CHAPTER 10
CROP COEFFICIENT METHOD

10.1 INTRODUCTION

Chapter 8 describes the combination of equations for sensible and latent heat transfer, following simplifying assumptions, to produce the well-known Penman combination equation (Penman 1948). Monteith (1965) and Rijtema (1965) independently introduced a surface resistance parameter to the Penman equation and replaced the linear wind function term with an aerodynamic resistance parameter. That resulting combination equation, known as the Penman-Monteith (PM) equation, is now the most widely used basis for estimating evapotranspiration (ET) in engineering, agriculture, and landscape applications, where the equation serves as the reference ET basis in the two-step crop coefficient (K_c)–reference ET (ET_{ref}) approach. The first step in the two-step approach is to estimate reference ET representing potential weather or climate impacts on the ET process. Chapter 8 describes the calculation of ET_{ref}. The second step is to apply a crop or vegetation coefficient to estimate actual ET, ET_c, according to growth stage, plant type, and cover and wetness of the soil surface and soil profile. The same general two-step approach has also been applied in hydrologic studies. This chapter focuses on the use of the two-step approach for estimating ET for farm crops, landscapes, and some natural vegetation. Applications to forests can be found in Chapter 4 of the ASCE *Hydrology Handbook* (Allen et al. 1996).

10.2 THE CROP COEFFICIENT

The crop coefficient (K_c) having a basis of reference crop ET_{ref} was clarified in 1968 (Jensen 1968) and first used in a computerized irrigation scheduling program (Jensen 1969; Jensen et al. 1970, 1971). The two-step procedures for estimating ET for well-watered agricultural crops can be applied to various types of natural vegetation and to crops under rain-fed conditions and in general hydrologic studies. For these reasons, the K_c term might be more appropriately referred to as a "vegetation cover coefficient" rather than as a "crop" coefficient. Usage and application would be the same. However, to be consistent with past literature and applications, this manual adheres to the use of the term "crop coefficient" with the understanding that this term can be applied to nonagricultural vegetation and to bare soil.

Early K_c curves had nonreference bases, with values determined by measuring depletion of soil water between two or more sampling dates (Hargreaves 1948; Veihmeyer and Hendrickson 1955; Erie et al. 1965, 1982). Later, more refined curves were developed based on daily ET measured in lysimeters that were then related to a grass or alfalfa reference ET. Some curves were refined for conditions of dry surface soil, or when the soil visually appeared dry, and were called *basal crop* coefficients (Wright 1982). More accurate ET estimates could be obtained using basal coefficients and then adjusted for the wetness of the surface soil for several days following rains or irrigation using the dual K_c approach (Wright 1982; Allen et al. 1998).

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. Many data sets have been based on lysimeter data. Publications have included information on cereal crops; fiber crops such as cotton, forage crops, fruit tree crops like olives, apricots, peaches, and pecans; grapes; cool- and warm-season grasses; turfgrasses; legume crops like beans and peas; oil crops like safflower; root crops like potatoes; tropical fruits like banana, cassava, and coffee; and various vegetable crops. In addition, there have been coefficients for natural vegetation such as grasslands and wet vegetation such as cattails, grasses, and reeds. Some of these publications have included models and systems for calculating the crop coefficient. Most of these publications have been from Australia, Brazil, China, India, Spain, England, Italy, and the United States. Appendix G describes recommended documentation for crop coefficient and ET data reporting that can improve the quality and consistency of published crop coefficients.

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 K_c as a function of some form of absolute or scaled time basis. However, some studies relate the rate of increase in LAI and therefore K_c for various crops as a function of daily weather such as cumulative degree days.

Crop Coefficient Variables

By expressing ET_c and ET_{ref} in terms of the PM equation following the form presented in Eq. (8-15), where the additional "c" subscripts represent characteristic values for the actual vegetation and the additional "r" subscripts represent the same for the reference crop, one can visualize that the value of K_c depends on the relative roughness, leaf area, and albedo (in the net radiation calculation) of the actual vegetative surface in relation to the same characteristics for the grass or alfalfa reference surface.

$$K_c = \frac{ET_c}{ET_{ref}} = \frac{\dfrac{\Delta(R_{nc} - G_c) + \rho c_p (e_z^o - e_z)/r_{ac}}{\Delta + \gamma(1 + r_{sc}/r_{ac})}}{\dfrac{\Delta(R_{nr} - G_r) + \rho c_p (e_z^o - e_z)/r_{ar}}{\Delta + \gamma(1 + r_{sr}/r_{ar})}} \tag{10-1}$$

The relative proportions of net radiation, wind, temperature, and vapor pressure deficit all affect the value of K_c to some degree. Clearly, the more similar the vegetative cover is to the reference condition, especially at full cover, the closer the value of K_c will be to 1.0 and the less varying the value of K_c will be with changing weather conditions. One precaution in applying Eq. (10-1) is that the equation does not consider the effects of differences between ET_c and ET_{ref} on conditioning the near-surface equilibrium boundary layer above the vegetation. This conditioning can modify levels of T, e_z^o, e_z, Δ, and wind speed to some degree, due to differences in partitioning available energy at the surface into H and λE when ET_c is different from ET_{ref}. These generally negative feedback effects can affect the value determined for K_c and are described in more detail in Chapter 11.

Field-Scale Applications

When applying the standardized reference ET equation [Eq. (8-15)] 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 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, 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 λE, so that the ratio of λE for any other tall, leafy crop to alfalfa λE will be near 1.0. This observation is borne out in viewing the maximum values for K_c reported by Wright (1982), reproduced for the standardized PM alfalfa reference in Appendixes E and F, where none of Wright's K_cs, based on the alfalfa reference, exceed 1.03 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).

Limiting K_c to approximately 1.0 for an alfalfa reference base or to 1.3 for a grass reference base applies to large expanses of vegetation (>200 m diameter) and is significant and important when evaluating field measurements of ET. Higher values for K_c may very likely indicate problems with field measurements. Measurement problems include (1) improper computation of vegetation area in lysimeter studies (Allen et al. 1991a, 2011c), (2) violation of necessary fetch requirements in boundary layer (energy balance) measurements, and (3) weather data collection difficulties and errors. The first two problems are discussed in Chapter 7. All are discussed in detail in Allen et al. (2011c).

Small Expanses of Vegetation

When ET is measured from small expanses of vegetation, the internal boundary layer above the vegetation may not be in equilibrium with the new surface and may not have developed up to the height of instrumentation. In addition, small expanses of tall vegetation surrounded by shorter cover can result in a "clothesline effect," where the interchange between air and vegetation is much more efficient than with the logarithmic type of equilibrium boundary layer established over large fields. In these cases, ET from the isolated stands, on a per unit area basis, may be significantly greater than the corresponding ET_r or ET_o computed for an alfalfa or grass reference, assuming an infinitely large fetch of similar reference vegetation. An example of these situations would be ET from a single row of trees surrounded by short vegetation, ET from a narrow strip of cattails along a stream channel, or a vegetated lysimeter surrounded by shorter vegetation. Allen et al. (1994a) report K_c values for small (6-m wide) stands of cattails and bulrushes surrounded by grass pasture equal to 1.6 to 1.8 during midseason, relative to an alfalfa reference. These measurements indicate a strong clothesline effect. Coefficients were only 1.15 for a cattail wetland that was 200 m in diameter (Allen et al. 1994a). In an extreme illustration, van Bavel et al. (1963) measured ET from 1-m tall Sudan grass in Arizona following cutting of the grass around the lysimeter, so that the vegetation inside the lysimeter functioned as a clothesline. After cutting, 14.7 mm of ET during a 24-h period was measured compared with 9.8 mm three days before the cutting—a 50% increase. The weather data were similar for both clear days. In a similar situation, Allen et al. (1991a) report measured ET from 0.6-m fescue grass to increase by 1.6 times relative to the PM equation when the surrounding grass was clipped to 0.1 m, but the vegetation inside the lysimeter remained at 0.6 m. The ET rate from the lysimeter under the clothesline condition reached 16 mm d^{-1}, whereas the PM equation estimated 11 mm d^{-1} for 0.6-m grass having extensive fetch of other 0.6-m grass.

Pruitt (personal communication, 1976) reported K_c values for a nearly isolated 4.2-m tall Monterey pine tree (*Pinus radiata*) varying from 1.4 in February–March to 2.0 during spring and summer and approaching 3.0 during late fall and dry, early-winter months relative to ET_o. The tree grew on a 1.83-m by 2.44-m hydraulic-pillow lysimeter located within a 1-ha dry, noncropped field. It was near the middle of a 10-tree windrow oriented normal to prevailing winds near Davis, California, thereby creating a clothesline effect.

The preceding discussion indicates the importance of knowing the type of setting for which ET estimates are needed and the conditions from which measurements are collected. If ET estimates are needed for small, isolated stands of vegetation, then K_c may be allowed to exceed the 1.0 value for an alfalfa reference and the 1.3 value for a grass reference by up to 50%. However, if ET estimates are to represent large expanses of vegetation or small stands of vegetation surrounded by mixtures of other vegetation having similar roughness and soil water conditions, then K_cs will generally be less than or equal to 1.0 for alfalfa and 1.3 for grass references. Allen et al. (1998) propose procedures for estimating K_c and ET for isolated stands of wetlands and tall wind breaks such as single rows of trees that are presented later in the section on natural vegetation. They caution that an upper limit on K_c exists for isolated vegetation that is governed by root uptake ability and stomatal behavior.

10.3 CROP (VEGETATION COVER) COEFFICIENTS

Two families of K_c curves for agricultural crops have been developed for the two commonly used reference crops (tall and short). These are the grass-based curves by Pruitt (Doorenbos and Pruitt 1977; Jensen et al. 1990; Allen et al. 1998) and others and alfalfa-based K_c curves by Wright (1981, 1982) and others (Tolk and Howell 2001; Howell et al. 2004, 2006). The user must exercise caution to avoid mixing grass-reference-based K_cs with an alfalfa reference and vice versa. Usually K_cs based on an alfalfa reference can be "converted" for use with a grass reference during summer months by multiplying by a factor ranging from 1.1 to 1.3, depending on climate (1.1 for humid, calm conditions and 1.3 for arid, moderately windy conditions). The conversion ratio can be estimated by ratioing ET_{rs} and ET_{os} from the standardized PM estimates from Chapter 8. Grass-based K_cs are presented and discussed first in this manual (Section 10.4) due to the large number of K_cs that have been presented in FAO-24, FAO-56, the ASABE publication *Design and Operation of Farm Irrigation Systems* (Allen et al. 2007c) and elsewhere (Snyder et al. 1989a, b) for agricultural crops. Alfalfa-based K_cs for eight irrigated crops in southern Idaho developed by Wright (1981, 1982) and presented in Manual 70, 1st edition (Jensen et al. 1990) have been updated in this edition of Manual 70 for use with standardized ET_{rs} and are presented in Appendix E.

Generalized crop coefficient curves for estimating crop ET_c for crops or other vegetation are shown in Figure 10-1. The K_{cb} curve represents "basal" crop coefficients for conditions where the soil surface is visually dry, so that evaporation from soil is minimal, but where the availability of soil water does not limit plant growth or transpiration. This curve represents a minimum ET_c situation for adequate soil water. The "spikes" in Figure 10-1 indicate occurrences of precipitation or irrigation that wet the soil surface and temporarily increase total ET_c for one to five days. These spikes decay to the K_{cb} curve as the soil surface dries. The spikes generally approach a maximum value of 0.8 to 1.0 for an alfalfa ET_r base (Wright 1982) and

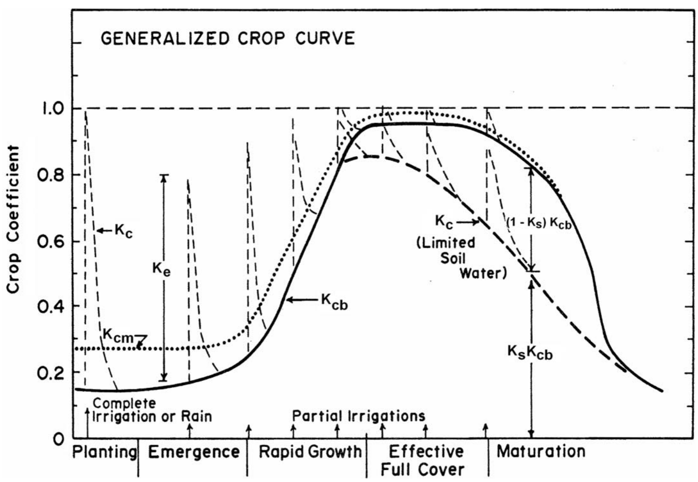

Fig. 10-1. Generalized cover coefficient curves showing the effects of growth stage, wet surface soil, and limited available soil water on crop coefficient values. The solid line represents the basal K_{cb} *curve, the short-dashed line represents the soil evaporation coefficient,* K_e*, addition to* K_{cb} *when the soil surface is wet, the dotted curve represents a time-averaged 'mean'* K_c *curve that averages the effects of the* K_e *spikes and the* K_{cb} *curve, and the long-dashed line represents a departure from the potential* $K_c = K_{cb} + K_e$ *curve under limiting soil water conditions*
Source: Data from Wright (1982); Jensen et al. (1990)

1.0 to 1.2 for a grass ET_o base (Allen et al. 1998). The K_{cm} curve in Figure 10-1 represents a so-called "mean" crop coefficient that includes averaged effects of wet soil (spikes) under specific rainfall or irrigation frequencies. Sometimes the K_{cm} is referred to as the "single" K_c. The final, "limited soil water" curve in the figure represents the decrease in ET_c when plant water uptake is limited by available soil water.

K_c and ET Terminology

Actual ET, denoted here as $ET_{c\,act}$ or ET_a, is the ET rate that occurs under actual field conditions. $ET_{c\,act}$ is often used interchangeably with the term crop ET, ET_c. The value for $ET_{c\,act}$ may be less than the value for potential ET_c, sometimes denoted as $ET_{c\,pot}$, when water stress occurs in the vegetation. $ET_{c\,act}$ or ET_c is calculated using Eq. (8-14) as $ET_{c\,act} = ET_c = K_c ET_{ref}$. Both $ET_{c\,act}$ and ET_c (and $ET_{c\,pot}$) terms can include varying degrees of direct evaporation from soil as represented by K_e.

In FAO and European literature, $ET_{c\,act}$ is often presented as "ET_{adj}" representing adjusted ET and based on an adjusted $K_{c\,adj}$ as determined from Eq. (10-2) (Pereira et al. 1999a, b). That same literature generally reserves the use of the term crop ET, denoted as ET_c, and the term K_c to represent only the potential, or upper limit on ET for a particular crop, in other words, representing a pristine, well-watered condition. In the European tradition, any reduction in K_c due to water stress or other factors such as reduced density, disease, or salinity are encapsulated into a second expression referred to as "actual" $K_{c\,act}$ or $K_{c\,act}$ (Allen et al. 1998).

