Annex 1.

FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions

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Abstract: Crop coefficient curves provide simple, reproducible means to estimate crop evapotranspiration (ET) from weather-based reference ET values. The dual crop coefficient (K_c) method of the Food and Agricultural Organization of the United States (FAO) Irrigation and Drainage Paper No. 56 (*FAO-56*) is intended to improve daily simulation of crop ET by considering separately the contribution of evaporation from soil. The dual method utilizes "basal" crop coefficients representing ET from crops having a dry soil surface and separately predicts evaporation from bare soil based on a water balance of the soil surface layer. Three extensions to the evaporation calculation procedure are described here that are intended to improve accuracy when applications warrant the extra complexity. The first extension uses parallel water balances representing the portion of the soil surface wetted by irrigation and precipitation together and the portion wetted by precipitation alone. The second extension uses three "stages" for surface drying and provides for application to deep cracking soils. The third extension predicts the extraction of the transpiration component from the soil surface layer. Sensitivity and analyses and illustrations indicate moderate sensitivity of daily calculated ET to application of the extensions. The dual K_c procedure, although relatively simple computationally and structurally, estimates daily ET as measured by lysimeter relatively well for periods of bare soil and partial and full vegetation cover.

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CE Database subject headings: Evapotranspiration; Evaporation; Crops; Crop moisture index; Soil water.

Introduction

A commonly used approach for estimating consumptive use of water by irrigated crops is the crop coefficient—reference evapotranspiration (K_c ET_0) procedure. Reference evapotranspiration (ET_0) is computed for a grass or alfalfa reference crop and is then multiplied by an empirical crop coefficient (K_c) to estimate crop evapotranspiration (ET_c) (Jensen et al. 1971; Doorenbos and Pruitt 1977; Wright 1981, 1982). In general, three primary characteristics distinguish ET from a crop from ET from the reference surface: aerodynamic roughness of the crop; general resistance within the crop canopy and soil to the flow of heat and water vapor; and reflectance of the crop and soil surface to short wave radiation. Because ET_0 represents nearly all effects of weather, K_c varies predominately with specific crop characteristics and only a small amount with climate. This enables the transfer of standard values and curves for K_c between locations and climates. This transfer has led to the widespread acceptance and usefulness of the K_c approach.

In situations where K_c has not been derived by ET measurement, it can be estimated from fraction of ground cover or leaf area index (Allen et al. 1998). K_c varies during the growing season as plants develop, as the fraction of ground covered by vegetation changes, and as plants age and mature (Fig. 1). K_c varies according to the wetness of the soil surface, especially when there is little vegetation cover. Under bare soil conditions, K_c has a high value when soil is wet and its value steadily decreases as the soil dries.

This paper describes the dual K_c procedure of FAO published as *FAO Irrigation and Drainage Paper No. 56* (Allen et al. 1998) and provides a brief rationale for various components of the procedure along with selected sensitivity analyses. Extensions to the original procedure are introduced that may improve accuracy of applications for special situations.

FAO-56 K_c Procedure

The *FAO-56* crop coefficients are intended for use with grass reference ET_0 similar to that predicted by the *FAO-56* Penman–Monteith method (Allen et al. 1998). The *FAO-56* Penman–Monteith equation predicts ET_0 from a hypothetical grass reference surface that is 0.12 m in height having a surface resistance of 70 s m^{-1} for 24 h time steps and albedo of 0.23. Standardized equations for computing parameters in the *FAO-56* Penman–Monteith equation are given in Allen et al. (1998, 1994) as well

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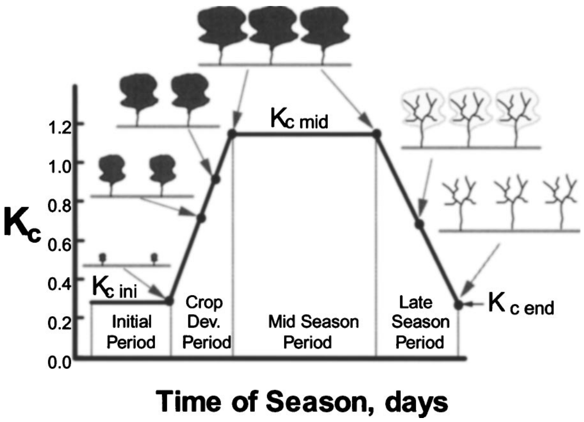

Fig. 1. Schematic showing generalized shape of Food and Agricultural Organization (FAO) K_c curve with four crop stages and three K_c (or K_{cb}) values and relative development of vegetation

as in Smith et al. (1991), Pereira et al. (1998), Pereira and Allen (1999), and ASCE (2002).

Crop Coefficient

Fundamentally, the crop coefficient is defined as the ratio of ET from any specific crop or soil surface to some reference ET as defined by weather data. In *FAO-56* nomenclature

$$K_c = \frac{\mathrm{ET}_c}{\mathrm{ET}_0} \tag{1}$$

In *FAO-56*, values listed for K_c represent ET under growing conditions having a high level of management and with little or no water or other ET reducing stresses and thus represent what are referred to as potential levels for crop ET

$$\mathrm{ET}_c = K_c \mathrm{ET}_0 \tag{2}$$

Actual ET_c can be less than the potential ET_c for a crop under nonideal growing conditions including those having water stress or high soil salinity. In this paper, ET_c representing ET under any condition, ideal or nonideal, is termed "actual ET_c" and is denoted as $\mathrm{ET}_{c\ \mathrm{act}}$. The $\mathrm{ET}_{c\ \mathrm{act}}$ was termed "adjusted ET_c" ($\mathrm{ET}_{c\ \mathrm{adj}}$) in *FAO-56*. The terms are synonymous and

$$\mathrm{ET}_{c\ \mathrm{act}} = K_{c\ \mathrm{act}} \mathrm{ET}_0 \tag{3}$$

where $K_{c\ \mathrm{act}}$ = "actual" crop coefficient that includes any effects of environmental stresses.

A linearized form for mean K_c and basal K_c curves in *FAO-56* was introduced in *FAO-24* (Doorenbos and Pruitt 1977) where the FAO K_c curve is comprised of four straight line segments representing the initial period, the development period, the midseason period, and the late season period (Fig. 1). These segments are defined by three primary K_c values: K_c during the initial period ($K_{c\ \mathrm{ini}}$), K_c during the midseason (full cover) period ($K_{c\ \mathrm{mid}}$), and K_c at harvest (or at the end of the late season) ($K_{c\ \mathrm{end}}$). The $K_{c\ \mathrm{ini}}$ defines the horizontal portion of the K_c curve during the initial period until approximately 10% of the ground is covered by vegetation. The $K_{c\ \mathrm{mid}}$ defines the value for K_c during the peak period for the crop, which is normally when the crop is at "effective full cover." This period is described by a horizontal line extending through $K_{c\ \mathrm{mid}}$. The development period is defined by a sloping line that connects the initial and midseason periods. The late season has a sloping line that connects the end of the midseason period with the harvest (end) date.

In *FAO-56*, two forms for K_c are presented: the "singular" K_c form used in *FAO-24* and the "dual" $K_c = K_{\mathrm{cb}} + K_e$ form introduced in *FAO-56*, where K_{cb} is the basal crop coefficient and K_e is the soil evaporation coefficient. In the dual form, K_{cb} represents the ratio of ET_c to ET_0 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. Under basal conditions, small amounts of evaporation from the surface soil layer occur by diffusion and are included in K_{cb} (and thus $K_{\mathrm{cb\ ini}}$ is usually not set to zero during the growing cycle). The majority of evaporation from soil following wetting by precipitation or irrigation is represented by the separate K_e. The total, actual $K_{c\ \mathrm{act}}$ is the sum of K_{cb} and K_e, reduced by any occurrence of soil water stress

$$K_{c\ \mathrm{act}} = K_s K_{\mathrm{cb}} + K_e \tag{4}$$

where K_{cb} and K_e range from $[0 \text{ to } \sim 1.4]$. The stress reduction coefficient K_s [0–1], reduces K_{cb} when the average soil water content or salinity level of the root zone are not conducive to sustain full plant transpiration. K_s for soil water stress is described later and the function for salinity induced stress is described in Allen et al. (1998). The sum of K_{cb} and K_e cannot exceed some maximum value for a crop–soil complex (generally ~ 1.4 for *FAO-56* based ET_0), based on energy limitations. The form and principle of Eq. (4) was developed by Jensen et al. (1971), Wright and Jensen (1978), and Wright (1981, 1982).

