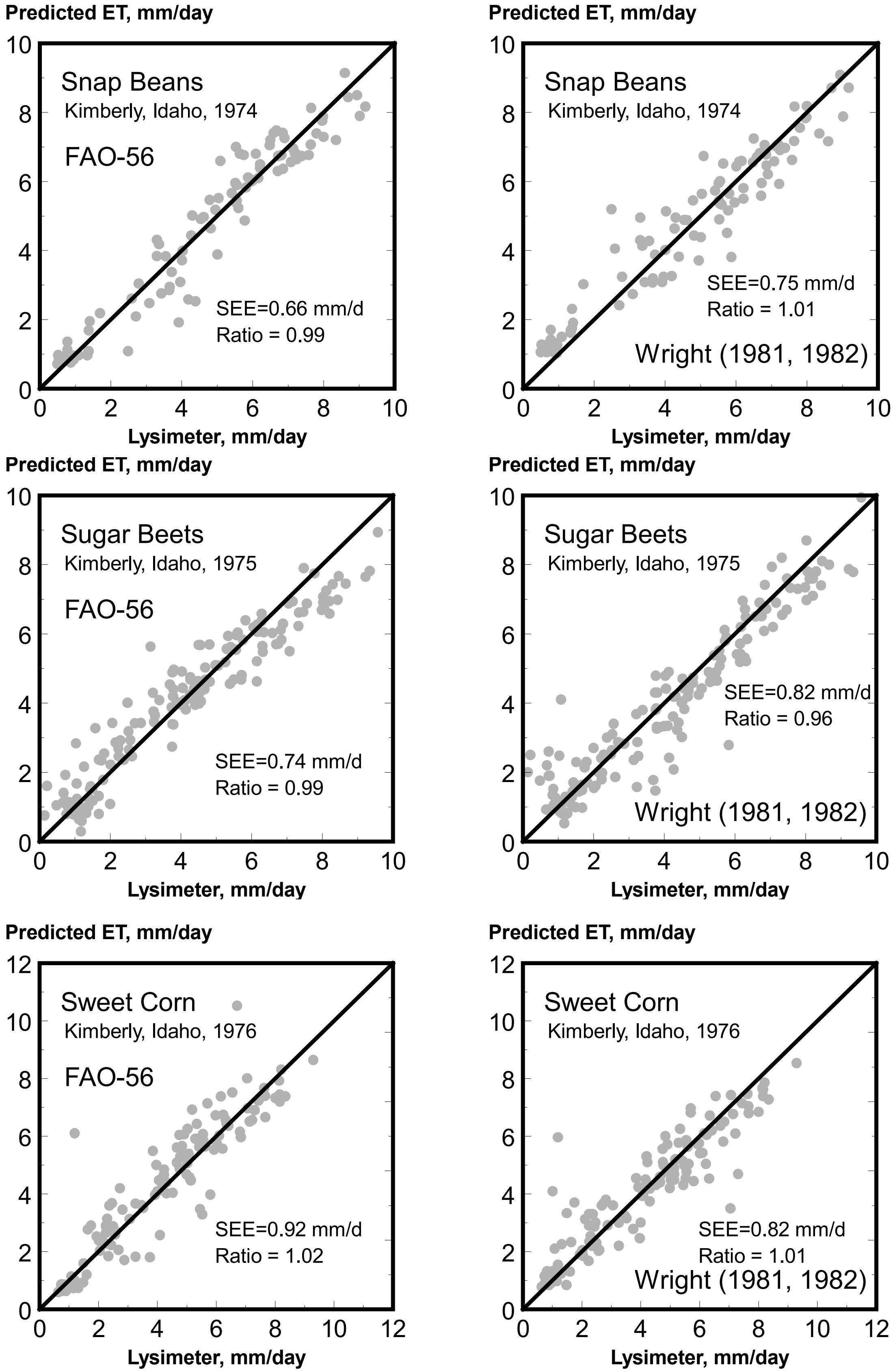

Figure 2. Daily measured and predicted ET at Kimberly, Idaho for a) snap beans with FAO-56 and, b) with Wright (1981, 1982), c) sugar beets with FAO-56 and, d) with Wright (1981, 1982), e) sweet corn with FAO-56 and, f) with Wright (1981, 1982). Figures run left to right and top to bottom.