The traditional American usage of the terms ET_c and K_c have tended to be more relaxed in their usage of the ET_c and K_c terms and allows these terms to represent both potential and actual conditions. The European usage is less ambiguous, but the American usage is more encompassing. The less formal American usage is defensible because when using the mean K_{cm} of the following section, the value for K_{cm} changes substantially with wetting frequency and therefore is not a well-defined, consistent coefficient. The differences between the two systems are largely semantic, but can cause confusion and some degree of frustration within the user community unless carefully defined. This manual follows the American tradition.

Basal Crop Coefficients

Basal crop coefficients represent primarily the transpiration component of ET and a small evaporation component from soil that is visually dry at the surface. Their use requires adjustment for wet soil effects after rain or irrigation. This 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 are included. The total crop coefficient, K_c, is computed from K_{cb} as

$$K_c = K_s K_{cb} + K_e \tag{10-2}$$

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. (10-2) equals 1. Actual ET_a is estimated as $ET_a = K_c ET_{ref}$ when K_s in Eq. (10-2) is less than 1. The values for K_e represent the "spikes" shown in Figure 10-1. Estimation of K_e for bare soil conditions is described in detail in Chapter 9, which presents and illustrates the square root of time (SRT) model and the FAO-56 K_e model [Eqs. (9-19)–(9-31)].

$K_{c\,max}$ is used in Eq. (9-19) to estimate the evaporation coefficient K_e and represents the maximum value for K_c following rain or irrigation, under conditions of both bare soil and 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. Because of the lower value for the grass reference (ET_o) as compared with the alfalfa reference, $K_{c\,max}$ for use with ET_o ranges from about 1.05 to 1.3 and varies with general climate (Allen et al. 1998, 2005b):

$$K_{c\,\max o} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\},\ \{K_{cbo} + 0.05\}\right) \tag{10-3a}$$

where u_2 is average wind speed at 2 m during the growth stage or period, RH_{min} is average daily minimum relative humidity during the growth state or period, h is the mean plant height (m) during the period of calculation (initial, development, midseason, or late season), and the max () function indicates the selection of the maximum of the values separated by the comma. $K_{c\,max\,o}$ denotes the use of $K_{c\,max}$ with ET_o and with K_{cb} based on ET_o, denoted as K_{cbo}. Parameters u_2 and RH_{min} are discussed later with Eqs. (10-15)–(10-17).

$K_{c\,max}$ for the tall reference ET_r, denoted as $K_{c\,max\,r}$, does not require adjustment for climate, due to the greater roughness of the reference basis:

$$K_{c\,max\,r} = \max[1.0, (K_{cbr} + 0.05)] \tag{10-3b}$$

where K_{cbr} denotes a basal K_{cb} used with ET_r. Eqs. (10-3a) and (10-3b) require that $K_{c\,max}$ be 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. Eqs. (10-3a) and (10-3b), and the FAO-56 evaporation Eqs. (9-19)–(9-31), can be applied with both the straight-line K_{cb} curve style of FAO and with the curvilinear K_{cb} curves such as by Wright (1982), as illustrated later in this section.

Water Stress Adjustment

Several linear and curvilinear functions have been proposed to adjust for the effects of decreasing available water on ET or for the K_s used in Eq. (10-2). The simple linear model for estimating K_s as described in FAO-33 (Doorenbos and Kassam 1979) is commonly used:

$$K_s = \frac{\theta - \theta_{wp}}{\theta_t - \theta_{wp}} \quad \text{for } \theta < \theta_t \tag{10-4}$$

where θ is mean volumetric soil water in the root zone in m^3m^{-3}, and θ_t is the threshold θ below which transpiration is decreased linearly due to water stress. $K_s = 1.0$ for $\theta \geq \theta_t$. The wilting point, θ_{wp}, is the soil water at the lower limit of soil water extraction by plant roots in m^3m^{-3}. Typical values of θ_{wp} for various soil texture classes are listed in Table 3-6. The threshold soil water, θ_t, can be estimated from the relationship:

$$\theta_t = (1 - p)(\theta_{fc} - \theta_{wp}) + \theta_{wp} \tag{10-5}$$

where p is the average fraction of available soil water that can be depleted before water stress and ET reduction occur. Variable θ_{fc} is the soil water content at field capacity or the drained limit of the soil in m^3m^{-3}. Values for all θ parameters should represent averages over the effective root zone. Values for θ_{fc} are listed in Table 7-1, and values for p for agricultural crops are listed in Appendix B.

Parameter p normally ranges from 0.30 depletion of available soil water ($\theta_{fc} - \theta_{wp}$) for shallow-rooted plants at high rates of ET_c (>8 mm d^{-1}) to 0.70 for deep-rooted plants at low rates of ET_c (<3 mm d^{-1}) (Raes et al. 2009; Appendix B). A value of 0.50 is commonly used for many agricultural crops. After computation of K_c, ET_c is computed using Eq. (8-14).

An equivalent expression to Eq. (10-4), but in terms of depletion, D_r, of available water in the root zone is, for $D_r > RAW$:

$$K_s = \frac{TAW - D_{r,i-1}}{TAW - RAW} = \frac{TAW - D_{r,i-1}}{(1-p)\ TAW} \quad \text{for } D_{r,i-1} > RAW \tag{10-6}$$

where TAW is the total depth of available soil water in the root zone in mm, RAW is the depth of readily available water in the root zone in mm, and p is the fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r \leq RAW$, $K_s = 1.0$. The total available water in the root zone is estimated as the difference between the water content at field capacity and wilting point:

$$TAW = 1{,}000\,(\theta_{fc} - \theta_{wp})\,z_r \tag{10-7}$$

where z_r is the effective rooting depth in m, and z_r contains z_e, the effective depth of the evaporation layer described in Chapter 9 and illustrated in Figure 9-4. The 1,000 factor converts from m to mm. RAW is estimated as

$$RAW = p\,TAW \tag{10-8}$$

where RAW has the same units as TAW (mm). Appendix B contains typical maximum effective values for z_r.

The mean soil water balance for the root zone in terms of θ can be computed on a daily basis using Eqs. (7-3) and (7-4). Computations are made for the complete z_r root depth, including the evaporation layer.

The soil water balance for the root zone in terms of depletion is

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c\,act,\,i} + DP_i \tag{10-9}$$

where $D_{r,i}$ is root zone depletion at the end of day i in mm; $D_{r,i-1}$ is root zone depletion at the end of the previous day, $i - 1$, in mm; P_i is precipitation on day i in mm; RO_i is runoff from the soil surface on day i in mm; I_i is net irrigation depth on day i that infiltrates the soil in mm; CR_i is capillary rise from the groundwater table on day i in mm; $ET_{c\,act,\,i}$ is actual crop evapotranspiration on day i in mm; and DP_i is water loss out of the root zone by deep percolation on day i in mm.

Although soil water content might temporally exceed field capacity following heavy rain or irrigation, in the previous equation, the total amount of water exceeding field capacity is assumed to be lost the same day via deep percolation, following any ET for that day. This permits the extraction of one day's ET from this excess before percolation. That assumption can be modified by delaying DP as in Eq. (10-12b). The root zone depletion will gradually increase as a result of ET and percolation. In the absence of a wetting event, the root zone depletion will ultimately reach the value TAW that is defined from rooting depth, θ_{fc} and θ_{wp} from Eq. (10-7). At that moment no water is left for ET, and K_s becomes zero, from Eq. (10-6). Limits imposed on $D_{r,i}$ are consequently

$$0 \leq D_{r,i} \leq TAW \tag{10-10}$$

The lower limit 0 can be relaxed if some delayed drainage from the root zone is allowed as discussed later with Eq. (10-12b).

To initiate the water balance for the root zone, the initial depletion $D_{r,i-1}$ can be derived from measured soil water content by

$$D_{r,\,i-1} = 1{,}000\,(\theta_{fc} - \theta_{i-1})\,z_r \tag{10-11}$$

where θ_{i-1} is the average soil water content at the end of day $i-1$ for the effective root zone. The 1,000 factor converts from m to mm. Following heavy rain or irrigation, the user can assume that the root zone is near field capacity, i.e., $D_{r,i-1} \approx 0$. Daily precipitation in amounts less than about 0.2 ET_{ref} is normally entirely evaporated and can generally be ignored in depletion calculations (in both the computation of $D_{r,i}$ and computation of $ET_{c\,act}$). In the case of using the dual K_c method of Eq. (10-2), light precipitation events will generally be evaporated using K_e and should be included in the P estimate. I_i is equivalent to the mean infiltrated irrigation depth expressed for the entire field surface. Runoff from the surface during precipitation can be estimated using standard procedures from hydrologic texts.

Capillary Rise (CR) The amount of water transported upward by capillary rise from the water table to the root zone or soil surface depends on the soil type, the depth of the water table, and the wetness of the root zone. *CR* can normally be assumed to be zero when the water table is more than a few meters below the bottom of the root zone. Figure 10-2 shows estimated flux of water from a shallow water table to a bare soil surface under dry conditions. Data in the figure were based on simulations by the UPFLOW model (Raes and deProost 2003; Raes 2004). Similar figures for wet soil conditions and for flux into a 1-m root zone are presented in Appendix I along with regression equations that reproduce the figures. Appendix I also describes an analytical technique for estimating capillary rise by Brutsaert (1982). Medium textured soils tend to have higher upward fluxes than fine and coarse textured soils due to a favorable combination of capillarity and hydraulic conductivity.

Deep Percolation from the Root Zone (DP) Following heavy rain or irrigation, the soil water content in the root zone may exceed field capacity. In application of Eq. (10-9), *DP* is assumed to occur at the end of the same day of a wetting event, so that the depletion $D_{r,i}$ becomes zero. Therefore,

$$DP_i = (P_i - RO_i) + I_i - ET_{c\,act,\,i} - D_{r,\,i-1} \tag{10-12a}$$

where DP_i is limited to $DP_i \geq 0$. As long as the soil water content in the root zone is below field capacity (i.e., $D_{r,i} > 0$), the soil is assumed to not drain

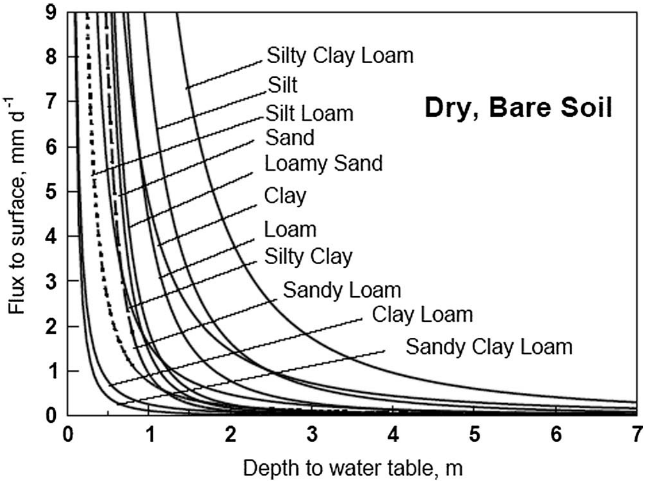

Fig. 10-2. Estimated flux of water to the ground surface for evaporation as a function of depth to the water table for various soil textures, based on numerical simulations using the UPFLOW (Raes 2004) model

and $DP_i = 0$. If drainage from the root zone is expected to be delayed by a day or more following a large infiltration event, then daily DP_i in Eq. (10-9) can be estimated as

$$DP_i = \max\{\min[(P_i - RO_i) + I_i - ET_{c\,act,\,i} - D_{r,\,i-1}, DR_i], 0\} \qquad (10\text{-}12b)$$

where DR_i is an expected maximum rate of drainage from the root zone on day i, with units for DR_i the same as P and I. Limiting $DP_{r,i}$ to DR_i has the effect of causing $D_{r,i}$ in Eq. (10-9) to be negative for one or more days. Values for DR_i can be estimated from hydraulic conductivity characteristics for the root zone soil layer.

The recommended order of calculation of parameters in the dual K_c procedure and associated equation numbers are as follow: K_{cb}, K_{cmax} (10-3), K_s (10-6), f_c (9-27), f_{ew} (9-26), F_{stage1} (9-22), K_r (9-21 or 9-24, 9-25), K_e (9-19), K_I (9-31), T_e (9-30), K_c (10-2), ET_c (8-14), RO_i, $E_i = K_e ET_{ref}$, $D_{e,i}$ (9-28), $D_{REW,i}$ (9-29), DP_i (10-12a,b), and $D_{r,i}$ (10-9). Examples of application of the FAO-56 dual K_c procedure include Hunsaker (1999), Tolk and Howell (2001), de Medeiros (2001), Hunsaker et al. (2002, 2003, 2005), Howell et al. (2004), Mutziger et al. (2005), and Allen et al. (2005c).

Mean Crop Coefficients

In basin-wide water balance studies or irrigation system planning, use of mean, or single, crop coefficients may be more useful and convenient than computing a daily K_c based on a combination of K_{cb}, K_s, and K_e as used in the dual K_c method of Eq. (10-2). The mean crop curve, K_{cm}, shown in

Figure 10-1, lies above the basal curve by an amount that depends on the frequency of soil wetting. When a mean coefficient is used, usually no additional adjustment is made for the effects of surface soil wetness. Adjustments can be made for the effects of limited soil water as

$$K_c = K_s K_{cm} \tag{10-13}$$

where K_s is defined in Eqs. (10-4) and (10-6). Values for K_{cm} during partial crop cover are dependent on precipitation frequency and irrigation practices that wet all or part of the soil surface. K_{cm} curves can be generated from K_{cb} curves for known or simulated precipitation or irrigation frequencies using the dual K_{cb} approach.

10.4 FAO GRASS-BASED CROP COEFFICIENTS

Although several crop coefficient models use a curvilinear curve shape, the linear segment model proposed by the FAO is widely used and easy to formulate (Figure 10-3). The procedure for constructing crop (cover) coefficients was presented in FAO-24 (Doorenbos and Pruitt 1977) and FAO-56 (Allen et al. 1998). In the FAO procedure, a K_c curve such as that shown in Figure 10-3 is constructed by

1. Dividing the growing season into four parts that describe crop phenology or growth stages:
   a. Initial period (1),
   b. Crop development period (2),
   c. Midseason period (3), and
   d. Late season period (4);

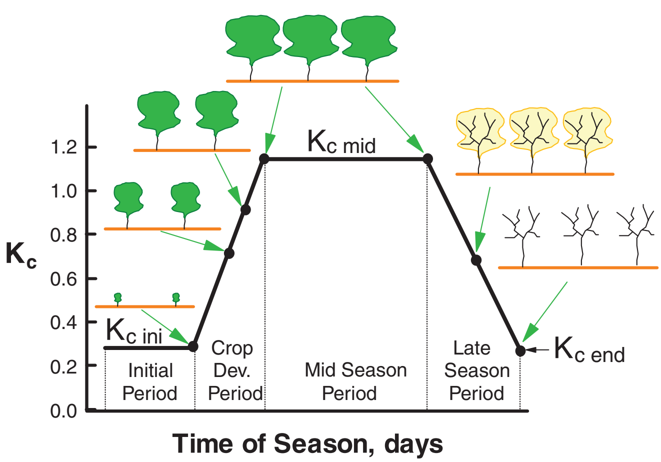

Fig. 10-3. FAO crop coefficient curve and stage definitions
Source: Allen et al. (2005b); copyright ASCE

2. Selecting three K_c values that represent
   a. Average K_c during the initial period ($K_{c\,ini}$),
   b. Average K_c during the midseason period ($K_{c\,mid}$), and
   c. Average K_c at the end of the late season (i.e., at the time of harvest or leaf-fall) ($K_{c\,end}$); and
3. Placing straight line segments through each of the four periods, with the lines through the initial and midseason periods placed horizontally.