The K_{cb} curve has the same shape as in Fig. 1 and three benchmark values for K_{cb} are used to construct the curve, namely $K_{\mathrm{cb\ ini}}$, $K_{\mathrm{cb\ mid}}$, and $K_{\mathrm{cb\ end}}$. Because K_{cb} can include "diffusive" or residual evaporation from soil for potentially long periods following wetting, $K_{\mathrm{cb\ ini}}$ is generally set to 0.15 in *FAO-56* for annual crops for the period from planting to before 10% ground cover. However, under dry conditions with long periods between wetting events or during the nongrowing season, $K_{\mathrm{cb\ ini}}$ can be set equal to 0. This is illustrated later.

FAO-56 describes the procedure for applying the dual method on a daily basis, with specific estimation of evaporation from wet soil. The dual approach is well suited for predicting the effects of day to day variation in soil water evaporation and the effectiveness of precipitation.

Adjustment for Climate

FAO-24 (Doorenbos and Pruitt 1977) presented, for each crop listing, four values for singular midseason and end-of-season crop coefficients, termed in *FAO-56* as $K_{c\ \mathrm{mid}}$ and $K_{c\ \mathrm{end}}$. The four values represented four climatic cases of wind and humidity that impact the value for K_c. In contrast, *FAO-56* includes only single entries for $K_{c\ \mathrm{mid}}$ and for $K_{c\ \mathrm{end}}$, or, in the case of K_{cb}, for $K_{\mathrm{cb\ mid}}$ and for $K_{\mathrm{cb\ end}}$. The single entries correspond to K_c or K_{cb} values associated with a standard subhumid climate having average daytime minimum relative humidity ($\mathrm{RH}_{\min}$) of about 45% and having calm to moderate wind speeds of $1\text{–}3\ \mathrm{m\,s^{-1}}$, averaging $2\ \mathrm{m\,s^{-1}}$. K_c and K_{cb} values are listed for about 80 crops in *FAO-56*. These can be accessed on the FAO web site (FAO 1998).

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

$$K_{\mathrm{cb\ mid}} = K_{\mathrm{cb\ mid\ (standard\ climate)}} + [0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (5)$$

where $K_{\mathrm{cb\ mid(standard\ climate)}}$=value for $K_{\mathrm{cb\ mid}}$ from Table 17 of *FAO-56*; u_2=mean daily wind speed at 2 m height (m s^{-1}); $\mathrm{RH}_{\min}$=mean daily minimum relative humidity (%) during the midseason period; and h=mean plant height during the midseason period (m). The adjustment in Eq. (5) accounts for impacts of differences in aerodynamic roughness between crops and the grass reference with changing climate and closely replicates the range in K_c values for the four climatic classes of *FAO-24*. Justification for Eq. (5) is given in Allen et al. (1998). Similar adjustment is made to $K_{\mathrm{cb\ end}}$ when values for $K_{\mathrm{cb\ end}} > 0.45$. Eq. (5) can be applied daily using daily values for u_2 and $\mathrm{RH}_{\min}$ or can be applied for the midseason in total using averages for u_2 and $\mathrm{RH}_{\min}$ for the period with relatively small loss in accuracy. When only mean daily dewpoint temperature or vapor pressure is known, $\mathrm{RH}_{\min}$ can be approximated as $\mathrm{RH}_{\min} \sim 100 e_a / e^0(T_{\max})$, where e_a is actual vapor pressure and $e^0(T_{\max})$ is saturation vapor at daily maximum air temperature. The crop height adjustment in Eq. (5) is applied to both the wind and the $\mathrm{RH}_{\min}$ terms because both terms appear in the aerodynamic term of the Penman–Monteith equation and both factors influence ET in some proportion to aerodynamic roughness.

Evaporation from Soil

The approach of *FAO-56* is similar to that of Ritchie (1972), Saxton et al. (1974), and Wright (1982) where evaporation from soil beneath a canopy or inbetween plants is predicted by estimating the amount of energy at the soil surface in conjunction with energy consumed by transpiration. When the soil is wet, evaporation is predicted to occur at some maximum rate and the sum $K_c = K_{\mathrm{cb}} + K_e$ is limited by some maximum value $K_{c\ \max}$.

As the surface soil layer dries, a reduction in evaporation occurs, and K_e is simulated as

$$K_e = K_r(K_{c\ \max} - K_{\mathrm{cb}}) \leqslant f_{\mathrm{ew}} K_{c\ \max} \quad (6)$$

where $K_{c\ \max}$=maximum value of K_c following rain or irrigation; K_r=dimensionless evaporation reduction coefficient and is dependent on the cumulative depth of water depleted (evaporated); and f_{ew}=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 $f_{\mathrm{ew}} K_{c\ \max}$. The *FAO-56* dual procedure differs from Ritchie (1972) and Saxton et al. (1974) in that the FAO procedure gives K_e (as limited by $f_{\mathrm{ew}} K_{c\ \max}$) equal priority to transpiration (as represented by K_{cb}) in regard to energy consumption, whereas the Ritchie and Saxton approaches give transpiration priority over evaporation.

$K_{c\ \max}$ represents an upper limit on evaporation and transpiration from the cropped surface and is introduced to reflect the natural constraints on available energy. $K_{c\ \max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_0

$$K_{c\ \max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{\mathrm{cb}} + 0.05\}\right) \quad (7)$$

where h=mean plant height during the period of calculation (initial, development, mid-season, or late-season) (m), and the max () function indicates the selection of the maximum of values separated by the comma. Eq. (7) ensures that $K_{c\ \max}$ is always greater than or equal to the sum $K_{\mathrm{cb}} + 0.05$, suggesting that wet soil always increases the K_c value above 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. The value also considers the effect of increased aerodynamic roughness of surrounding crops during development, midseason, and late season growth stages which can increase the turbulent transfer of vapor from the exposed soil surface. Bonachela et al. (2001) noted $K_{c\ \max}$ of over 1.5 for soil evaporation from a drip-irrigated olive orchard caused by microadvection of heat from dry surface areas to wet surface areas. Under complete surface wetting, $K_{c\ \max}$ would be expected to be lower, for example ranging from 1.0 to 1.2. In addition, if irrigation or precipitation events are more frequent than 3 days each, for example daily or 2 days each, then the soil has less opportunity to absorb heat between wetting events, and the 1.2 value can be reduced to about 1.1.

The surface soil layer is presumed to dry to an air dry water content approximated as halfway between wilting point θ_{WP} and oven dry. The amount of water that can be removed by evaporation during a complete drying cycle is estimated as

$$\mathrm{TEW} = 1000(\theta_{\mathrm{FC}} - 0.5\theta_{\mathrm{WP}}) Z_e \quad (8)$$

where (total evaporable water) (TEW)=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 ($\mathrm{m}^3\ \mathrm{m}^{-3}$) and Z_e(m)=effective depth of the surface soil subject to drying to 0.5 θ_{WP} by way of evaporation. Typical values for θ_{FC}, θ_{WP}, and TEW are given in Table 1 for various soil types. Z_e is an empirical value based on observation. *FAO-56* recommended values for Z_e of 0.10–0.15 m, with 0.1 m recommended for coarse soils and 0.15 m recommended for fine textured soils. However, the user should select the value for Z_e, or even TEW, that represents evaporation amounts observed over complete drying cycles via gravimetric or other measurement. Some evaporation or soil drying will be observed to occur below the Z_e depth.

Evaporation from exposed soil is presumed to take place in two stages: an energy limiting stage (Stage 1), and a falling rate stage (Stage 2) (Philip 1957 and Ritchie 1972). During Stage 1, the soil surface remains wet and evaporation is predicted to occur at the maximum rate limited only by energy availability at the soil surface and therefore, $K_r = 1$. As the soil surface dries, the evaporation rate decreases below the potential evaporation rate (defined as $K_{c\ \max} - K_{\mathrm{cb}}$), and K_r becomes less than one. K_r becomes zero when no water is left for evaporation in the evaporation layer.

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 readily evaporable water (REW). Readily evaporable water normally ranges from 5 to 12 mm and is highest for medium and fine textured soils (Ritchie 1972; Ritchie et al. 1989).