Only three tabularized values for K_c are required to describe and construct the FAO-style K_c curve. $K_{c\,mid}$ represents the average value for K_c expected during the total midseason period, rather than the absolute peak daily K_c reached by the crop.

The four crop growth stages are generally characterized in terms of benchmark crop growth stages or cultivation practices. Definitions of these stages are given in Table 10-1 and are closely tied to crop phenology.

Values for $K_{c\,ini}$, $K_{c\,mid}$, and $K_{c\,end}$ are listed in Appendix B for mean K_{cm} for various agricultural crops. Most information in Appendix B was taken from FAO-24 (Doorenbos and Pruitt 1977) and FAO-56 (Allen et al. 1998) with additional information from Wright (1982), Snyder et al. (1989a, b), Jensen et al. (1990), Allen and Pereira (2009), and Allen et al. (2011a). Lengths of growth stages common to crops are listed in Appendix C. Values for K_{cb} are listed in Appendix D. Lengths of growth stages are strongly influenced by air temperature, time of year, and crop variety. Therefore the values for lengths in Appendix C are useful for general estimates only and should be verified or varied using local information and observation, including remote sensing (Bausch and Neale 1987; Neale et al. 1989; Tasumi et al. 2005a; Singh and Irmak 2009).

Table 10-1. General Benchmark Growth Stages for Defining FAO Crop Stages

Period	Growth Stages
Initial	*planting to 10% ground cover* (length is strongly dependent on crop and time of year)
Crop development	*10% ground cover to effective cover* (effective cover = initiation of flowering for many crops)
Midseason	*effective cover to start of maturity* (start of maturity is often indicated by the beginning of aging, yellowing or senescence of leaves, browning of fruit, etc.)
Late season	*start of maturity to harvest*

Adjustment of K_c for Climate

The ratio of ET_c to grass reference ET_o for many crops increases as wind speed increases and as minimum daily relative humidity, RH_{min}, decreases (Doorenbos and Pruitt 1977). This is due primarily to differences in roughness between tall agricultural crops and the clipped grass reference. The result is a high K_c value caused by increased roughness and perhaps leaf area for a tall crop, making the aerodynamic aspects of vapor transport more important and significant. The adjustment to K_c is generally required only for coefficients based on the grass ET_o reference. No adjustment for climate is necessary for coefficients based on the alfalfa ET_r reference because of the greater height, roughness, and leaf area of alfalfa (Wright 1982; Pereira et al. 1999a). The FAO procedure for adjusting the ET_o-based K_c values uses mean RH_{min} and wind speed, where $K_{c\,mid}$ and $K_{cb\,mid}$ values are adjusted for climates having RH_{min} greater than or less than 45%, or having mean wind speed at $2\,\mathrm{m}(u_2)$ that is greater than or less than $2.0\,\mathrm{m\,s^{-1}}$, as

$$K_{c\,mid} = K_{c\,mid(\mathrm{table})} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{10-14}$$

where $K_{c\,mid(table)}$ is the value for $K_{c\,mid}$ or $K_{cb\,mid}$ taken from Appendix B or D, and h is the mean maximum plant height in m during the midseason period, or full cover period. Eq. (10-14) is valid for h to 20 m. Mean values for h are listed in Appendix B for the crops and vegetation listed. For local applications, h should be based on field observations. Eq. (10-14) will increase $K_{cb\,mid}$ by about 0.1 for mean wind speed of $5\,\mathrm{m\,s^{-1}}$ or RH_{min} of 15% when crop height is about 1–2 m.

The $K_{c\,end}$ or $K_{cb\,end}$ at the time the growing period ends is adjusted for climate with RH_{min} less than or greater than 45% or with wind speed at $2\,\mathrm{m}(u_2)$ less than or greater than $2\,\mathrm{m\,s^{-1}}$ as

$$K_{c\,end} = K_{c\,end(\mathrm{table})} + [0.04\,(u_2 - 2) - 0.004\,(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}, \quad \text{for } K_{c\,end(\mathrm{table})} \geq 0.4 \tag{10-15a}$$

$$K_{c\,end} = K_{c\,end(\mathrm{table})} + 0.001\,(RH_{\min} - 45), \quad \text{for } K_{c\,end\,(\mathrm{table})} < 0.4 \tag{10-15b}$$

where $K_{c\,end(\mathrm{table})}$ is the value taken from Appendix B or D.

Minimum daily relative humidity, RH_{min}, is defined as the average daily minimum relative humidity during a growth stage. It can be calculated as

$$RH_{min} = \frac{e^o(T_d)}{e^o(T_{\max})} \tag{10-16}$$

When dew point temperature or other hygrometric data are not available, then $RH_{\min}$ can be estimated by substituting $T_{\min}$ for T_d. Then

$$RH_{\min} \cong \frac{e^o(T_{\min} - K_o)}{e^o(T_{\max})} \tag{10-17}$$

where K_o is a dew point offset coefficient introduced with Eq. (8-17) and has values of approximately 2 to 5°C in semiarid and arid climates and approximately 0°C in humid to subhumid climates. The values for u_2 and RH_{min} in Eqs. (10-14) and (10-15) need only be approximate, averaged values representing the midseason or late season periods. Application of these equations can be made on a daily basis, but may not improve accuracy over using averaged values.

Estimation of Initial $K_{c\,ini}$ with the FAO Mean K_c Procedure

Values for mean $K_{c\,ini}$ in Appendix B represent mean soil wetting conditions expected for each type of crop during the initial period. These $K_{c\,ini}$s can be used for making approximate estimates of ET during planning studies. More accurate estimates of $K_{c\,ini}$ consider local characteristics including the frequency that the soil surface is wetted and soil type, as this significantly affects the ET rate during the initial and development periods, when ET predominantly comprises evaporation. Values for $K_{c\,mid}$ and $K_{c\,end}$ are less affected by wetting frequency because vegetation during these periods is generally near full ground cover so that effects of surface evaporation are generally small.

When the ground surface is bare or nearly bare, then $K_{c\,ini}$ is dominated by the evaporation from bare soil, denoted here for time-averaged periods as K_{soil}. Figures 10-4a–10-4c from FAO-56 present K_{soil} as a function of ET_o, soil type, and wetting frequency. Figure 10-4a is used for all soil types when wetting events (precipitation and irrigation) are light (i.e., infiltrated depths average about 10 mm per wetting event); Figure 10-7b is used for "heavy" wetting events, where infiltrated depths are greater than 30–40 mm, on coarse textured soils; and Figure 10-4c is used for heavy wetting events on fine and medium textured soils. In general, the mean time interval is estimated by counting all rainfall and irrigation events occurring during the initial period that are greater than a few mm. Wetting events occurring on adjacent days are typically counted as one event. When average infiltration depths are between 10 and 40 mm, the value for K_{soil} can be interpolated between Figure 10-4a and Figure 10-4b or Figure 10-4c. Besides the use of K_{soil} for $K_{c\,ini}$ when the ground is nearly bare during the initial period (so that $K_{c\,ini} = K_{soil}$), estimates for K_{soil} are used later in Eq. (10-26) to estimate the effect of soil evaporation on the value for K_{cm} estimated from fraction of ground covered by vegetation. K_{soil} is also used to estimate landscape water use in Eq. (10-33b).

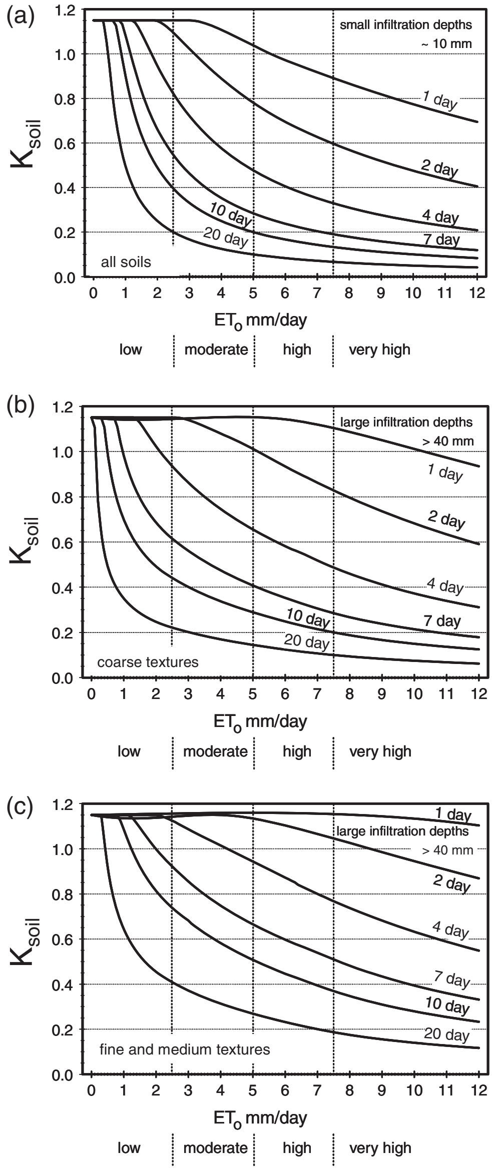

Fig. 10-4. Average K_{soil} *for the initial crop development stage as related to the level of grass reference* ET_o *and the interval between irrigations and/or significant rain during the initial period for (a) all soil types when wetting events are light (about 10 mm per event), (b) coarse-textured soils when wetting events are greater than about 40 mm, and (c) medium and fine-textured soils when wetting events are greater than about 40 mm.* K_{soil} *is equivalent to* K_{cini} *when the soil surface is primarily bare Source: Data from FAO-56, Allen et al. (1998)*

In equation form, K_{soil}, following Allen et al. (1998, 2005c), is

$$K_{\text{soil}} = \frac{TEW - (TEW - REW)e^{\left[\frac{-(t_w E_{so} - REW)}{TEW - REW}\right]}}{t_w ET_{ref}} \quad \text{for } t_w > t_1 \tag{10-18}$$

where TEW is total evaporable water, REW is readily evaporable water, t_w is the average time interval between wetting events in days, and E_{so} is the potential evaporation rate during stage 1 drying in mm d^{-1}. The symbol e in Eq. (10-18) is the base of the natural logarithm. Eq. (10-18) is valid when $t_w > t_1$ where t_1 is the length of stage 1 evaporation in days. The length of stage 1, t_1, is calculated as

$$t_1 = \frac{REW}{E_{so}} \tag{10-19}$$

and parameter E_{so} is potential evaporation calculated as

$$E_{so} = (K_{c\,max} - K_{cb})\, ET_{ref} \tag{10-20}$$

where, during the initial period, when K_{cb} mostly represents residual, basal evaporation, K_{cb} can be set equal to 0.0 in Eq. (10-20) to combine all evaporation, so that $E_{so} = K_{c\,max} ET_{ref}$. Under frequent wetting, where $t_w \le t_1$, the entire evaporation process resides within stage 1 and K_{soil} is calculated as

$$K_{\text{soil}} = \frac{E_{so}}{ET_{ref}} = \frac{(K_{c\,max} - K_{cb})}{ET_{ref}} \tag{10-21}$$

Figures 10-4a–10-4c are reproduced from Eqs. (10-18) and (10-21) using the values for TEW and REW summarized in Table 10-2. The max () and min() functions in Table 10-2 indicate the selection of the maximum or minimum value of parameters separated by the comma. K_{soil} values from Figure 10-4 are for use with the grass reference ET_o. For use with the alfalfa reference ET_r, the K_{soil} from Figure 10-4 can be divided by 1.2. Eqs. (10-13)–(10-21) can be applied directly with alfalfa reference ET_r using $K_{c\,max} = 1.0$.

Allen et al. (1998, 2005a) describe the calculation of t_w from precipitation and irrigation information. Allen et al. (2005a) provide calculation of a weighted f_w used in Eq. (9-26) when f_w for irrigation is less than the $f_w = 1$ for precipitation.

A second and more accurate procedure for estimating mean $K_{c\,ini}$ is to apply the dual $K_{cb} + K_e$ approach using actual sequences of precipitation and irrigation during the initial period for one or more years, assuming that the basal K_{cb} is 0.10 to 0.15 when the initial condition is nearly bare soil. A time-averaged value for $K_{cb} + K_e$ can then be determined.

Table 10-2. Values for TEW and REW in mm to Recreate Fig. 10-4a–c in Allen et al. (2005a) where ET_o is Grass Reference ET in mm d^{-1}

Figure	Parameter in Eqs. (10-18), (10-19)
Fig. 10-4a	$TEW = 10$ mm
	$REW = \max[2.5, 6/(ET_o)^{0.5}]$
Fig. 10-4b	$TEW = \min[15, 7(ET_o)^{0.5}]$
	$REW = \min(6, TEW - 0.01)$
Fig. 10-4c	$TEW = \min[28, 13(ET_o)^{0.5}]$
	$REW = \min(9, TEW - 0.01)$

Lengths of Growth Stages

FAO-24 (Doorenbos and Pruitt 1977) and FAO-56 (Allen et al. 1998) provide general lengths for growth (development) stages for various types of climates and locations. Appendix C summarizes this information. The rate of vegetative development and attainment of effective full cover is affected by weather conditions, especially by mean daily air temperature (Ritchie and NeSmith 1991). Therefore, the length in time between planting or plant emergence and effective full cover for various crops or other vegetation will vary with climate, latitude, elevation, and planting date (if cultivated) and with species and cultivar (variety). Generally, once effective full cover for a plant canopy has been reached, the rate of phenological development (flowering, seed development, ripening, and senescence or death of leaf tissue) often proceeds at a rate that depends on plant genotype rather than weather (Wright 1982). In some situations, the emergence of vegetation, greenup, and attainment of effective full cover can be estimated using cumulative degree-based regression equations or plant growth models (Sinclair 1984; Sammis 1985; Snyder 1985; Flesch and Dale 1987; Ritchie and NeSmith 1991; Ritchie 1991; Slack et al. 1996; Snyder et al. 1999; Cesaraccio et al. 2001; Sammis et al. 2004; Allen and Robison 2007). The use of cumulative growing degree days provides a quantitative stretching or shrinkage of the generated K_c curves for years or growing seasons that run cooler or warmer than average. Appendix F provides K_c curves traceable to those of Wright (1981, 1982) for Kimberly, Idaho, that are converted to a cumulative growing degree day basis.

Local observations of plant stage development should be used when possible, with values in Appendix C used as a guide and for comparison. Local information can be obtained from farmers, ranchers, agricultural extension agents, local researchers, or remote sensing. When determining stage dates from local observations, the following guidelines may be helpful.

Effective full cover for row crops such as beans, sugar beets, potatoes, and corn is generally considered to occur when leaves of plants in adjacent rows intermingle so that soil shading becomes nearly complete near solar noon, or when plants reach nearly full size, if no intermingling occurs and plant cover >75% (Wright 1982). If, for some reason, shading of the soil does not become complete for crops that generally do nearly completely shade the soil, then the value for $K_{c\,mid}$ should be scaled down accordingly (perhaps 0.5% decrease in the standardized $K_{c\,mid}$ for each 1% of unshaded soil; Allen et al. 1998). Incomplete ground cover may occur from reduction in plant growth due to disease, grazing, pests, soil water stress, or cultural practices calling for vegetation-free strips between crop rows.

Because visually determining when densely sown vegetation such as winter and spring cereals and grasses reach effective full cover is difficult, the more easily detectable stage of heading has been used (Wright 1982). For dense grasses, effective full cover will occur at about 0.10–0.15 m height. For thin stands of grass (dry rangeland), grass height may approach 0.3 to 0.5 m before effective full cover is reached. Densely planted forage such as alfalfa and clover reaches effective full cover at about 0.3 to 0.4 m height.

For many agricultural plants, effective full cover is considered to occur when the leaf-area index, LAI, approaches 3.0 (Ritchie 1972; Wright 1982; Ritchie and NeSmith 1991). Kang et al. (2003) and Duchemin et al. (2006) report similar results. LAI is defined as the average total area of leaves (one side) per unit area of ground surface.

The length of the initial and development periods may be relatively short for deciduous trees and shrubs that develop leaves in spring at relatively fast rates. Under some conditions, the initial period may include the time period from flowering until leaf bloom. The $K_{c\,ini}$ selected for trees and shrubs should reflect the ground condition prior to leaf bloom (the amount of grass or weed cover, wetness, mulch density, etc., affect $K_{c\,ini}$). For example, the $K_{c\,ini}$ for a deciduous orchard having grass ground cover may be as high as 0.8 to 0.9 prior to and during leaf initiation in frost-free climates, whereas the $K_{c\,ini}$ for a deciduous orchard having a bare soil surface may be as low as 0.3 to 0.4 prior to leaf initiation if wetting of the soil by irrigation or by precipitation is infrequent.

The end of the midseason and beginning of the late season are usually marked by senescence (browning or dying) of leaves, often beginning with the lower leaves of plants. This, along with less efficient stomates in aging leaf surfaces, causes the reduction in K_c.The length of the late season may be relatively short (on the order of 5 to 10 days) for vegetation killed by frost or for agricultural crops that are harvested fresh. The value of $K_{c\,end}$ used after the termination of plant growth or following harvest should reflect the condition of soil (surface soil water, mulch cover) and condition of the vegetation following plant death or harvest. Often K_c after harvest can be estimated using $K_{c\,\mathrm{soil}}$ from Eq. (10-18) or Figure 10-4.

An FAO K_c Example

An example for constructing an FAO K_c curve under mean soil wetness conditions is presented in Figure 10-5 for spring barley planted at Logan, Utah (latitude of about 42°). The initial, development, midseason, and late season stages were taken from Appendix C to have lengths equal to 20, 25, 60, and 30 days for March/April planting at a high latitude site (35–45°). Values for $K_{c\,ini}$, $K_{c\,mid}$, and $K_{c\,end}$ were selected from Appendix B as 0.3, 1.15, and 0.25. Mean wind speed at Logan during the mid and late seasons is about $2\,\mathrm{m\,s^{-1}}$ and average RH_{min} is about 30%. Therefore, $K_{c\,mid}$ is adjusted using Eq. (10-14) as $K_{c\,mid} = 1.15 + [0.04(2–2)–0.004(30–45)](1/3)^{0.3} = 1.19$. $K_{c\,end}$ was adjusted using Eq. (10-15b) as $K_{c\,end} = 0.25 + 0.001(30–45) = 0.23$. $K_{c\,end}$ is slightly lower than the value in Appendix B ($RH_{min} = 45\%$), because the adjustment considers that the soil surface and crop during the late season would be slightly drier under the more arid conditions (Doorenbos and Pruitt 1977).

ET_o during the initial and development periods (April) averaged $4\,\mathrm{mm\,d^{-1}}$, and the irrigation and precipitation wetting interval during April was about 12 days. Therefore, from Figure 10-4c, $K_{c\,soil}$ is approximately 0.5. This is an improved estimate for $K_{c\,ini}$ for Logan over that listed in Appendix B (0.3). An FAO mean K_c curve can now be constructed based on the three K_{cm} values of 0.5, 1.19, and 0.23 and the four lengths of growth stages (20, 25, 60, and 30 days) as shown in Figure 10-5.

Crops that are harvested several times during the growing season, such as forage crops, are typically modeled as a series of individually constructed curves, one for each growing cycle, as shown in Figure 10-6. Lengths of growth stages may vary from cycle to cycle as weather conditions change.

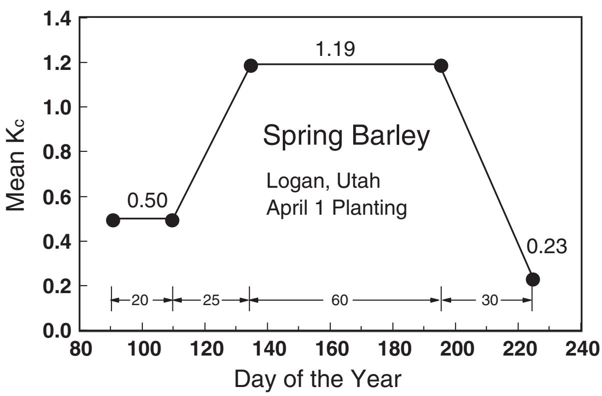

Fig. 10-5. Example construction of an FAO-24 crop coefficient curve

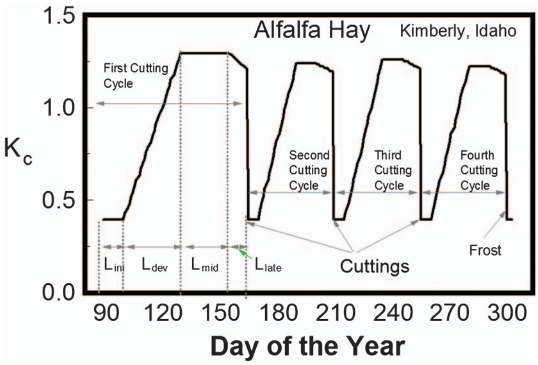

Fig. 10-6. Example mean K_c *curve constructed for four growing cycles of alfalfa hay near Kimberly, Idaho, using* K_c *values from Appendix B for grass reference* ET_o *following adjustment for climate using Eqs. (10-14)–(10-15)*

Use of the FAO Basal Crop Coefficient Procedure in Calculations

Estimates of K_c and ET_c made using the basal K_{cb} approach with calculations of soil evaporation made on daily time steps can be up to 10 to 20% more accurate than mean K_c estimates that are based on values in Appendixes B and E, especially for the first few days following soil wetting. This is especially true during the initial and development periods.

The FAO crop coefficients can be used in basal calculations by selecting $K_{cb\,mid}$ and $K_{cb\,end}$ from Appendix D and by setting $K_{cb\,ini} = K_{c\,min}$ during the initial period to represent conditions of a nearly bare soil surface. Appropriate adjustment to $K_{cb\,mid}$ and $K_{cb\,end}$ for the ET_o basis is made using Eqs. (10-14) and (10-15) to reflect general humidity and wind speed conditions. The *basal* curve is then drawn using the values for $K_{cb\,ini}$, $K_{cb\,mid}$, and $K_{cb\,\mathrm{end}}$ following the same procedures described previously for the general FAO K_c curve. $K_{c\,min}$ represents residual evaporation from a nearly dry bare soil. A typical value for $K_{c\,min}$ for a nearly dry, bare agricultural soil is generally taken as 0.10 to 0.15, recognizing that periodic tillage, precipitation, and irrigation tend to support this residual rate. Over extended fallow periods having no tillage, irrigation, or precipitation, the value for $K_{c\,min}$ tends toward zero. For grasses, brush, and trees, the $K_{c\,min}$ at the start of greenup or leaf development may be on the order of 0.3.

The first step in applying the FAO K_c in basal computations is to construct the basal K_{cb} curve using $K_{cb\,ini}$, $K_{cb\,mid}$, and $K_{cb\,\mathrm{end}}$ as described previously. Eq. (10-2), repeated here,

$$K_c = K_s K_{cb} + K_e \tag{10-22}$$

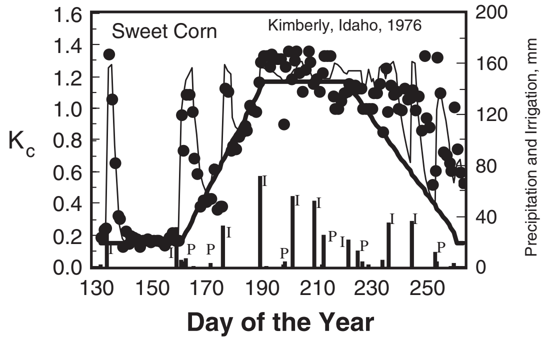

Fig. 10-7. Measured and estimated daily crop coefficients for a sweet corn crop near Kimberly, Idaho, for grass reference ET_o. *The basal crop curve* (K_{cb}) *was derived setting* $K_{cb\,ini} = K_{c\,min} = 0.15$ *and using data from J. L. Wright (1990, personal communication to R. G. Allen)*

is used to calculate K_c using the K_{cb} curve, where K_e and K_s are calculated on a daily time step using Eqs. (9-19) and (10-4) or (10-6). $K_{c\,max}$ in Eqs. (9-19) and (10-21) ranges from 1.2 to 1.25 for use with the grass-based FAO coefficients [Eq. (10-3a)] and generally equals 1.0 when used with alfalfa-based basal coefficients [Eq. (10-3b)].

An example of applying the FAO K_c procedure in a basal fashion is shown in Figure 10-7 for a sweet corn crop that was harvested as dry seed. The data in the figure were measured using a precision lysimeter system near Kimberly, Idaho (J. L. Wright, personal communication, 1990). The 24-hour K_c measurements (symbols) were calculated by dividing daily measured ET_c by daily calculated ET_o. The agreement between the estimated daily K_cs from Eq. (10-2) (shown as a thin, continuous line) and measured K_cs is relatively good. Measured and calculated K_cs increased following wetting by rainfall or irrigation. The measured K_c tended to be well above the K_{cb} line between days 230 and 250 due to effects of soil wetting on evaporation and thus total ET. This was reflected in the estimated K_c as well. A small amount of moisture stress may have occurred around day 220, where measured K_c fell below the K_{cb} curve that was not picked up by the K_c simulation. Some of the day-to-day variation in measured K_cs shown in Figure 10-7 was due to measurement variation in the lysimeter (about 0 to 5%). However, much of the variation is likely caused by random error in the ET_o estimate caused by timescale effects in the daily ET_o equation and fixed aerodynamic, reflectance, and surface conductance characteristics implicit to the ET_o definition that vary from the day-to-day characteristics of the sweet corn vegetation and by error in weather measurements. Other error is caused by error in the K_e estimation and by the assumption of a relatively constant ratio of ET_c to

ET_o (constant K_{cb}) from one day to the next. Total root mean square error (RMSE) calculated on a daily basis over the time period shown in Figure 10-7 is 0.17 on a K_c basis and 0.83 mm d^{-1} on an ET basis. The measured K_{cb} from the lysimeter for the silt loam soil averaged about 0.15 during the period from day 140 to 155 prior to growth of vegetation. That low background rate was supplied by slow diffusive evaporation from the wet subsoil. Even though the K_{cb} during late season was well below measured K_c, the addition of estimated K_e from irrigation and precipitation events caused the summed K_{cb} and K_e to approximate measured K_c relatively well.

Application of the FAO-56 K_{cb} procedure involving Eqs. (9-19)–(9-31) and (10-2) was made by Hunsaker et al. (2002) over a growing season of alfalfa containing eight cutting cycles at a field site in Phoenix, Arizona. Estimated ET_c was compared against measurements by three weighing lysimeters with good results, as shown in Figure 10-8. The RMSE for the Hunsaker et al. comparisons was 0.44 mm d^{-1}. Custom K_{cb} values for constructing local climate–adjusted FAO-56 style K_{cb} curves were determined as 0.30, 1.22, and 1.05 for the initial, middle, and end of late season,

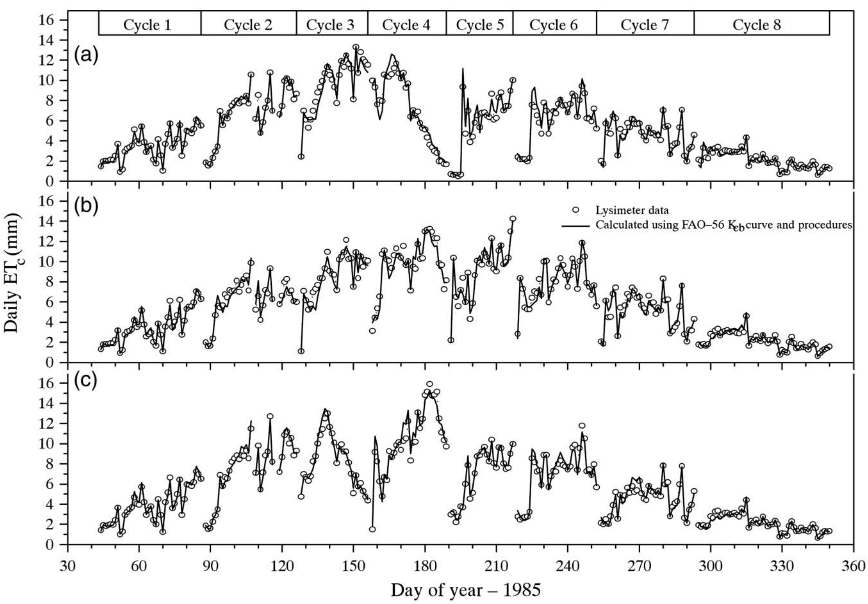

Fig. 10-8. Measured and estimated daily crop evapotranspiration over an entire growing season of alfalfa containing eight cutting cycles at a field site in Phoenix, Arizona. Measurements are shown for three lysimeter systems (a, b, c)
Source: Hunsaker et al. (2002); reproduced with permission from ASABE

respectively. Lengths of growth stages were varied for each cycle and lysimeter according to visual observation.