The second stage, where K_r is decreasing, begins when D_e exceeds REW. At this point, the soil surface is visibly dry, and evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer. Most early Stage 2 models (Philip 1957; Ritchie 1972) proportion the evaporation rate according to the square root of time since the begin-

Table 1. Typical Soil Water Characteristics for Different Soil Types (from *FAO-56*)

				Evaporation parameters		
	Soil water characteristics			Amount of water that can be depleted by evaporation		
Soil type (USDA soiltexture classification)	θ_{FC} $m^3\,m^{-3}$	θ_{WP} $m^3\,m^{-3}$	$(\theta_{FC}\text{-}\theta_{WP})$ $m^3\,m^{-3}$	Stage 1 REW (mm)	Stages 1 and 2 TEW[a] ($Z_e=0.10$ m) (mm)	Stages 1 and 2 TEW[a] ($Z_e=0.15$ m) (mm)
Sand	0.07–0.17	0.02–0.07	0.05–0.11	2–7	6–12	9–13
Loamy sand	0.11–0.19	0.03–0.10	0.06–0.12	4–8	9–14	13–21
Sandy loam	0.18–0.28	0.06–0.16	0.11–0.15	6–10	15–20	22–30
Loam	0.20–0.30	0.07–0.17	0.13–0.18	8–10	16–22	24–33
Silt loam	0.22–0.36	0.09–0.21	0.13–0.19	8–11	18–25	27–37
Silt	0.28–0.36	0.12–0.22	0.16–0.20	8–11	22–26	33–39
Silt clay loam	0.30–0.37	0.17–0.24	0.13–0.18	8–11	22–27	33–40
Silty clay	0.30–0.42	0.17–0.29	0.13–0.19	8–12	22–28	33–42
Clay	0.32–0.40	0.20–0.24	0.12–0.20	8–12	22–29	33–43

Note: USDA=United States Department of Agriculture; REW=readily evaporated water; and TEW=totally evaporated water.

[a] $\text{TEW}=(\theta_{FC}-0.5\theta_{WP})Z_e$.

ning of Stage 2. This requires manipulation of time terms as new water enters the system. Moreover, the proportionality factor changes with ET_0 demand and therefore requires frequent recalibration (Snyder et al. 2000). In the *FAO-56* model, the reduction in evaporation during Stage 2 is proportional to the cumulative evaporation from the surface soil layer, resulting in a more simple, easily managed computation procedure that is based on a soil–water balance and that does not require recalibration

$$K_r = \frac{\text{TEW} - D_{e,j-1}}{\text{TEW} - \text{REW}} \tag{9}$$

for $D_{e,j-1} > \text{REW}$, where $D_{e,j-1}$=cumulative depletion from the soil surface layer at the end of day $j-1$ (the previous day) (mm); and TEW and REW are in millimeters (REW<TEW). The general form for the K_r function is illustrated in Fig. 2. The prediction by Eq. (9) is similar to that predicted by a square-root-of-time Stage 2 model, and differences are in general smaller than the uncertainties caused by the continuously changing effects of soil hydraulic properties, tillage, soil temperature, wetting characteristics, and root extraction. Saxton et al. (1974) used a nonlinear proportionality based on water content of the surface layer that had similar behavior as Eq. (9). A three-stage drying process can be applied to cracking soils as described in a following section. Mutziger et al. (2001) found good agreement between K_r predicted using the *FAO-56* dual method using REW and TEW from Table 1 (with Z_e=0.1 m) and relative evaporation measurements published by Chanzy and Bruckler (1993) for loam, silty clay loam, and clay soils.

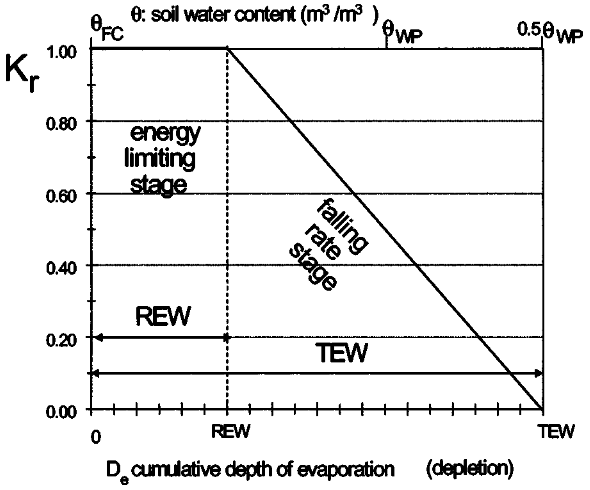

Fig. 2. General function for soil evaporation reduction coefficient K_r for two-stage *FAO-56* model (from *FAO-56*)

In crops having partial ground cover, evaporation from the soil usually occurs nonuniformly over the surface, and is greater between plants having dense canopies near the ground where exposure to sunlight occurs and where more air ventilation is able to transport vapor from the soil surface to above the canopy. This is especially true where only part of the soil surface is wetted by irrigation. While it is recognized that both the locations and the fractions of the soil surface exposed to sunlight and ventilation may change with the time of day and depend on row orientation and near surface canopy density, the procedure of *FAO-56* predicts a general, averaged fraction of soil surface from which the majority of evaporation is expected to occur. Most evaporation from the soil beneath the crop canopy, occurring at a slower rate, is in many situations included in the basal K_{cb} coefficient.

Table 2. Common Values for Fraction of Soil Surface Wetted by Irrigation or Precipitation (after *FAO-56*)

Wetting event	f_w
Precipitation	1.0
Sprinkler irrigation, field crops	1.0
Sprinkler irrigation, orchards	0.7–1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6–1.0
Furrow irrigation (every furrow), wide bed	0.4–0.6
Furrow irrigation (alternated furrows)	0.3–0.5
Microspray irrigation, orchards	0.5–0.8
Trickle (drip) irrigation	0.3–0.4

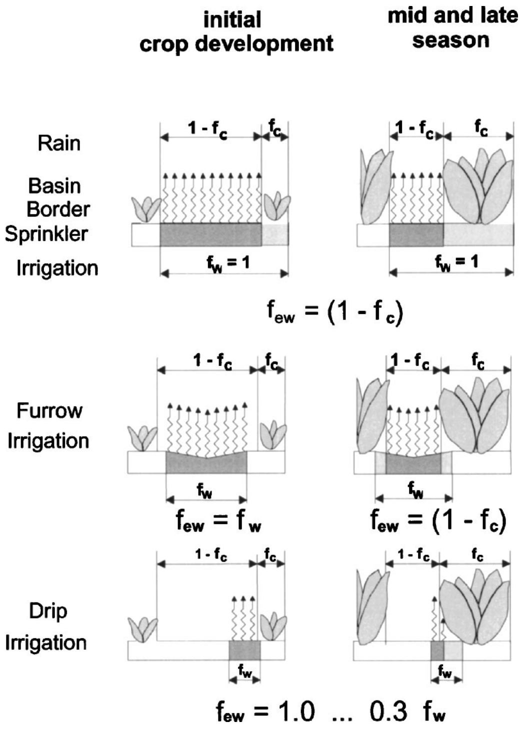

Fig. 3. Determination of f_{ew} (greyed areas) as function of fraction of ground surface coverage (f_c) and fraction of surface wetted (f_w) (from *FAO-56*)

In the *FAO-56* model, the term f_w is defined as the fraction of the surface wetted by irrigation and/or precipitation. This term defines the potential spatial extent of evaporation. Common values for f_w are listed in Table 2. An extension to Eq. (10) is described later.

When the soil surface is completely wetted, as by precipitation or sprinkler, f_{ew} of Eq. (6) is set equal to $(1-f_c)$, where f_c is the fraction of soil surface effectively covered by vegetation and $(1-f_c)$ represents the approximate fraction of soil surface that is effectively exposed to evaporation energy. For irrigation systems where only a fraction of the ground surface (f_w) is wetted, f_{ew} is limited to f_w

$$f_{\mathrm{ew}} = \min(1 - f_c, f_w) \tag{10}$$

Both $1-f_c$ and f_w, for numerical stability, have limits of [0.01–1]. The limitation imposed by Eq. (10) presumes the fraction of soil wetted by irrigation occurs within the primary fraction of soil exposed to sunlight and ventilation. This is generally the case, except with some drip irrigation (Fig. 3). In the case of drip irrigation, Allen et al. (1998) recommended multiplying f_w by $[1-(2/3)f_c]$. Pruitt et al. (1984) and Bonachela et al. (2001) have described evaporation patterns and extent under drip irrigation.