10.5 ALFALFA-BASED CROP COEFFICIENTS

The primary set of alfalfa-based crop coefficients developed in the United States is traceable to data from Wright (1981, 1982) in southern Idaho. Coefficients developed by Howell et al. (2006) from measurements in northern Texas have recently supplemented these. The Wright K_c curves are curvilinear, rather than linearly segmented like the FAO-style K_c curves, and attempt to more closely follow the expected progression of K_c with crop development. Wright developed K_c curves for eight crops common to the intermountain west of the United States. Wright's crop coefficients have been widely used in the United States, and many engineers and agronomists are familiar with adjusting the timescale to match local crop conditions. The mean and basal alfalfa-based crop coefficients of Wright (1981, 1982), converted for use with the ASCE Standardized Reference ET equation, are presented in Appendix E. Those same K_cs are converted to a cumulative growing-season time basis in Appendix F.

Procedure

Many of the principles and procedures described for using the FAO grass-based crop coefficients are applicable when using alfalfa-based crop coefficients. The main exception is that the alfalfa-based K_cs do not need to be adjusted for climate [Eqs. (10-14) and (10-15)], because most agricultural crops at full cover have roughness and leaf areas similar to alfalfa. Therefore, alfalfa-based crop coefficients for many agricultural crops have a maximum K_c near 1.0. The proximity of measured maximum K_c near 1.0 under full cover conditions serves as a useful reality check for field data and helps users visualize the development and shape of the crop coefficient curve for annual crops and forage crops that are cut periodically. Another advantage of alfalfa-based crop coefficients is that they are more convenient for use with satellite imagery–based energy balance methods for estimating ET over large areas, because maximum ET_c of many crops corresponds to the alfalfa-based ET_r. For example, the Landsat satellite imagery program for mapping evapotranspiration at high resolution (METRIC) that Allen et al. (2007b) describe uses alfalfa-based ET_r for calibration and produces crop coefficients that are alfalfa based. The alfalfa-based K_{cb} values from Appendixes E and F can be applied in Eq. (10-2) with K_e derived from Eq. (9-18) from Wright (1982), or the alfalfa-based K_{cb} values can be applied with the FAO-56 K_e procedure [Eqs. (9-19)–(9-31) and (10-2)], with the $K_{c\,max}$ term in Eq. (9-19) estimated using Eq. (10-3b).

In the Wright K_c time-based procedure, the time base for K_c is scaled based on the relative time from planting to effective full cover and, following the time of effective full cover, on days after effective full cover. Wright (1982) defines effective (full) cover as the time when leaves between row crops begin to interlock, at heading of grain, and flowering of peas. The shape of the K_c curve from planting or greenup to effective full cover is described by expressing values for K_c for each 10% of the total time length (Appendix E) and values for K_c for time after effective full cover are expressed for each 10 days following attainment of effective full cover. The K_c curves are constructed from decadal data (Appendix E) using linear or curvilinear interpolation between adjacent data columns or by fitting regression equations to the first half (planting to effective full cover) and to the second half (days after effective full cover) for each curve. Appendix E summarizes strategic dates of crop development recorded by Wright (1982).

The K_{cb} curves of Wright (1982) have been re-expressed in Appendix F as functions of cumulative growing degree days (CGDD) to provide automated flexure of the curve basis for varying weather conditions. Wright (2001) and Allen and Wright (2006) converted the Wright (1982) K_{cb} curves into CGDD-based curves where the K_{cb} values for the growing season were expressed as a ratio of the CGDD required for the crop to develop from the date of planting or greenup until effective full cover. The winter wheat curve of Allen and Wright (2006) was applied by Allen and Robison (2007) during the Idaho winter by beginning the curve in October, with reductions in CGDD applied when T_{min} fell below threshold values during cold winter periods.

An Alfalfa-Based Example

Figure 10-9 is an example comparing K_c estimated using basal alfalfa-based crop coefficients from Appendix F and the FAO-56 K_e procedure [Eqs. (9-19)–(9-31) and (10-2)–(10-3)] with daily ET measured with a precision lysimeter for a sweet corn crop near Kimberly, Idaho (data by J. L. Wright 1990, in personal communication to R. G. Allen, are the same as shown in Figure 10-7). The lysimeter data are the same data used by Wright (1982) to develop the K_{cb} curve, so that the K_{cb} estimates are not statistically independent of the measurements. The maximum K_{cb} for the sweet corn crop is about 0.9 for the alfalfa reference. The FAO-56 style method for estimating K_e performed relatively well with the curvilinear K_{cb} curve. The RMSE calculated on a daily basis over the time period shown in Figure 10-9 is 0.13 on a K_c basis and 0.75 mm d^{-1} on an ET basis. This compares with the RMSE of 0.17 on a K_c basis and 0.83 mm d^{-1} on an ET basis for the linear FAO-56 calculations of Figure 10-7. The magnitude of RMSE is affected by how the K_{cb} curves were originally constructed and measurement data

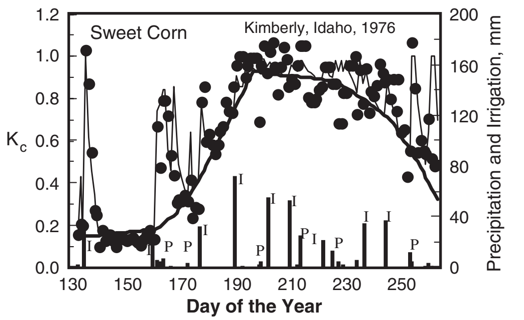

Fig. 10-9. Measured and estimated daily crop coefficients for a sweet corn crop near Kimberly, Idaho, based on alfalfa reference ET_r*. The basal (*K_{cb}*) crop curve is based on Wright (1982) curvilinear* K_{cb} *from Appendix F, and* K_e *is based on the FAO-56 procedure [Eqs. (9-19)–(9-31) and (10-1)–(10-12)]*
Source: Data from J. L. Wright (personal communication to R. G. Allen, 1990)

interpreted. In this case, the K_{cb} estimates are not statistically independent of the lysimeter measurements, although the K_e estimates are independent.

Expression of K_c Curves and the Time Basis

Because of uncertainty in day-to-day values for K_c or K_{cb} due to random error in weather data and ET_{ref} estimates and in determination of K_c from field or research measurements, the straight-line K_c curve method of the FAO method is generally appropriate for most applications. Hunsaker (1999) developed and compared K_{cb} curves for a cotton crop in Arizona using the straight-line method of FAO and curvilinear curves based on days after planting and based on cumulative growing degree days (Figure 10-10). Hunsaker concludes that any of the three K_{cb} curve construction methods should result in good estimates of daily ET_c for the early-maturity cotton measured, when grown under climatic conditions similar to those of the study.

10.6 ESTIMATES OF K_c CURVES FOR NATURAL AND AGRICULTURAL VEGETATION

The two-step K_cET_{ref} approach provides a simple, convenient way to estimate ET_c from natural vegetation, where K_c, if unknown, can be estimated according to the fraction of ground covered by vegetation. The developed cover (crop) coefficient curves represent the ratios of ET_c to ET_{ref} during various growth stages. A previous section describes estimation of lengths of growth stages. Often, for unknown K_c curves, the K_c during the

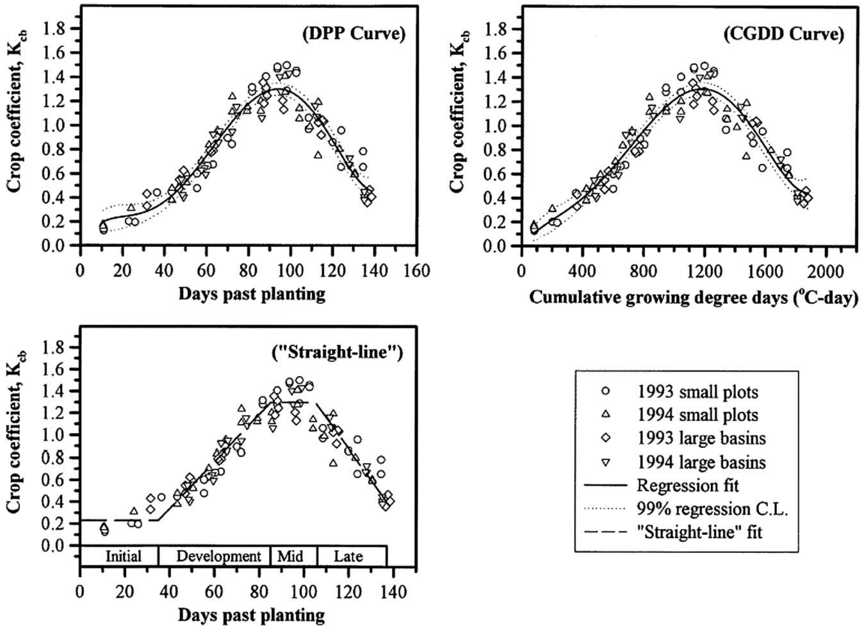

Fig. 10-10. Basal crop coefficient (K_{cb}) curves derived as functions of days past planting (DPP) and cumulative growing degree days (CGDD) and using the FAO straight-line method for an early maturing cotton crop in Arizona with comparison to measurements (symbols)
Source: Hunsaker 2003; reproduced with permission from Springer International Publishing

peak growth period ($K_{c\,mid}$) can be estimated according to the amount of ground shaded by vegetation, the density and height of plants, and the amount of stomatal regulation under moist soil conditions. The value for K_c for conditions of low soil water availability is generally determined using Eq. (10-4) or (10-6).

The K_c development process should adhere to upper limits for K_c of 1.1 for an alfalfa reference and about 1.25 for a grass reference for stands of vegetation larger than 500 to $2,000\,m^2$. Energy exchange principles within established equilibrium boundary layers and the principle of conservation of energy as discussed in the previous sections on field-scale applications and small expanses of vegetation govern ET from these stands. K_cs for small stands ($<500\,m^2$) should also adhere to these limits when the vegetation height and leaf area are less than or equal to those of surrounding vegetation and soil water availability is similar. Only under conditions of "clothesline effects" (where vegetation height is greater than surroundings) or "oasis effects" (where vegetation has higher soil water availability than

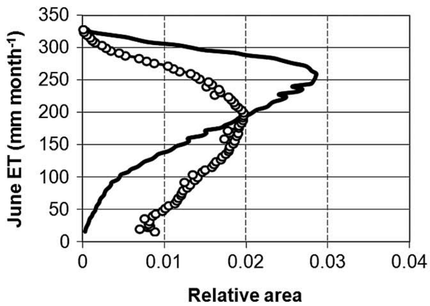

Fig. 10-11. Frequency distributions of ET from 6,000 ha of cottonwood and salt cedar (tamarisk) along the Middle Rio Grande in New Mexico during June and all of 2002
Source: Allen et al. (2007a); copyright ASCE

surroundings) will peak K_cs exceed the previously stated limits. The user should exercise caution when extrapolating ET measurements from small vegetation stands or plots to large stands or regions, as overestimation of regional ET may occur.

Derived K_c values for natural vegetation based on vegetation amount represent the potential K_c when soil water is available for full *ET*. Often, however, soil water levels for natural plant communities fall below adequate supplies due to drought or, for riparian vegetation, due to declining water tables. Therefore, the frequency distribution of ET can be broad for a population of vegetation, as shown in Figure 10-11, where a frequency distribution of June and annual ET for cottonwood and salt cedar along the Middle Rio Grande valley is shown as derived from satellite-based energy balance (Allen et al. 2007a). ET from salt cedar (e.g., tamarisk) showed larger variance due to its tendency to grow across a broad range of water availability (water table depth), soil types, and salinity conditions, whereas cottonwoods, which exhibited a smaller variance in the population of ET, are typically found close to stream channels and consistent water supply. Wide variation was also noted for tree population density, which added to variance in the populations of ET.

Allen et al. (1998) propose estimating K_c and ET for isolated, narrow stands of wetlands and tall wind breaks such as single rows of trees using a description of stand height and width and with dampening for vegetation with a high degree of stomatal control:

$$K_c = \min\left(K_{c\,max} + \frac{F_r h_{\text{canopy}}}{\text{width}},\ 2.5\right) \tag{10-23}$$

where $K_{c\,max}$, the maximum K_c expected for large fields, is 1.2 for use with ET_o and 1.0 for use with ET_r; F_r is a stomatal resistance correction factor;

h_{canopy} is the mean vertical height of the canopy area in m; and width is the horizontal thickness of the windbreak or patch of wetland vegetation normal to the general wind direction in m. For vegetation such as some desert vegetation and trees with leaf resistance significantly greater than that of most agricultural crops where r_l is commonly about 100 s m^{-1}, F_r can be approximated based on the FAO form of the PM equation:

$$F_r = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)} \tag{10-24}$$

where r_l is the mean leaf resistance for the vegetation in question in s m^{-1}. The mean leaf resistance, r_l is 100 s m^{-1} for the ET_o and ET_r references and for many agricultural crops. Values for r_l for many agricultural and nonagricultural plants can be found in Table 11-2 and Körner et al. (1979).

As discussed earlier, the value for $K_{c\,mid}$ for natural vegetation reduces when plant density or leaf area fall below full ground cover (LAI < 3). Because K_c tends to increase in proportion to the amount of vegetation, K_c at midseason, $K_{c\,mid}$, can be expressed as a function of a density coefficient, K_d (Allen and Pereira 2009), where

$$K_{cb\,mid} = K_{c\,min} + K_d\,(K_{cb\,f\text{ull}} - K_{c\text{ min}}) \tag{10-25a}$$

where $K_{cb\,mid}$ is the approximation for K_{cb} during the midseason period, $K_{cb\,\text{full}}$ is the estimated basal K_c during peak plant growth for conditions of nearly full ground cover (or LAI > 3), and $K_{c\,min}$ is the minimum basal K_c for bare soil ($K_{cb\,min} \sim 0.15$ under typical agricultural conditions and $K_{cb\,min} \sim 0.0$ to 0.15 for native vegetation, depending on rainfall frequency). The density coefficient K_d can be estimated as a function of measured or estimated leaf-area index (LAI) or as a function of fraction of ground covered by vegetation. For tree crops having grass or other ground cover, Eq. (10-25a) can take the form

$$K_{cb\,mid} = K_{cb\,\text{cover}} + K_d\left[\max\left(K_{cb\,\text{full}} - K_{cb\,\text{cover}}, \frac{K_{cb\text{ full}} - K_{cb\,\text{cover}}}{2}\right)\right] \tag{10-25b}$$

where $K_{cb\,\text{cover}}$ is the K_{cb} of the ground cover in the absence of tree foliage. The second term of the max function reduces the estimate for $K_{cb\,mid}$ by half the difference between $K_{cb\,\text{full}}$ and $K_{cb\,\text{cover}}$ when this difference is negative. This accounts for impacts of shading of the surface by vegetation with K_{cb} lower than that of the surface cover, due to differences in stomatal conductance. Eq. (10-25) can be applied to estimate K_{cb} during other periods besides the midseason by estimating K_d using Eqs. (10-27) and (10-28) with LAI or $f_{c\,eff}$ for that period.

Eq. (10-25) can similarly be applied to estimate a mean K_{cm} for any period with less than full vegetative cover by accounting for the effect of evaporation from predominantly exposed areas of soil among the vegetation, much as is done in the dual $K_{cb} + K_e$ approach:

$$K_{cm} = K_{\text{soil}} + K_d \left[\max \left(K_{cb\,\text{full}} - K_{\text{soil}}, \ \frac{K_{cb\,\text{full}} - K_{\text{soil}}}{2} \right) \right] \tag{10-26}$$

where K_{soil} is obtained from Figure 10-4 or Eq. (10-18) and represents the average K_c from the nonvegetated (exposed) portion of the surface. The value for K_{soil} reflects the effect of wetting frequency, soil type, and relative ET rate (i.e., ET_{ref}) during the same period as K_d and $K_{cb\,\text{full}}$. The K_{cm} represents an average K_c value that considers the mean impact of evaporation from soil. K_{cm} can be used to represent the midseason or other period as defined by K_d, K_{cm}, and $K_{cb\,\text{full}}$.

For large stand size (>about 500 m^2), $K_{cb\,\text{full}}$ for use with ET_o can be approximated for crops not listed in Appendix D as a function of mean plant height and adjusted for climate similar to the $K_{cb\,mid}$ parameter and following Allen et al. (1998):

$$(\text{for } ET_o)\ldots\ldots K_{cb\,\text{full}} = \min(1.0 + 0.1h, \ 1.20) + [0.04\,(u_2 - 2) - 0.004\,(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{10-27a}$$

For use with alfalfa reference ET_r, $K_{cb\,\text{full}}$ can be approximated for crops not listed in Appendix F as

$$(\text{for } ET_r)\ldots\ldots K_{cb\,\text{full}} = \min(0.8 + 0.1h, \ 1.0) \tag{10-27b}$$

where h is mean maximum plant height in m, u_2 is the mean value for wind speed at 2-m height during the midseason in m s^{-1}, and $RH_{\min}$ is the mean value for minimum daily relative humidity during the midseason in percent. The climatic correction is not required for $K_{cb\,\text{full}}$ when used to derive the K_{cb} for ET_r because of the aerodynamic and canopy characteristics of the alfalfa reference crop.

The value $K_{c\,\text{full}}$ represents a general upper limit on $K_{cb\,mid}$ for tall vegetation with full ground cover and LAI > 3 under full water supply. The min function in Eq. (10-27b) selects the minimum expression in the parentheses. Eqs. (10-27a) and (10-27b) produce general approximations for the increase in $K_{cb\,\text{full}}$ with plant height and climate. The estimate from Eq. (10-27) may need adjustment downward if the vegetation exhibits more stomatal control on transpiration than is typical for agricultural crops, for example, for some types of trees or natural vegetation.

Where LAI can be measured or approximated, K_d can be approximated under normal conditions (Allen et al. 1998) as

$$K_d = (1 - e^{[-0.7\,LAI]}) \tag{10-28}$$

LAI is defined as the area of leaves per area of ground surface averaged over a large area with units of m^2m^{-2}. Only one side of green healthy leaves that are active in vapor transfer is considered. The relationship in Eq. (10-28) is similar to one used by Ritchie (1974).

Where estimates of the fraction of ground surface covered by vegetation are available, the K_d can be estimated as (Allen and Pereira 2009)

$$K_d = \min\left[1, M_L f_{c\,eff}, f_{c\,eff}^{\left(\frac{1}{1+h}\right)}\right] \tag{10-29}$$

where M_L is a multiplier on $f_{c\,eff}$ describing the effect of canopy density and conductance on maximum relative ET per fraction of ground shaded (1.5–2.0), $f_{c\,eff}$ is the effective fraction of ground covered or shaded by vegetation (0.01–1) near solar noon, and h is the mean height of the vegetation in m. For canopies such as trees or randomly (nonrow) planted vegetation, $f_{c\,eff}$ can be estimated from Allen et al. (1998) as

$$f_{c\,eff} = \frac{f_c}{\sin(\beta)} \le 1 \tag{10-30}$$

where β is the mean angle of the sun above the horizon during the period of maximum ET (generally between 11.00 and 15.00). Generally, $f_{c\,eff}$ can be assigned to solar noon (12.00), so that β can be calculated as

$$\beta = \arcsin[\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)] \tag{10-31}$$

where parameters ϕ and δ are defined in Chapter 4 [see Eq. (4-10) for example]. Figure 10-12 schematically illustrates f_c, $f_{c\,eff}$, and β.

The M_L multiplier on $f_{c\,eff}$ in Eq. (10-29) imposes an upper limit on the relative magnitude of transpiration per unit of ground area as represented by $f_{c\,eff}$ (Allen et al. 1998) and is expected to range from 1.5 to 2.0, depending on the canopy density, thickness, and maximum conductance. Parameter M_L is an attempt to simulate the physical limits imposed on water flux through the plant root, stem, and leaf systems (Allen and Pereira 2009). The value for M_L can be modified to fit the specific vegetation. Values for M_L used to calculate values for K_{cb} for orchard crops in Appendix D and that served as the basis for K_{cm} for orchard crops in Appendix B are listed in Table D-2 of Appendix D. Figure 10-13 shows values for K_d over a range of $f_{c\,eff}$ and a range of h for $M_L = 1.5$ and for $M_L = 2$ when $h = 5$ m. The estimates by Eq. (10-29) agree with those

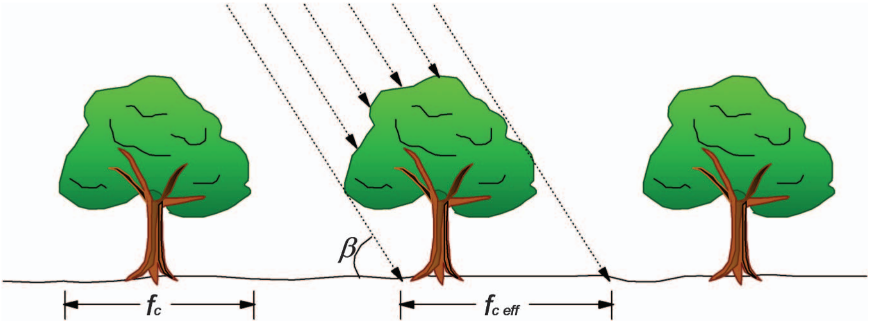

Fig. 10-12. Schematic showing extent of f_c, $f_{c\,eff}$, *and* β *for tree vegetation where* f_c *is the fraction of surface covered by vegetation as measured from directly overhead*

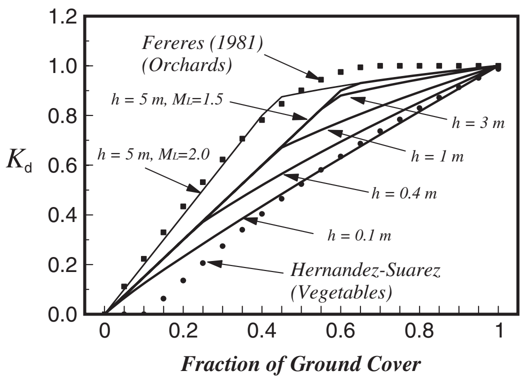

Fig. 10-13. Density coefficient, K_d, *estimated from Eq. (10-29) with* $M_L = 1.5$ *over a range of ground cover fractions and various plant heights and compared with estimates by Fereres (1981) for orchards and Hernandez-Suarez (1988) for vegetables*
Source: Comparative data from Fereres (1981) and Hernandez-Suarez (1988)

previously suggested by Fereres (1981) and Hernandez-Suarez (1988) for specific types of vegetation.

When the mean stomatal control by the vegetation is greater than for agricultural vegetation, then FAO-56 suggests that the estimate by Eq. (10-29) be reduced by about 10 or 20% for each doubling of r_1 above 100 s m^{-1}. The value for $K_{cb\,mid}$ estimated by Eq. (10-25) is applied as a basal coefficient using the dual $K_{cb} + K_e$ method, where the actual K_c may increase to 1.0 for ET_r or 1.2 for ET_o following precipitation even if the estimated $K_{cb\,mid}$ is small, due to surface evaporation from among sparse vegetation. In addition, K_c should be reduced via Eq. (10-2) or (10-22) using K_s from Eq. (10-4) or (10-6) when soil water is low.

Eq. (10-29) suggests that as h increases, total leaf area and resulting net radiation capture will increase, thereby increasing K_c. In addition, as h increases, more opportunity for microadvection of heat from soil to canopy occurs, and turbulent exchange within the canopy increases for the same amount of ground coverage. Both of these conditions increase the relative magnitude of $K_{cb\,mid}$. Values for $K_{cb\,end}$ can be scaled from $K_{cb\,mid}$ in proportion to the health and leaf condition of the vegetation at termination and the length of the late season period (i.e., whether leaves senesce slowly or are killed by frost). The f_c parameter and h are probably the simplest indices to estimate in the field.

Ringersma and Sikking (2001) apply Eqs. (10-25), (10-27a), and (10-29) to estimate ET from Sahelian vegetation barriers. They find Eq. (10-27a) to overestimate $K_{cb\,\text{full}}$, even with adjustment using F_r, but find Eq. (10-29) to produce representative estimates. Ringersma and Sikking suggest distinction between C3 and C4 photosynthetic behavior for LAI and f_c based estimation, because C4 vegetation can have limited stomatal control. Descheemaeker et al. (2011) apply Eqs. (10-25), (10-26), and (10-29) to savannah vegetation in Ethiopia and find good agreement between estimated ET and ET measured gravimetrically. Vegetation types ranged from sparse, grazed grasses to full forest canopy.

10.7 LANDSCAPE COEFFICIENTS

Water requirements and consumption by residential and urban landscapes have become increasingly important because of the quantity and value of water consumed. Procedures similar to those from agriculture have been adapted to estimate ET from landscapes. However, two distinctions are made between agriculture and landscapes: (1) landscape systems often comprise mixtures of types and species of vegetation, thereby complicating the estimation of ET, and (2) typically, the objective of landscape irrigation is to promote appearance rather than biomass production, whereas biomass production is generally maximized in agriculture. Therefore, target ET for landscapes may include intentional water stress in the baseline estimate for ET_c, because landscape plants are watered less than they would be if they were irrigated like a crop. Landscape vegetation should generally be watered sufficiently for acceptable appearance and to survive, but the plants can often be stressed to some degree and will not be at maximum productivity. This adjustment can produce significant water conservation. The magnitude of the stress factor depends on physiological and morphological requirements of the plants;

the goal is to sustain health and appearance with minimal irrigation. For example, water conservation studies on turfgrass have demonstrated water savings of 30% for cool-season turfgrasses and 40% for warm-season turfgrasses without significant loss of quality (Meyer and Gibeault 1986; Pittenger and Shaw 2001, 2004). Some shrubs and ground covers can be managed for even more stress-induced reduction in ET (Kjelgren et al. 2000). A third departure of landscape ET from agricultural ET is that few landscape sites meet the "extensive surface" requirement needed to ensure equilibrium between the lower boundary layer of the atmosphere and the vegetation that is implied in the Penman-Monteith equation. Therefore, compensating adjustments are necessary to the landscape coefficient in the form of a microclimate factor to account for effects of local surroundings.

Because of the frequent inclusion of water stress in target ET values for landscape design and management, distinction must be made between these target ET values and actual ET values. Actual ET values may exceed target ET values if the landscape receives more water than required by the target that includes intentional stress. Under these conditions, landscape vegetation may exploit the additional available water, subject to some limit constrained by environmental energy available for evaporation and leaf area. The upper environmental energy limit, which follows behavior and principles used for agricultural crops, may exceed the targeted ET rate for the particular landscape cover. Conversely, actual ET may be less than targeted ET values if actual stress levels to the landscape are more excessive than targeted. Therefore, two ET values for landscape are distinguished here. The first is the *target landscape ET*, referred to as ET_L, that is based on minimum ET levels, relative to climate, necessary to sustain a healthy, attractive landscape. The second ET value is the actual landscape ET, ET_{Lact}, that is based on landscape type and on actual water availability. Traditionally, landscape ET estimation is based on the grass reference ET_o rather than on alfalfa reference ET_r. The target ET for a landscape is calculated as

$$ET_L = K_L \, ET_o \tag{10-32}$$

where ET_L is the target landscape ET (in mm d^{-1}, mm month^{-1}, or mm year^{-1}), and ET_o is the grass reference ET in the same units. K_L is the target landscape coefficient, similar to the crop coefficient used in agricultural applications.

Somewhat limited experimental research exists on quantifying water needs of the vast and diverse array of landscape plant types (Pittenger and Henry 2005). Some of the leading work on landscape *ET* from ground covers and shrubs has been done in California, where water applied to landscapes in southern California is estimated to be 25 to 30% of all water used in the region (Pittenger and Shaw 2001). St. Hilaire et al. (2008)

produced a table of K_L values for 35 landscape ground covers and shrubs that are targeted to provide acceptable landscape performance after initial establishment and that induce a managed amount of moisture stress via limited water application. Costello et al. (2000) and Irrigation Association (2003) describe a procedure from California termed WUCOLS (water use classification of landscape species), where the K_L was decoupled into reproducible and visually apparent components representing the effects of three or four factors that control the value for K_L. The decoupling was done to facilitate application to the wide diversity of vegetation types and environments of landscape systems. Snyder and Eching (2004, 2005) propose a similar decoupled procedure for estimating a formulated K_L that uses different ranges for the components:

$$K_L = K_v\, K_d\, K_{sm}\, K_{mc} \tag{10-33a}$$

where K_v is a vegetation species factor, K_d is a vegetation density factor, K_{mc} is a microclimate factor, and K_{sm} is a managed stress factor. K_v can be considered to be the ratio of ET_v to ET_o for a specific single or mixture of plant species under full or nearly full ground cover and full soil water supply, where ET_v is the vegetation ET assuming no water deficits and greater than 70 to 80% ground cover. Factors K_d, K_{mc}, and K_{sm} modify K_v for less than effective full ground cover (K_d), for effects of shading or for exposure to advective or reflective sources (K_{mc}), and for intentional water stress (K_{sm}). Each of these factors can be estimated separately from the other based on visual observation of the landscape (for K_d and K_{mc}) and based on grower experience (for K_{sm}). Following the estimation of the individual factors, K_L is calculated using Eq. (10-33) and represents a generally accurate and reproducible estimate of relative landscape ET. The procedure of Snyder and Eching (2004, 2005), used in the University of California-Davis's LIMP software, differs from that of WUCOLS (Costello et al. 2000; Irrigation Association 2003) in the ranges used to define K_d. The Snyder-Eching definition and range for K_d are congruent with estimates for K_d from Eq. (10-29), where K_d ranges from 0 to 1.