Predicting Fraction of Surface Cover

The difference $(1-f_c)$ represents the fraction of the soil effectively exposed to sunlight and air ventilation and serves as the site where the majority of evaporation is expected to occur. The value for f_c is limited to <0.99 for numerical stability and is generally determined by visual observation. For purposes of estimating f_{ew}, f_c can be estimated from K_{cb} as

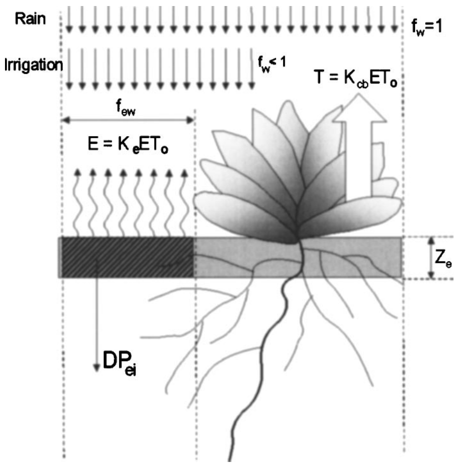

Fig. 4. Water balance of soil surface layer (from *FAO-56*)

$$f_c = \left(\frac{K_{\mathrm{cb}} - K_{c\,\min}}{K_{c\,\max} - K_{c\,\min}}\right)^{(1+0.5h)} \tag{11}$$

where f_c is limited to [0–0.99] and $K_{c\,\min}$=minimum K_c for dry bare soil with no ground cover. Eq. (11) assumes that the value for K_{cb} is largely governed by the fraction of vegetation cover. The $1+0.5h$ exponent in Eq. (11) represents the impact of plant height on shading of the soil surface and in increasing the value for K_{cb} given a specific value for f_c. The difference $K_{\mathrm{cb}}-K_{c\,\min}$ is limited to $\geqslant 0.01$ for numerical stability. The value for f_c will change daily as K_{cb} changes. $K_{c\,\min}$ ordinarily has the same value as $K_{\mathrm{cb\ ini}}$ used for annual crops under nearly bare soil conditions (i.e., $K_{c\,\min} \sim 0.15$). The value for 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.

Under vegetation having an open canopy near the ground surface, for example some types of orchards, a large proportion, if not all, of the ground surface is effectively exposed to evaporative energy (Bonachela et al. 2001). In these situations, $1-f_c$ does not have large impact on f_{ew}, and $f_{\mathrm{ew}}=f_w$ can be applied. The decision in assigning values for f_c and f_{ew} should be based on field observation of drying patterns.

Water Balance of Soil Surface Layer

Calculation of K_e requires a daily water balance for the f_{ew} fraction of the surface soil layer. The daily soil water balance equation is (Fig. 4)

$$D_{e,j} = D_{e,j-1} - (P_j - \mathrm{RO}_j) - \frac{I_j}{f_w} + \frac{E_j}{f_{\mathrm{ew}}} + T_{\mathrm{ei},j} + \mathrm{DP}_{\mathrm{ei},j} \tag{12}$$

where $D_{e,j-1}$ and $D_{e,j}$=cumulative depletion depth at the ends of days $j-1$ and j (mm); P_j and RO_j=precipitation and precipitation runoff from the soil surface on day j (mm); I_j=irrigation depth on day j that infiltrates the soil (mm); E_j=evaporation on day j (i.e., $E_j=K_e\mathrm{ET}_0$) (mm); $T_{\mathrm{ei},j}$=depth of transpiration from the exposed and wetted fraction of the soil surface layer on day j (mm); and $\mathrm{DP}_{\mathrm{ei},j}$=deep percolation from the soil surface layer on day j if soil water content exceeds field capacity (mm). Assuming that the surface layer is at field capacity following heavy rain or irrigation, the minimum value for $D_{e,j}$ is zero and limits imposed are $0 \leqslant D_{e,j} \leqslant \mathrm{TEW}$. It is recognized that water content of the soil surface layer can exceed TEW for short periods of time while drainage is occurring. However, because the length of time that this occurs varies with soil texture, wetting depth, and tillage, $D_{e,j} \geqslant 0$ is assumed. Additionally, it is recognized that some drainage in soil occurs at very small rates at water contents below field capacity. To some extent, impacts of these simple assumptions can be compensated for, if needed, in setting the value for Z_e or TEW.

RO_j can be computed using the USDA curve number procedure (Hawkins et al. 1985). The irrigation depth I_j is divided by f_w to approximate the infiltration depth to the f_w portion of the soil surface. Similarly, E_j is divided by f_{ew} because it is assumed that all E_j (other than residual evaporation implicit to the K_{cb} coefficient) is taken from the f_{ew} fraction of the surface layer.

Except for shallow rooted crops, where the depth of the maximum rooting is less than 0.5–0.6 m, the amount of transpiration extracted from the f_{ew} portion of the surface soil layer is small and can be ignored (i.e., $T_{\mathrm{ei}}=0$). Where transpiration is known to extract water from the f_{ew} fraction of the surface layer, but is not considered in Eq. (12), *FAO-56* advises that the depth of the surface layer Z_e be decreased to compensate for the quicker drying. Estimation of T from the f_{ew} fraction of the surface layer is described in a following section.

Following heavy rain or irrigation, the soil water content in the surface layer (Z_e layer) might exceed field capacity for short time periods until excess water moves into the root zone and perhaps even deeper. In the simple water balance procedure used in *FAO-56*, however, it is assumed that the soil water content is limited to $\leqslant \theta_{\mathrm{FC}}$ on the day of a complete wetting event. This is a reasonable assumption considering the shallowness of the surface layer. Downward drainage (percolation) of water from the surface layer is calculated as

$$\mathrm{DP}_{e,j} = (P_j - \mathrm{RO}_j) + \frac{I_j}{f_w} - D_{e,j-1} \geqslant 0 \qquad (13)$$

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

Initialization of Water Balance

To initiate the water balance for the evaporating layer, the user can assume that the soil surface layer is near θ_{FC} following a heavy rain or irrigation so that $D_{e,j-1}=0$. Where a long period of time has elapsed since the last wetting, the user can assume that all evaporable water has been depleted from the evaporation layer at the beginning of calculations so that $D_{e,j-1}=\mathrm{TEW}=1{,}000(\theta_{\mathrm{FC}} - 0.5\,\theta_{\mathrm{WP}})\,Z_e$.

Order of Calculation

Calculations for the *FAO-56* dual $K_{\mathrm{cb}}+K_e$ procedure, for example when using a spreadsheet, proceed in the following order: K_{cb}, h, $K_{c\ \mathrm{max}}$, f_c, f_w, f_{ew}, K_r, K_e, E, DP_e, D_e, I, K_c, and ET_c.

Extensions to FAO-56 Procedure

The evaporation component of the *FAO-56* dual K_c procedure was intended for routine application under a wide range of conditions. The procedure constitutes a balance between simplicity, understandability, and completeness and is recommended for most applications. The following three extensions to the *FAO-56* procedure may increase accuracy and definition of the total evaporation and drying process under special conditions.

Separate Prediction of Evaporation from Soil Wetted by Precipitation Only

The evaporation component is assumed to be fully concentrated in the exposed and wetted fraction of the surface layer. The slower rate of evaporation occurring from beneath the vegetation canopy is generally included in K_{cb} and is therefore not explicitly quantified. E is computed as $K_e\ \mathrm{ET}_0$. The quotient E/f_{ew} in Eq. (12) describes the concentration of evaporation over the fraction of the soil that is both exposed and wetted.

Parameter $f_w=1$ for precipitation but is often <1 for some types of surface irrigation and micro irrigation. *FAO-56* recommended a procedure for calculating f_w according to the type of last wetting event and its extent. However, this determination can be subjective and uncertain. This section describes an extension to *FAO-56* that incorporates a separate water balance and procedure for K_r for the fraction of soil that is wetted by precipitation only (i.e., not by irrigation). The extension reduces uncertainty in determining the value for f_w and has been applied by Mutziger et al. (2005) in estimating annual evaporation losses from agricultural areas in California.

In the extension to the *FAO-56* procedure, the evaporation calculation is divided into two separate calculations. One calculation is made for the exposed fraction of soil wetted by both irrigation and precipitation and one calculation is made for the exposed fraction of soil wetted by precipitation only. The coefficient K_e is calculated as

$$K_e = K_{\mathrm{ei}} + K_{\mathrm{ep}} \qquad (14)$$

where K_{ei}=evaporation coefficient for the exposed fraction of the soil wetted by both irrigation and by precipitation and K_{ep} =evaporation coefficient for the exposed fraction of the soil wetted by precipitation only.

The modification to Eq. (6) that applies to the fraction wetted by both irrigation and by precipitation is

$$K_{\mathrm{ei}} = K_{\mathrm{ri}} W (K_{c\ \mathrm{max}} - K_{\mathrm{cb}}) \leqslant f_{\mathrm{ewi}} K_{c\ \mathrm{max}} \qquad (15)$$

and the application of Eq. (6) to the fraction of soil that is exposed and wetted by precipitation only is

$$K_{\mathrm{ep}} = K_{\mathrm{rp}} (1 - W)(K_{c\ \mathrm{max}} - K_{\mathrm{cb}}) \leqslant f_{\mathrm{ewp}} K_{c\ \mathrm{max}} \qquad (16)$$

where f_{ewi}=fraction of soil wetted by both irrigation and precpitation and is exposed to rapid drying due to exposure to solar radiation and/or ventilation; f_{ewp}=fraction of soil exposed to rapid drying and is wetted by precipitation only; W=weighting coefficient for partitioning the energy available for evaporation into the f_{ewi} and f_{ewp} soil fractions, depending on water availability; K_{ri} and K_{rp}=evaporation reduction coefficients for the f_{ewi} and f_{ewp} fractions; and f_{ewp} is calculated as

$$f_{\mathrm{ewp}} = 1 - f_c - f_{\mathrm{ewi}} \qquad (17)$$

and f_{ewp} and f_{ewi} are limited to 0.001–1.0. Eq. (10) is reexpressed for f_{ewi} as

$$f_{\mathrm{ewi}} = \min(1 - f_c, f_w) \qquad (18)$$

where $1-f_c$ has limits of [0.01–1] and f_w=average fraction of soil surface wetted by irrigation, only [0.01–1].

The weighting factor W is calculated according to water availability in the two wetted, exposed fractions of the surface layer

$$W = \frac{1}{1 + \frac{f_{\mathrm{ewp}}}{f_{\mathrm{ewi}}} \frac{(\mathrm{TEW} - D_{\mathrm{ep}})}{(\mathrm{TEW} - D_e)}} \tag{19}$$

where D_e = cumulative depletion depth (mm) from the evaporating layer for the f_{ewi} fraction of soil; and D_{ep} = cumulative depletion depth (mm) from the evaporating layer for the f_{ewp} fraction of soil. The limits D_e and $D_{\mathrm{ep}} < \mathrm{TEW}$; D_e and $D_{\mathrm{ep}} \geqslant 0$; and $f_{\mathrm{ewi}}(\mathrm{TEW} - D_e) > 0.001$ are imposed for numerical stability.

An associated water balance is computed for the fraction of the evaporation layer wetted by precipitation, but not by irrigation, and is in the exposed portion of the soil

$$D_{\mathrm{ep},j} = D_{\mathrm{ep},j-1} - (P_j - \mathrm{RO}_j) + \frac{E_{p,j}}{f_{\mathrm{ewp}}} + T_{\mathrm{ep},j} + \mathrm{DP}_{\mathrm{ep},j} \tag{20}$$

where $D_{\mathrm{ep},j-1}$ and $D_{\mathrm{ep},j}$ = cumulative depletion depths at the ends of days $j-1$ and j in the f_{ewp} fraction of the surface (mm); $E_{p,j}$ = evaporation from f_{ewp} fraction on day j ($E_{p,j} = K_{\mathrm{ep}}\ \mathrm{ET}_0$) (mm); $T_{\mathrm{ep},j} = T_e$ from f_{ewp} fraction of the evaporation layer on day j (mm); ($T_{\mathrm{ep},j}$ can be set equal to zero for simplification); and $\mathrm{DP}_{\mathrm{ep},j}$ = deep percolation from the f_{ewp} fraction of the evaporation layer on day j if soil water content exceeds θ_{FC} (mm). The limits on $D_{\mathrm{ep},j}$ are $0 \leqslant D_{\mathrm{ep},j} \leqslant \mathrm{TEW}$. The $E_{p,j}$ is divided by f_{ewp} because it is assumed that all E_p is taken from the f_{ewp} fraction of the surface layer.

Eq. (12) is expressed for the f_{ewi} fraction as

$$D_{e,j} = D_{e,j-1} - (P_j - \mathrm{RO}_j) - \frac{I_j}{f_w} + \frac{E_j}{f_{\mathrm{ewi}}} + T_{\mathrm{ei},j} + \mathrm{DP}_{\mathrm{ei},j} \tag{21}$$

where f_w = fraction of soil surface wetted by irrigation.

Eq. (9) is expressed for the f_{ewi} and f_{ewp} fractions as

$$K_{\mathrm{ri}} = \frac{\mathrm{TEW} - D_{e,j-1}}{\mathrm{TEW} - \mathrm{REW}} \tag{22}$$

and

$$K_{\mathrm{rp}} = \frac{\mathrm{TEW} - D_{\mathrm{ep},j-1}}{\mathrm{TEW} - \mathrm{REW}} \tag{23}$$

for $D_{e,j-1}$ and $D_{\mathrm{ep},j-1} \geqslant 0$.

The total evaporation rate from the exposed fraction of the surface is $E = K_e\ \mathrm{ET}_0 = (K_{\mathrm{ei}} + K_{\mathrm{ep}})\ \mathrm{ET}_0$. K_{ei} and K_{ep} are both constrained so that $K_{\mathrm{ei}} \geqslant 0$ and $K_{\mathrm{ep}} \geqslant 0$

Eq. (13) is expressed for the f_{ewi} fraction of the surface layer as

$$\mathrm{DP}_{\mathrm{ei},j} = (P_j - \mathrm{RO}_j) + \frac{I_j}{f_w} - D_{\mathrm{ei},j-1} \geqslant 0 \tag{24}$$

As long as the soil water content in the evaporation layer is below field capacity (i.e., $D_{\mathrm{ei},j} > 0$), the soil will not drain and $\mathrm{DP}_{\mathrm{ei},j} = 0$. For the fraction of exposed soil that is wetted by precipitation but not by irrigation

$$\mathrm{DP}_{\mathrm{ep},j} = (P_j - \mathrm{RO}_j) - D_{\mathrm{ep},j-1} \geqslant 0 \tag{25}$$

Transpiration from Surface Layer

The amount of transpiration extracted from the f_{ew} fraction of the evaporating soil layer is generally small and can be ignored. However, for shallow-rooted annual crops where the depth of the maximum rooting is less than about 0.5 m, T_e may have significant effect on the water balance of the surface layer and therefore on prediction of the evaporation component, especially for the period midway through the development period.

Under conditions of uniform water availability within the soil profile, the ratio of T extracted from the evaporation layer to total T is presumed proportional to $(Z_e/Z_r)^{0.6}$ (Allen et al. 1996), where Z_e is the depth of the surface evaporation layer and Z_r is the effective depth of the root zone ($Z_e \leqslant Z_r$ and Z_e is contained in Z_r). This relationship is based on the commonly used 40–30–20–10% root extraction pattern for quartile rooting depths (top to bottom) of the root zone for moist soils.

In this extension, it is assumed that the previous extension using f_{ewi} and f_{ewp} is applied. If this is not the case, then only T_{ei} is used and all occurrences of f_{ewi} are set to f_{ew}. The equation for T_e from the f_{ewi} fraction of the evaporation layer T_{ei} is

$$T_{\mathrm{ei}} = K_{\mathrm{ti}} K_{\mathrm{cb}} K_s \mathrm{ET}_0 \tag{26}$$

where K_{ti}, [0–1] = proportion of basal ET(= $K_{\mathrm{cb}}\mathrm{ET}_0$) extracted as transpiration from the f_{ewi} fraction of the surface soil layer, and K_s = soil water stress factor computed for the root zone [0–1]. K_{ti} is determined by comparing relative water availability in the Z_e and Z_r layers along with the presumed rooting distribution. For the f_{ewi} fraction

$$K_{\mathrm{ti}} = \left(\frac{1 - \frac{D_e}{\mathrm{TEW}}}{1 - \frac{D_r}{\mathrm{TAW}}} \right) \left(\frac{Z_e}{Z_r} \right)^{0.6} \tag{27}$$

where the numerator and denominator of the first expression of Eq. (27) are limited to $\geqslant 0.001$ and TAW is total available water in the root zone [see Eq. (33) introduced later]. In addition, the value for K_{ti} is limited to $\leqslant 1.0$ to limit T_{ei} to $\leqslant \mathrm{ET}_c$. A value of $K_{\mathrm{ti}} \sim 1.0$ would represent conditions where the soil profile is near wilting point, but the shallow surface layer is partially or fully rehydrated by a light precipitation or irrigation event, or where the root zone is very shallow.

Transpiration from the f_{ewp} fraction of the soil T_{ep} is calculated as

$$T_{\mathrm{ep}} = K_{\mathrm{tp}} K_{\mathrm{cb}} K_s \mathrm{ET}_0 \tag{28}$$

where

$$K_{\mathrm{tp}} = \left(\frac{1 - \frac{D_{\mathrm{ep}}}{\mathrm{TEW}}}{1 - \frac{D_r}{\mathrm{TAW}}} \right) \left(\frac{Z_e}{Z_r} \right)^{0.6} \tag{29}$$

where K_{tp}, [0–1] = proportion of basal ET(= $K_{\mathrm{cb}}\mathrm{ET}_0$) extracted as transpiration from the f_{ewp} fraction of the surface soil layer. The same limitations apply as for Eq. (27).