An alternative form of Eq. (10-33a) conforms to the procedure used to derive the agricultural K_c as a function of vegetation density where account is made for evaporation from exposed bare soil among the vegetation [see Eqs. (10-25a, b)]:

$$K_L = (K_{\text{soil}} + K_{vsd}\; K_d\, K_{sm})\, K_{mc} \tag{10-33b}$$

where K_{vsd} is a coefficient describing the difference in ET, per unit of surface, between K_v and K_{soil}:

$$K_{vsd} = \max\left(K_v - K_{\text{soil}}, \frac{K_v - K_{\text{soil}}}{2}\right) \tag{10-34}$$

and K_{soil} is the evaporation coefficient representing the evaporation (relative to ET_o) from bare soil caused by wetting by precipitation or irrigation. K_{soil} is included in Eq. (10-33b) to consider the impact of evaporation occurring between plants, and its inclusion becomes more significant with lower plant density (K_d) and with frequency of soil wetting. K_{soil} is estimated as a function of soil wetting frequency and magnitude of ET_o from Figure 10-4 or using Eqs. (10-18)–(10-21). As in Eq. (10-25b) and (10-26), the second term of the max function in Eq. (10-34) reduces the estimate for K_L by about half the difference between K_v and K_{soil} when this difference is negative. This accounts for effects of shading of the soil surface by vegetation with K_v lower than that of the evaporating soil, due to high stomatal resistance. As an alternative to Eq. (10-33b), a daily dual $K_{cb} + K_e$ procedure, described previously, can be applied where K_{cb} is set equal to K_L from Eq. (10-33b), using $K_{soil} = 0.15$, and K_e is estimated daily in accordance with wetting frequency. Eq. (10-33b) reverts to Eq. (10-33a) when $K_{soil} = 0$. Eq. (10-33b) is useful to assess the impact of irrigation frequency on total ET of turf with less than full ground cover. Effects of evaporation of water intercepted by vegetation following irrigation or precipitation are estimated later with Eq. (10-37).

The Vegetation Coefficient

The K_v for landscape vegetation represents the near maximum ratio of ET_v to ET_{omc} that occurs when generally 70% or more cover (shading) of the ground exists and soil water supply is full. ET_{omc} is the ET_o for the microclimate where the vegetation grows. ET_{omc} can deviate from the standard ET_o, where ET_o is a regional estimate of reference evapotranspiration based on measured weather data, whereas ET_{omc} is a local ET_o corrected for microclimate differences. The microclimate coefficient, $K_{mc} = ET_{omc}/ET_o$, is estimated or determined experimentally and is described in the following section. K_v establishes the maximum ratio $K_L = ET_v/ET_{omc}$ for the vegetation under ideal conditions. Based on the definition for K_v, where K_v is the fraction of ET_{omc} when the foliage is at near maximum density ($K_d = 1$) and has full water availability ($K_{sm} = 1$), many types of landscape vegetation tend to exhibit similar values for K_v due to similarities in total leaf area, stomatal response, and energy absorption. Therefore, condensed tables of typical values for general species types can be used to provide general estimates for K_v, where K_v ranges from about 0.8 to 1.2. Because landscape vegetation is usually taller and rougher than grass, the upper limit for K_v can exceed 1.0 for well-watered landscapes. Table 10-3 contains general values for K_v for general types of landscape vegetation. Primary sources for values in Table 10-3 are listed in the table footnote.

The typical K_v values in Table 10-3 represent full effective ground cover ($f_c > \sim 0.7$–0.8) and no water stress. The values are general and, under most

Table 10-3. General Vegetation (Species) Factors, K_v, for General Plant Types for High-Density Cover of the Ground and Full Water Supply

Vegetation Category[a]	K_v
Trees	1.15
Shrubs	
desert species	0.7
nondesert	0.8
Ground cover	1.0
Annuals (flowers)	0.9
Mixture of trees, shrubs, and ground cover[b]	1.2
Cool-season turfgrass[c]	0.9
Warm-season turfgrass[d]	0.9

[a]The tree, shrub, and ground cover categories listed are for landscapes composed solely or predominantly of one of these vegetation types with somewhat dense coverage (shading) of the ground.
[b]Mixed plantings are composed of two or three vegetation types (i.e., where a single vegetation type does not dominate).
[c]Cool-season grasses include Kentucky bluegrass, fescues, and perennial ryegrass.
[d]Warm-season grasses include Bermuda grass, St. Augustine grass, buffalo grass, and blue grama.
Source: Data from Irrigation Association (2011). Primary sources of data include cool-season turfgrass (Aronson et al. 1987; Brown et al. 2001); warm-season turfgrass (Brown et al. 2001; Jia et al. 2009); other vegetation (Irrigation Association 2011)

conditions, are not met due to the density factor being less than 1.0 and due to intentional moisture stress (Brown et al. 2001; Jia et al. 2009). The K_v value for warm-season grass is equal to that for cool-season grass in Table 10-3 because both of these grass types tend to have similar ET_v/ET_{omc} under conditions of no water stress. Typically, however, warm-season grasses tolerate higher levels of moisture stress than cool-season grasses; so that a lower managed stress factor can be applied to warm-season grasses with less visual effect, as is illustrated in Table 10-5. The K_v values for both cool-season and warm-season grasses are less than 1.0 in Table 10-3 due to the tendency for their mean height to be less than that of the standardized 0.12-m grass reference. Comparison of K_L for warm-season grasses from Eq. (10-33a) and Tables 10-3–10-5 and measurements for a Florida application are presented as Figure 10-14.

K_v values for ground cover and annuals or flowers are assumed to be nearly or equal to 1.0, reflecting the likely K_v when the vegetation completely covers the ground ($K_d = 1.0$) and when no stress occurs ($K_{sm} = 1.0$). Because of the hundreds, if not thousands, of species of flowers and ground cover types, estimating or establishing K_v values for each of

Table 10-4. Microclimate Factor, K_{mc}, for Landscape Plant Types

Vegetation	High (Hostile Environment)	Average (Reference Condition)	Low (Protected or Shaded Environment)
Trees	1.4	1.0	0.5
Shrubs	1.3	1.0	0.5
Ground cover, flowers	1.2	1.0	0.5
Mixture of trees, shrubs, and ground cover	1.4	1.0	0.5
Turfgrass	1.2	1.0	0.8

Source: Data from Irrigation Association (2003, 2011)

Table 10-5. Managed Stress Factors, K_{sm}, for General Landscape Plant Types and the Depletion Fraction for No Stress

Vegetation Category	High Stress	Average Managed Stress	Low Stress	Depletion Fraction, p, for No Stress
Trees	0.4	0.6	0.8	0.6
Shrubs				
desert species	0.3	0.4	0.6	0.6
nondesert	0.4	0.6	0.8	0.6
Ground cover	0.3	0.5	0.8	0.5
Annuals (flowers)	0.5	0.7	0.8	0.4
Mixture of trees, shrubs, and ground cover[a]	0.4	0.6	0.8	0.6
Cool-season turfgrass	0.7	0.8	0.9	0.4
Warm-season turfgrass	0.6	0.7	0.8	0.5

[a]Mixed plantings are composed of two or three vegetation types where a single vegetation type does not predominate.
Source: Data from Irrigation Association (2011)

these species is difficult. Rather, the upper limit for K_v is established, which can be reduced when specific information on a species is determined. The K_v for mixed systems of trees, shrubs, and/or ground cover is discussed in the next section.

Carrow (2004) suggests common target values for K_L for cool-season grasses to range from about 0.70 to 0.95 in the southeast United States as

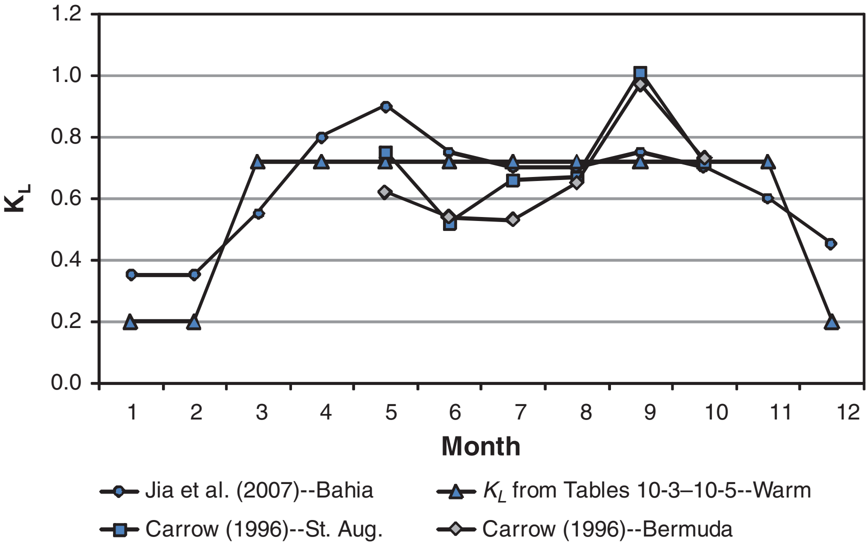

Fig. 10-14. Measured monthly K_L *for Bahia grass in Florida by Jia et al. (2009) and for St. Augustine and Bermuda grasses in Georgia by Carrow (1996) compared with a steady target* K_L *from Eq. (10-33b) and Tables 10-3–10-5 for a warm-season grass*
Source: Data from Jia et al. (2009) and Carrow (1995, 1996)

compared with K_L for warm-season turfgrasses of 0.65 to 0.85 when the irrigation regime is 3 to 7+ days between events, which allows mild moisture stress during hot periods. At these K_L values, turf generally maintains acceptable quality and growth. As K_L values fall below these general ranges using a similar irrigation schedule but with smaller doses per irrigation, turf performance and appearance may rapidly decline. Carrow (1995) reports turfgrass ET_c to be 40 to 60% less in a humid environment compared with the same cultivar in an arid environment, but with similar K_L values for both environments.

Density Factor

Landscapes can vary considerably in vegetation density, due to wide variation in plant spacing and maturity. The plant density factor, K_d, can be estimated using Eq. (10-29). Vegetation density refers to the collective leaf area of all plants in the unit landscape area. More densely growing vegetation will have a higher K_d and will transpire and require more water. Immature and sparsely planted landscapes have less total leaf area per unit landscape area than mature landscapes and have a lower value for K_d. Often, landscapes have two and three tiers (horizontal levels) of vegetation including turf or ground cover, shrubs, and trees. Overlapping tiers are capable of more radiative and other energy exchange and tend to increase ET, as shown by the K_v value of 1.20 in Table 10-3 for the "mixture" class. When two substantial tiers of vegetation are present, for example, trees shading grass or flowers, the value for height, h, can be approximated in proportion to the f_c for each tier. The important factor is the fraction of the sunlight intercepted by the plants and the fraction that reaches the ground. By observation at different times of the day, one can estimate the fraction of direct sunlight reaching the ground. The plant light interception is usually slightly more than the percentage of ground cover, so that the observed light interception can be used to estimate the K_d factor. If more than 80% of the sunlight onto the landscape is intercepted by the plants over the day, then one should expect the K_d factor to be close to 1.0.

Microclimate Factor

The microclimate factor, K_{mc}, accounts for impacts on ET by sun, shading, protected areas, hot and cool areas, reflected and emitted radiation from structures, wind, and transfer of heat energy from low ET surroundings. Structures and paved areas typical of urban landscapes can have pronounced effect on the local energy balance due to the transfer of energy for evaporation from these surfaces to local vegetation. The environmental conditions of a landscape can vary significantly across the landscape, for example, areas on the south side of a building vs. areas on the north side. Vegetation plantings adjacent to paved, open areas may have 50% higher ET demand than similar plantings among other vegetation due to the transfer of energy to the vegetation from the nonevaporating areas. Conversely, plantings in areas shaded from sun and wind may have ET rates that are only one-half as high as those for open settings. Another important factor is wind blockage by buildings and vegetation. Reference evapotranspiration weather stations are typically placed in well-exposed areas with wind speeds that represent the region. If the landscape is exposed to less wind due to shielding by buildings or vegetation, then the $ET_{o\,mc}$ (see earlier definition) may be less than ET_o. The LIMP program from Snyder and Eching (2004, 2005) provides a methodology to address these microclimate factors.

Values for K_{mc} are listed in Table 10-4 for general classes of vegetation. The "high" category ($K_{mc} > 1$) in Table 10-4 reflects harsh microclimate conditions such as planting in direct sunlight near paved or other nonvegetated surfaces, near reflective or heat-absorbing surfaces such as windows or buildings, or in exposed, windy conditions. "Hot" surfaces of buildings can emit substantial amounts of long-wave radiation to nearby vegetation. The "low" category ($K_{mc} < 1$) represents environments where the plantings are located in shade, are shielded from wind, and are away from dry, hot surfaces. The average or medium category ($K_{mc} = 1$)

represents reference conditions similar to open settings, such as in parks, where conditions caused by buildings, pavement, shade, and reflection do not influence the ET by the landscape. The values given for K_{mc} are only approximate, and local measurements can confirm or be used to derive local values. Values for K_{mc} can be interpolated between the high, average, and low classes and should be selected for each sector of a landscape.

Managed Stress Factor

Typically, the objective of landscape irrigation is to promote appearance rather than biomass production, unlike agriculture, where biomass is generally maximized. Therefore, target ET for landscapes can include an intentional and managed "stress" factor in the baseline value for ET_L, where landscape plants are watered less than they would be if they were irrigated like a crop. This management is done by adjusting irrigation water schedules to apply less water than the vegetation will potentially transpire. The magnitude of the stress factor depends on physiological and morphological requirements of the plants.

The managed stress factor, K_{sm}, represents the fraction of the full ET rate targeted to obtain the functional and visual characteristics of the landscape vegetation. Parameter K_{sm} has a range of 0 to 1.0, where 1.0 represents conditions of no moisture stress and 0 represents complete lapse of plant transpiration and probable plant death or dormancy. High values for K_{sm} will sustain predominantly lush, high leaf-area vegetation stands that tend to maximize ET. Low values for K_{sm} represent substantial managed plant water stress and reduction in ET, generally at the cost of biomass accumulation and potentially loss of pleasant visual effects (Richie and Pittenger 2000). Typical values for K_{sm} are presented in Table 10-5. Those values, when inserted into Eq. (10-33a) with values for K_v from Table 10-3, produce values for K_L that are similar to those reported by Meyer and Gibeault (1986), Smeal et al. (2001), Carrow (2004), and Pittenger and Shaw (2007).

Many landscape species exercise significant stomatal control and can be forced toward relatively lower levels of ET. For instance, the low range for K_{sm} for ground cover is 0.2, which is appropriate for a select group of drought-tolerant ground cover species. This value may not be appropriate for some ornamental ground covers that require more water (and less water stress) to maintain health and appearance. One should consult local or regional sources to determine appropriate values for K_{sm}. Pittenger and Shaw (2007) suggest K_L for more than 30 ground covers and shrubs grown in southern California that contain low K_{sm} components and thus provide good water conservation. Many of the vegetation types listed by Pittenger and Shaw are native desert vegetation types that tolerate water stress. Other sources of K_L information for specific species include the WUCOLS publication by Costello and Jones (1999), where the K_L includes an implied $K_{sm} < 1$.