When there is Stage 3 evaporation, as defined in the next section, TEW in Eqs. (27) and (29) is set equal to TEW_3, the upper limit for evaporable water.

Stage Three Evaporation

The third extension to the *FAO-56* procedure applies to soils that crack substantially upon drying, thereby exposing progressively deeper depths of soil to drying by evaporation. This progressive drying continues at a low rate for an extended period of time. Drying to depths as deep as 0.5 m is possible for severely cracking soils containing large amounts of montmorillinite clay where cracks can extend as deep as 1 m (Pettry and Switzer 1996).

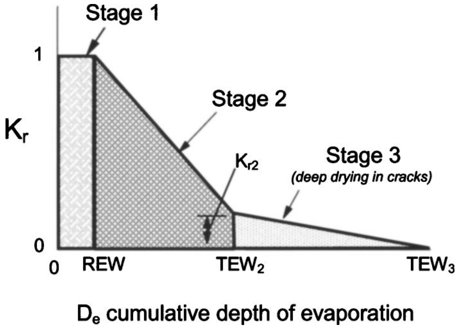

Fig. 5. General schematic showing evaporation reduction coefficient K_r as function of depth of water evaporated (depleted) from surface soil layer for cracking soil having three-stage evaporation.

In the extension for cracking soils, the evaporation process is expanded from two to three stages. The three stages are illustrated in Fig. 5. For normal agricultural soils that do not crack or only mildly crack, only Stage 1 and Stage 2 drying is applied. For cracking soils that have Stage 3 drying, Stage 3 is presumed to begin when K_r reduces to a threshold value labeled K_{r2}.

For three-stage drying, K_r is calculated for the second stage as

$$K_r = K_{r2} + (1 - K_{r2})\frac{\mathrm{TEW}_2 - D_{e,j-1}}{\mathrm{TEW}_2 - \mathrm{REW}}$$

$$\text{for REW} < D_{e,j-1} < \mathrm{TEW}_2 \qquad (30)$$

where TEW_2=maximum cumulative depth of evaporation (depletion) from the soil surface layer when $K_r = K_{r2}$ (point at which evaporation transitions into stage three drying) (mm), and K_{r2} =value for K_r at the junction of Stage 2 and Stage 3 drying. Generally, the value for K_{r2} should be some relatively low value between about 0.1 and 0.4, depending on the nature and degree of cracking as the soil dries. Allen et al. (1998) recommended $K_{r2} \sim 0.2$. Mutziger et al. (2001) found best fit values for K_{r2} for two cracking soils in Texas to be 0.3 and 0.2 when comparing against lysimeter measurements of evaporation for a black clay and clay loam.

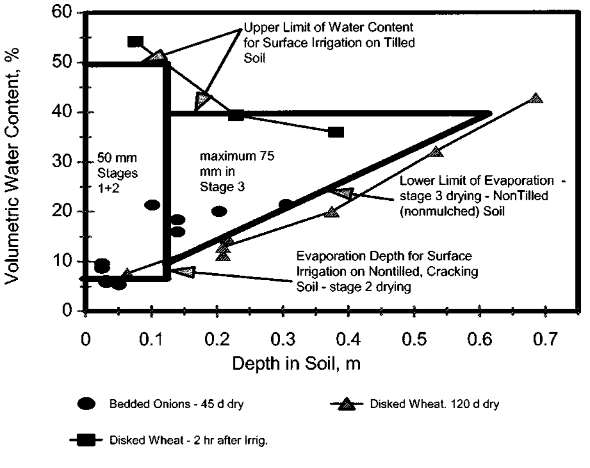

Fig. 6. Field measurements of volumetric water content for cracking soils in Imperial Irrigation District when wet (square symbols) and after 45 and 120 days of drying (circles and triangles). Superimposed on data are abstracted water content profiles associated with Stages 1 and 2 and with Stage 3 evaporation components

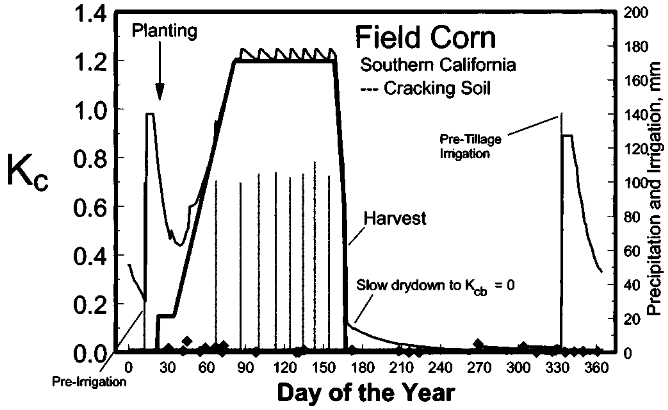

Fig. 7. Simulated K_{cb} (heavy line) and $K_{\mathrm{cb}}+K_e$ (light line) curves for crop of field corn planted in late January in southern California on cracking soil having REW=8 mm, TEW_2=50 mm, TEW_3=100 mm, K_{r2}=0.2, and f_w=0.7 for growing period irrigations and f_w=1.0 for preirrigations. Bars denote predicted timing and depths of irrigation and diamonds denote rainfall

K_r is calculated for the third stage as

$$K_r = K_{r2}\frac{\mathrm{TEW}_3 - D_{e,j-1}}{\mathrm{TEW}_3 - \mathrm{TEW}_2}$$

$$\text{for } \mathrm{TEW}_2 \leqslant D_{e,j-1} \qquad (31)$$

where TEW_3=maximum cumulative depth of evaporation (depletion) from the soil surface layer when the soil is dry and no further evaporation occurs (K_r=0) (mm). The value TEW_3 includes REW and TEW_2. For application of the three-stage drying extension with the first extension, Eqs. (22) and (23) are expanded using Eqs. (30) and (31), with each application ($\mathrm{I}+P$) and (P) having its own water balance.

The three stage drying extension has been applied to cracking heavy clay soils in the Imperial Irrigation District of California (Allen et al. 2005) and to two cracking or partially cracking soils in Texas (Mutziger et al. 2001). Values used for the Imperial soils were REW=8 mm, TEW_2=50 mm, TEW_3=100 mm, and K_{r2}

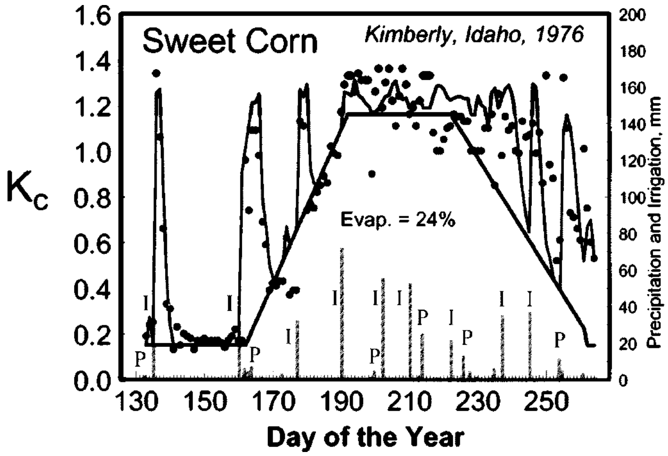

Fig. 8. Daily crop coefficients based on measured evapotranspiration and simulated using *FAO-56* dual K_c approach at Kimberly, Id. for a crop of sweet corn (lysimeter data from Wright 1982, personal communication 1990).

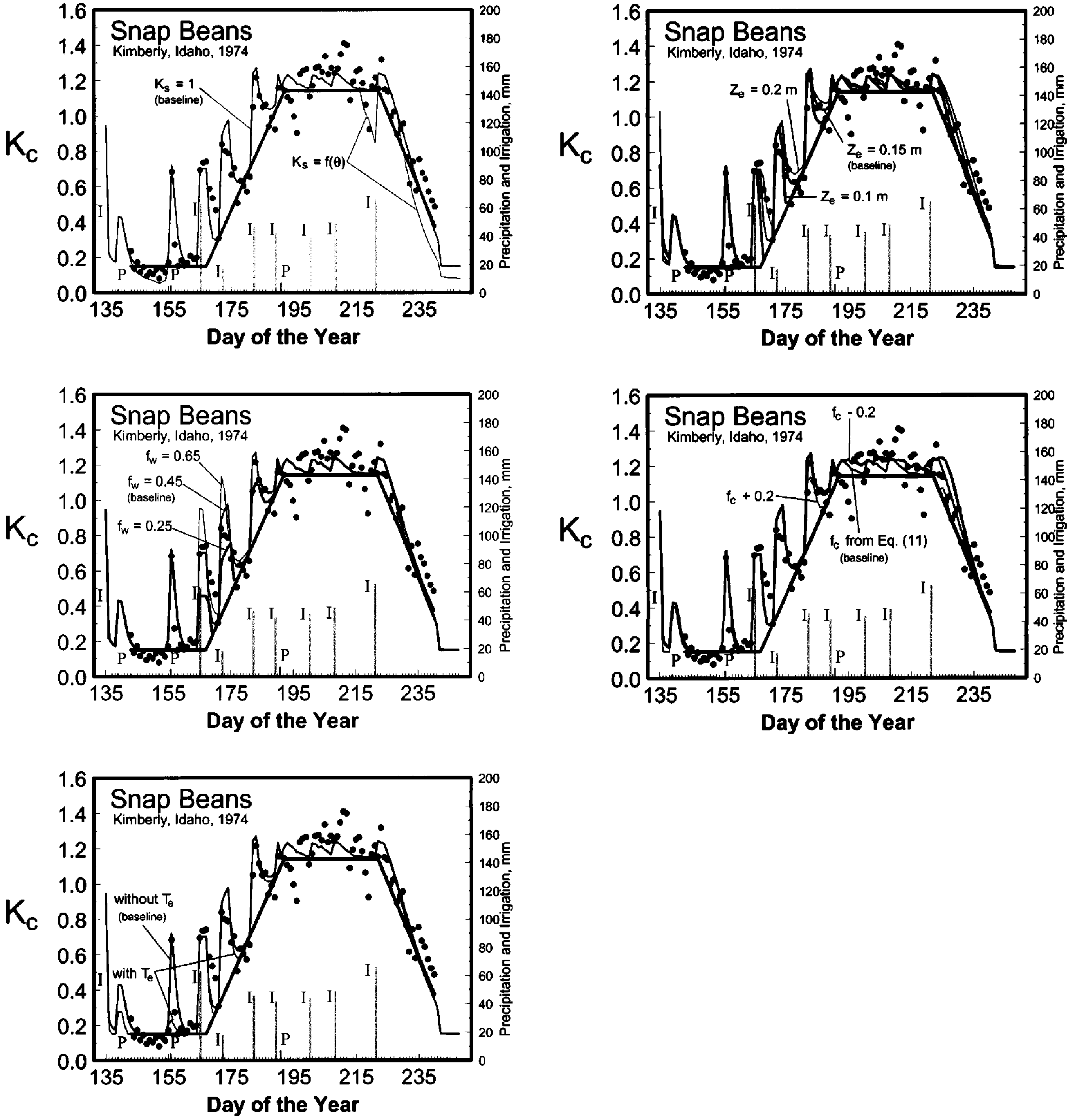

Fig. 9. Sensitivity of daily $K_{c\ \mathrm{act}}$ estimation for snap bean crop near Kimberly, Id. (lysimeter data from J. L. Wright, unpublished) to: (a) application of water stress function [Eq. (32)] (thin line) with comparison to K_c predicted using $K_s=1$ (medium line), K_{cb} (thick line), and measured K_c (symbols); (b) value for f_w; (c) application of T_e in Eq. (12); (d) value for Z_e; and (e) value for f_c

$=0.2$. Best fit values (to lysimeter evaporation measurements) for the Houston black clay and Pullman clay loam soils evaluated by Mutziger were REW$=$7 mm; $\mathrm{TEW}_2=30$ and 22 mm; and $\mathrm{TEW}_3=50$ and 45 mm.

TEW_2 and TEW_3 for the Imperial Valley soils were estimated from sampled soil water contents at the beginning and end of drying cycles in fallow fields as shown in Fig. 6. The sampling sites were in an area of mixed Imperial silty clay and Imperial-Glenbar silty clay loam soil. Cracks penetrated to about 1 m on drying on an approximately 0.5 to 2 m grid and average crack width was 10 mm. Moisture was gravimetrically determined from cored samples. In the case of sampling the dry profile where the soil was deeply cracked, samples were taken approximately 0.3 m in from the face of cracks. The areas between the upper horizontal and the lower horizontal or diagonal lines in the figure suggest the equivalent depth of water evaporated during Stages 1 and 2 and during Stage 3 from the cracking soil. The sampling indicated drying to a depth of more than 0.5 m due to cracking. Even though the apparent depletable depth from 0.12 to 0.6 m shown in Fig. 6 was about 75 mm, a value of 50 mm for Stage 3 drying

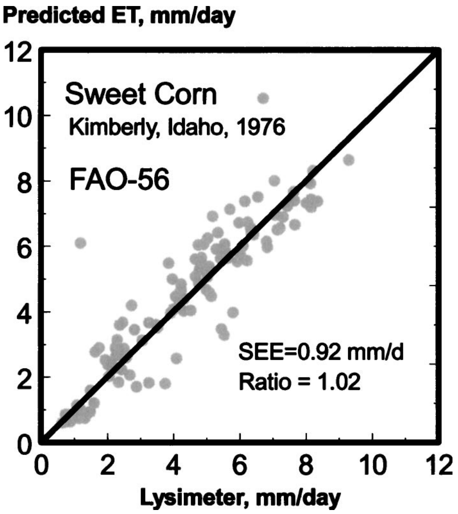

Fig. 10. Daily measured and estimated evapotranspiration for sweet corn near Kimberly, Id. using *FAO-56* dual K_c procedure (data from Wright 1982, personal communication 1990).

(so that $\mathrm{TEW}_3=50+50=100$ mm) was selected for routine application in the Imperial Valley to account for dampening effects of disking and other tillage on creating a surface soil mulch and any effects of water extraction by roots (Allen et al. 2005).

The net impact of Stage 3 drying is to prolong the time for K_r to decrease to zero, thereby creating a prolonged "base-line" evaporation rate. As shown in Fig. 7, where the *FAO-56* $K_{cb}+K_e$ method was applied with Stage 3 drying, base-line evaporation was prolonged following harvest for more than 60 days, even when time between wetting events was large. Without the Stage 3 drying, $K_{c\ \mathrm{act}}$ reduced to zero within 5–10 days following harvest. The K_{cb} prior to planting and following harvest was set to zero to allow evaporation (and total ET) to approach zero during extended dry periods.

Impacts of Water Stress

The final component in Eq. (4) is the water stress coefficient K_s used to reduce K_{cb} under conditions of water stress or salinity stress. Allen et al. (1998) describes the salinity stress function and computation. The water stress function is described here and is illustrated later. Mean water content of the root zone in the *FAO-56* procedure 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 initiate when D_r exceeds RAW, the depth of readily available water in the root zone. For $D_r>\mathrm{RAW}$, K_s is

$$K_s=\frac{\mathrm{TAW}-D_r}{\mathrm{TAW}-\mathrm{RAW}}=\frac{\mathrm{TAW}-D_r}{(1-p)\mathrm{TAW}} \qquad (32)$$

where TAW = total available soil water in the root zone (mm), and p = fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r \leqslant \mathrm{RAW}$, $K_s=1$. The total available water in the root zone is estimated as the difference between the water content at field capacity and wilting point

$$\mathrm{TAW}=1000(\theta_{\mathrm{FC}}-\theta_{\mathrm{WP}})Z_r \qquad (33)$$

where Z_r = effective rooting depth (m) and Z_r contains Z_e. RAW is estimated as

$$\mathrm{RAW}=p\mathrm{TAW} \qquad (34)$$

where RAW has units of TAW (mm). *FAO-56* contains recommended values for p for 60 crops and describes several means to model the development (increase) in Z_r with time for annual crops including in proportion to development of K_{cb} and in proportion to time. Other methods for Z_r development include a sine function of time (Borg and Grimes 1986), an exponential function of time dampened by soil temperature and soil moisture (Danuso et al. 1995), and a full root growth simulation model by Jones et al. (1991).

Example Applications and Sensitivity Analyses

Illustrative applications of the *FAO-56* procedure are given in Fig. 8 for a sweet corn crop and in Fig. 9 for a snap bean crop grown near Kimberly, Id. during 1976 and 1974 by Wright (1982). Daily ET was measured using a precision weighing lysimeter planted to and immediately surrounded by a specific crop. Fetch of the lysimeter was at least 50 m in all directions for the specific crop and resolution of the lysimeter system was about 0.05 mm (Wright 1982). The daily measured K_c values in the figures were calculated by dividing daily lysimeter measurements by ET_0 as computed by Eq. (1). Weather data were assembled from a grassed weather station located about 1 km north of the lysimeter site. Dates for planting and harvest and for precipitation and irrigation were based on field notes (Wright, personal communication 1990; Vanderkimpen 1991). Values for K_{cb} were taken from *FAO-56*. Dates for beginning of development, midseason and late season periods for the *FAO-56* procedure were selected to fit the lysimeter data.

The application used the original *FAO-56* procedure with extension for T_e. The Portneuf silt loam soil at Kimberly was modeled using two-stage drying with Z_e set to 0.15 m and REW = 8 mm and TEW = 34 mm. The value for f_w was 0.6 for the furrow-irrigated sweet corn and 0.45 for alternate furrow-irrigated beans.

For the application to beans, ranges in values for parameters K_s, f_w, T_e, Z_e, and f_c were applied to illustrate the sensitivity of the *FAO-56* model predictions to these parameters. In the case of K_s and T_e, the sensitivity was with and without the inclusion of functions for these parameters.

Results

Simulated daily K_{cb} and $K_{c\ \mathrm{act}}$ and measured $K_{c\ \mathrm{act}}$ for the growing period for the sweet corn crop shown in Fig. 8 indicate relatively

Table 3. Standard Error of Estimate (SEE) and Ratio of Estimated to Measured Daily Evapotranspiration for Full Season of Snap Beans in 1974 near Kimberly, Id. ($n=98$ days), where Baseline Conditions were $f_w=0.45$, $T_e=0$, $K_s=1$, $Z_e=0.15$ m, and f_c from Eq. (11)

	Baseline	$f_w=0.25$	$f_w=0.65$	with T_e	with K_s	$Z_e=0.10$ m	$Z_e=0.20$ m	$f_c-0.2$	$f_c+0.2$
SEE (mm day^{-1})	0.63	0.74	0.68	0.67	0.78	0.76	0.61	0.66	0.68
Ratio to measured	1.00	0.96	1.03	0.98	0.96	0.96	1.04	1.03	0.95

good agreement between simulated and measured values. The peak spikes in $K_{c\ \mathrm{act}}$ following wetting agreed well with measurements as did the rate of decay of the K_e curve. There was some underestimation of $K_{c\ \mathrm{act}}$ during the midseason period which may have been caused by underestimation of ET_0 by Eq. (1) or underestimation of the midseason K_{cb} for corn by *FAO-56*. The $K_{c\ \mathrm{act}}$ predicted during the late season overestimated measured $K_{c\ \mathrm{act}}$ for some days and underestimated over two 5 day periods. Much of the under- and overestimation during the senescence period was probably caused by uncertainty in the estimation of f_c during that period and the impact of ground shading on the wetted portion of the soil surface.

The unadjusted standard error of estimate (SEE) between the estimated and lysimeter-measured daily ET (Fig. 10) was $0.92\ \mathrm{mm\ day}^{-1}$ and the seasonal ratio of predicted ET to measured ET was 1.02. Total seasonal evaporation for the sweet corn crop was estimated to be 24% of the total seasonal ET. Because the lysimeter measurements provide only integrated values of ET, the separate estimation of evaporation cannot be evaluated for accuracy. Estimates of soil evaporation do not include the evaporation from soil that occurs as a diffusive component of K_{cb} over time.

Sensitivity of the $K_{\mathrm{cb}}+K_e$ procedure of *FAO-56* to invocation of a K_s soil moisture stress function under conditions where mild stress may have occurred is shown in Fig. 9(a) for the 1974 snap bean crop. Without the K_s function (thus $K_s=1.0$), the $K_{c\ \mathrm{act}}$ curve (medium gage line) "bottomed" against the K_{cb} curve (heavy line). With the K_s function [Eq. (32)], drying below the p level of the root zone was predicted during the development period, late midseason, and latter part of the late season. These predictions were based on actual irrigation dates and values for soil water holding properties from Table 1 ($\mathrm{AW}=160\ \mathrm{mm\ m}^{-1}$), and $p=70\%$ during the initial period and $p=55\%$ for the other three periods, and maximum rooting depth of 1.6 m, based on measurements by Wright (unpublished data, 2000). The application of the K_s function improved estimation of $K_{c,\mathrm{act}}$ for some dates and caused underestimation for others. No visual or measured stress by the lysimeter crop in 1974 was noted by Wright (1982).

Figure 9(b) illustrates the impact that f_w, the fraction of soil surface wetted by irrigation, has on the $K_{c\ \mathrm{act}}$ estimate. Higher values for f_w extended the magnitudes and time lengths of drydown for K_e "spikes" during the development period when the value $1-f_c$ in Eq. (10) was large. During midseason period, $1-f_c$ in Eq. (10) limited the value for f_{ew} regardless of range in f_w. Thus, sensitivity to f_w is generally prominent only during the initial and development periods.

The inclusion of the T_e function for extraction for transpiration from the Z_e layer impacted the estimation for K_c during the initial and development periods and had no impact during the mid and late season periods when the evaporation layer was largely shaded. The T_e function reduced the prediction of K_e for the precipitation event on Day 156 [Fig. 9(b)] because T_e extraction during prior days increased D_e so that the 6 mm precipitation depth was absorbed into the Stage 2 depletion reservoir, rather than adding to Stage 1 drying. This illustrates a weakness of the *FAO-56* model in that any light precipitation event is subtracted from the total D_e for the Z_e depth, rather than left on the soil skin for immediate evaporation. D_e was increased during the initial period with the application of the T_e function because all of the K_{cb} value [0.15 in Fig. 9(b)] is assigned to basal transpiration in the dual procedure, even though the 0.15 value may contain significant amounts of diffusive evaporation. There is danger in assigning too large a value for K_{cb} in the dual method, including the method of Wright (1982), since no limit is placed on K_{cb} extraction from a shallow, initial root depth unless the K_s function is invoked. The fact that inclusion of the T_e function did not improve predictions for the snap beans may reflect the tillage practices for beans, where open spaces between rows are cultivated two to three times during the growing season, thus reducing root activity there and thus extraction by transpiration. The $1-f_c$ parameter in Eq. (10) represents these open spaces.

The impact of the value assigned to Z_e, the effective depth of the evaporating layer, is illustrated in Fig. 9(d). With all other parameters fixed, the impact of greater Z_e is to extend the lengths of drydown periods and to increase the estimated evaporation component of ET. The impact of Z_e was pronounced during all periods.

Sensitivity to the estimation of fraction of surface covered by vegetation is illustrated in Fig. 9(e), where 0.2 was added and subtracted from the value for f_c predicted by Eq. (11). The impact of value for f_c was negligible for the initial and most of the development period when $1-f_c$ exceeded the value assigned to f_w. In this case, f_w controlled the estimate of evaporation. As f_c increased, its value began to control f_{ew} from Eq. (10) and impact on K_e and K_c increased. The smaller value for f_c (i.e., $f_c-0.2$) during late development and mid season tended to improve estimates during those periods.

Table 3 lists summary statistics for the five sensitivity tests. The smallest SEE ($0.61\ \mathrm{mm\ day}^{-1}$) occurred when Z_e was increased from 0.15 to 0.20 m, however, the reduction in SEE over the baseline was very small. The impact by the individual ranges in the parameters on the ratio of estimated seasonal ET to measured ET ranged from −5 to +4%.

Summary and Conclusions

The *FAO-56* dual K_c procedure was established to provide daily estimates of evaporation from wet soil in conjunction with crop transpiration. The procedure uses a daily water balance of the soil surface layer and accounts for the fraction of soil surface wetted by irrigation or by precipitation and exposed to radiation and ventilation. Three optional extensions to the original method are described. The first is the establishment of a separate water balance for the fraction of the surface wetted by precipitation, only, and for the fraction wetted by both irrigation and precipitation. The second extension is a procedure to approximate the drying of the surface layer by transpiration in addition to evaporation. The third extension provides for the application to deep cracking soils. The dual K_c procedure is useful when short term estimates of evapotranspiration are needed, for example in research and in irrigation scheduling for individual fields as well as in estimation of total consumption of water where impacts of wetting frequency are important.

The sensitivity analysis indicates that inclusion of a function to estimate transpiration from the evaporating layer may not substantially impact or improve estimates, especially for crops having periodic cultivation. Calculations are moderately sensitive to values specified for the depth of the evaporation layer and fraction of surface wetted by irrigation, and to the estimation of fraction of ground cover.

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