Management of landscape vegetation to implement a particular value for K_{sm} requires selection of a target depletion fraction prior to irrigation that produces the K_{sm}, on average. Typically the high stress category for trees, shrubs, and ground cover does not require irrigation, but relies on natural rainfall. In situations where irrigation is practiced, the irrigation interval must be sufficiently long to produce increasingly greater stress as soil water is depleted so that the stress averaged over the entire interval equals the desired value for K_{sm}. The stress factor K_s equals 1.0, for no stress, for a period following irrigation (assuming that the irrigation depth was substantial) until the soil water depletion from the root zone exceeds *RAW*. Following that point in time, K_s will progressively decrease until the next irrigation. The K_s prior to the next irrigation will be less than the K_{sm}, because K_{sm} represents the average K_s over the entire interval. Tables 10-6 and 10-7 list target values for management-allowed depletion fraction, *MAD*, at the time of irrigation to produce the desired average managed stress factor K_{sm} to be used in Eq. (10-33). The target values for *MAD* (at the initiation of irrigation) are a function of the depletion fraction, p, when the particular vegetation begins to experience stress. The values for p in

Table 10-6. Management-Allowed Depletion Fraction, *MAD*, to Produce the Stated Managed Stress Factor (K_{sm}), Given the Depletion Fraction for No Stress (p) and Assuming Complete Refilling of the Root Zone Each Irrigation (*MAD* Expressed as a Decimal)

Managed Stress Factor, K_{sm}	Depletion Fraction, p, for No Stress				
	0.3	0.4	0.5	0.6	0.7
1.00	0.30	0.40	0.50	0.60	0.70
0.95	0.47	0.57	0.66	0.75	0.86
0.90	0.55	0.65	0.73	0.81	0.88
0.85	0.62	0.71	0.79	0.86	—
0.80	0.68	0.76	0.83	0.89	—
0.75	0.74	0.80	0.87	—	—
0.70	0.78	0.84	0.89	—	—
0.65	0.82	0.88	—	—	—
0.60	0.86	0.90	—	—	—
0.55	0.90	—	—	—	—
0.50	—	—	—	—	—

Note: "—" as an entry indicates that the value for *MAD* approaches or exceeds 1 so that the soil water content approaches or exceeds the permanent wilting point and the vegetation is, by definition, in danger of death or dormancy.
Source: Data from Irrigation Association (2003, 2011)

Table 10-7. Average Management-Allowed Depletion Fraction, *MAD*, to Produce the Stated Managed Stress Factor (K_{sm}), Given the Depletion Fraction for No Stress (p) and Assuming Only Partial Refilling of the Root Zone Each Irrigation, Where the Depletion between Wetting Events Is Managed to Range from $MAD - 0.1$ to $MAD + 0.1$ (*MAD* Expressed as a Decimal)

Managed Stress Factor, K_{sm}	Depletion Fraction, p, for No Stress				
	0.3	0.4	0.5	0.6	0.7
1.00	0.20	0.30	0.40	0.50	0.60
0.95	0.30	0.39	0.48	0.57	0.66
0.90	0.35	0.44	0.53	0.61	0.69
0.85	0.39	0.47	0.56	0.64	0.72
0.80	0.43	0.51	0.58	0.66	0.74
0.75	0.46	0.54	0.61	0.68	0.76
0.70	0.50	0.57	0.64	0.70	—
0.65	0.53	0.59	0.66	0.72	—
0.60	0.57	0.62	0.68	0.74	—
0.55	0.60	0.66	0.71	0.76	—
0.50	0.64	0.68	0.73	—	—
0.45	0.67	0.71	0.76	—	—
0.40	0.70	0.74	—	—	—
0.35	0.74	—	—	—	—

Note: "—" indicates that the value for *MAD* approaches or exceeds 1 so that the soil water content approaches or exceeds the permanent wilting point and the vegetation is, by definition, in danger of death or dormancy.
Source: Data from Irrigation Association (2003, 2011)

Tables 10-6 and 10-7 should be modified for specific vegetation types or species when information is available. The values for *MAD* in the tables exceed the values for p that produce stress.

As an example of using Table 10-6, for $p = 0.4$, the *MAD* should be 0.76 prior to irrigation to produce a K_{sm} of 0.8 when the root zone is completely refilled each irrigation. This means that 76% of the total available water (*TAW*) is depleted prior to irrigation. To produce a K_{sm} of 0.6, *MAD* must be 0.90, and the amount of depletion prior to irrigation is $0.9 \times TAW$. The values for *MAD* in Tables 10-6 and 10-7 were derived by integrating Eq. (10-6) over a range in depletion, D_r, from 0 to *MAD* that produced an average value for K_s equal to K_{sm}.

The values for *MAD* in Table 10-6 assume that irrigation, when it occurs, completely replenishes soil water to field capacity so that depletion of the root zone $D_r = 0$ and the equivalent depth of water added equals

$MAD \times TAW$. Note that for a typical p of 0.5, drying the soil 90% of the way to wilting point will only reduce the K_{sm} to 0.7 for an irrigation cycle comprising large irrigations spaced relatively far apart in time. The reduced ET will still average 70% during the total period. This is due to the complete recharging of the root zone to field capacity after large irrigation events and a substantial period of no stress.

An alternative strategy to implementing soil water stress is to add less than $MAD \times TAW$ depth at a higher frequency, where irrigation additions are low enough to create some degree of moisture stress over a greater portion of the irrigation interval. This strategy can provide less stress at the time of the more frequent, but reduced depth, irrigations and thus reduce the risk of plant death or dormancy. This can be done in an automated, soil-moisture-sensor-based irrigation system by applying relatively frequent, small doses of water but with the trigger soil moisture level setting at a "dry" level. The drawback to this strategy is that the percentage of water lost from evaporation from the soil surface increases as the irrigation frequency increases, especially when the irrigation doses are small. Evaporation of water from the soil surface is not nearly as effective in sustaining vegetation health and appearance as is transpiration through the plant system.

Table 10-7 lists MAD values required to produce the managed K_{sm} values listed, given the p value for the vegetation and given that soil water depletion will be managed in the interval of $MAD - 0.1$ to $MAD + 0.1$. For the same example, given $p = 0.4$ for a specific plant variety and a target K_{sm} of 0.8, the value of MAD from Table 10-7 is 0.51, so that soil water depletion would be maintained between 0.41 and 0.61. In other words, the soil would be watered when 61% of available water is depleted, and enough water would be added by irrigation to reduce the depletion to 41% depletion of available water. Therefore, 20% of the water between field capacity and wilting point would be added back to the soil each irrigation. The percentage of water lost from evaporation from the soil surface increases as the irrigation frequency increases, especially when the irrigation doses are small.

The values for MAD in Table 10-6 were derived by integrating Eq. (10-6) over a range in depletion, D_r, from 0 to MAD that produced an average value for K_s equal to K_{sm}. Values in Table 10-7 were derived by integrating Eq. (10-6) over a range of $MAD - 0.1$ to $MAD + 0.1$ that produced an average value for K_s equal to K_{sm}. Depleting soil water to 0.9 of available water, as in the first example of Table 10-6, is risky in that, by definition, a depletion of 1.0 will result in permanent wilting and generally plant death or dormancy. Following the second strategy of Table 10-7, where smaller doses of water maintain stress at a more level value, would suggest recharging the root zone to $MAD = 0.41$ following irrigation and allowing the root zone to dry to $MAD = 0.61$ prior to irrigation, so that MAD averages 0.51 over the irrigation and drying cycle. Both management strategies will produce a $K_{sm} = 0.8$. For more reduction in K_{sm}, managing for MAD ranging from 0.52 to 0.72 and averaging 0.62 will produce an average $K_{sm} = 0.6$. This latter range in MAD is less risky and likely easier to manage than the value of 0.9 required by the strategy of Table 10-6.

Actual ET from Landscapes

The vegetation coefficient K_v described in previous sections represents the landscape K_c under a water supply that is sufficient to support full ET from somewhat dense vegetation with near maximum ground cover and open environmental exposure. However, the K_L coefficient may contain an implicit amount of managed stress for purposes of water conservation. The degree of implied managed stress is quantified in Eq. (10-33) by the K_{sm} term. However, the K_L derived from Eq. (10-33a) or (10-33b) using a targeted K_{sm} term may not represent actual conditions where actual stress may be higher or lower than the target managed stress. Under these conditions, for purposes of water balance and determination of consumptive use from landscaped or larger areas, the managed stress coefficient in Eq. (10-33a, b) is replaced by an actual stress coefficient, K_s, where K_s is computed using Eq. (10-4) or (10-6) based on soil water depletion determined from a daily balance of root zone soil water. Eq. (10-33a) therefore takes the form

$$K_{L\,act} = K_v\, K_d\, K_s\, K_{mc} \tag{10-35a}$$

where K_{sm} in Eq. (10-33a) is replaced by an actual stress coefficient K_s and where $K_{L\,act}$ is the actual K_L anticipated from the landscape under actual water availability. Eq. (10-33b), which includes effects of evaporation from soil, becomes

$$K_{L\,act} = (K_{\text{soil}} + K_{vsd}\, K_d\, K_s)\, K_{mc} \tag{10-35b}$$

where K_{vsd} is a coefficient describing the difference between K_v and K_{soil}, defined in Eq. (10-34). K_{soil} is from Eq. (10-18) or Figure 10-4. Actual ET from the landscape under actual watering conditions is

$$ET_{L\,act} = K_{L\,act}\, ET_{\text{o}} \tag{10-36}$$

When K_s is estimated from Eq. (10-4) or (10-6), the depletion fraction p parameter, used to estimate RAW, should be set to specific values determined for the species if these are available. The effective depth of the root zone used to estimate *TAW* is species or variety specific and therefore obtaining information specific to the variety is important.

Impact of Canopy Wetting and Irrigation Frequency on K_L

Wetting of landscape vegetation by irrigation or rainfall can substantially increase the potential ET from the landscape due to the combined influence of evaporation from exposed, wet soil and evaporation from water intercepted by vegetation during the wetting event, if by rainfall or sprinkler. The more frequent the wetting events, the greater the potential ET rate. Often, landscape irrigation is accomplished with automatic controllers that are easily set to irrigate frequently, even daily. The water intercepted and retained on the vegetation surfaces is freely evaporated during and following a wetting event, even if the underlying vegetation is experiencing some level of water stress and the soil is dry. Evaporation of intercepted water can occur even with nighttime irrigation where the primary evaporation may occur the following day.

The impact of evaporation from exposed soil among vegetation when the density coefficient, K_d, is less than 1 is accounted for using Eq. (10-33b), coupled with estimates for K_{soil} from Figure 10-4 or Eqs. (10-18)–(10-21). The process of evaporation of intercepted water from vegetation is described in the form of the direct Penman-Monteith ET method in Chapter 11. Here, a simpler general method is used to estimate the impact of evaporation of intercepted water stored on the vegetation canopy on increasing the value for K_L, as

$$K_L = K_{Lb} + \frac{S}{t_w\, ET_o}\left(1 - \frac{K_{Lb}}{K_{c\ \max}}\right) \tag{10-37}$$

where

$$K_{Lb} = K_v K_d K_{sm} K_{mc} \tag{10-38}$$

and K_{Lb} represents the K_L estimated by Eq. (10-33a) under conditions where any exposed soil surface is assumed to be dry (when K_d is less than 1.0). K_{Lb} is, in effect, a "basal" landscape coefficient. The value for K_{Lb} is the same as that produced by Eq. (10-33a) when effects of intercepted rain or wet exposed soil are not considered. Parameter S is the depth of intercepted water on vegetation leaves from precipitation or irrigation in mm, and t_w is the time between wetting events in days. $K_{c\,max}$ is the maximum limit on K_L, estimated from Eq. (10-3a). ET_o has units of $\mathrm{mm\,d^{-1}}$. Values for S are typically about 1 mm for trees (Tables 11-5 and 11-6) and about 0.5 to 1 mm for turf (Hoffman et al. 1992; Breuer et al. 2003). The derivation of Eq. (10-37) assumes that evaporation of intercepted water on leaves dominates the ET process until the vegetation surface is dry, so that transpiration is depressed by the energy consumed by E. This observation was noted by Tolk et al. (1995). In the application of Eq. (10-37), the limits $K_{Lo} = K_v K_d K_{mc} K_{sm} \leq K_{c\,max}$ and $K_L \leq K_{c\,max}$ are applied.

For applications where ground cover is less than full ($K_d < 1$) and the exposed soil is occasionally wetted by rain or irrigation, Eq. (10-37) can be combined with a form of Eq. (10-34b) to yield

$$K_L = K_{Lb} + (1 - K_d)(K_{\text{soil}} - K_{c\text{ min}}) + \frac{S}{t_w ET_o} \max\left(K_d - \frac{K_{Lb}}{K_{c\text{ max}}}, 0\right) \quad (10\text{-}39)$$

where K_{Lb} is calculated in Eq. (10-38) and K_{soil} is taken from Figure 10-4 or Eqs. (10-18)–(10-21) and is a function of wetting frequency and ET_o rate. $K_{c\,min}$ is the minimum basal K_c for a "dry" bare soil. Under typical landscape conditions, $K_{cb\,min} \sim 0.10$ to 0.15. The effect of Eq. (10-39) is to increase the value for K_L over that estimated by Eq. (10-33a) or (10-33b) alone so that K_L includes effects of both wet soil surface and wet canopy surface following rainfall of irrigation.

The effect on K_L by evaporation of intercepted water from vegetation is illustrated in Table 10-8 where Eq. (10-37) is applied to a range of $K_{Lb} = K_v K_d K_{sm} K_{mc}$ under three levels of ET_o and for three irrigation intervals (1, 2, and 7 days). Interception depth, S, was assumed to be 1 mm and $K_{c\,max} = 1.2$. The effect of evaporation of intercepted water on K_L is most pronounced for daily watering intervals and at lower values for K_{Lb}. For turfgrass under typical conditions where when $ET_o = 4\text{ mm d}^{-1}$, K_d and $K_{mc} = 1$ and $K_{sm} = 0.9$ (mild imposed stress), $K_{Lb} = K_v K_d K_{mc} K_{sm} \sim 0.8$, and daily watering is estimated to increase K_L to 0.88 as compared with $K_L = 0.81$ for weekly watering. The K_L under daily watering increases to only 0.84 under $ET_o = 8\text{ mm d}^{-1}$ because the amount of interception (1 mm) becomes relatively small compared with the higher total daily ET rate.

Application of Eq. (10-39), where evaporation of intercepted water on vegetation from sprinklers and evaporation from wet soil in between plants are both considered, is illustrated in Table 10-9 over a range of K_{Lb} under two levels of ET_o and for irrigation intervals of 1, 2, 3, and 7 days. Two entries are shown for $K_{Lb} = K_v K_d K_{sm} K_{mc} = 0.8$, where $K_d = 1.0$ and 0.8. These two values for K_d represent (1) full surface cover, as for turfgrass, and (2) a landscape with approximately 20% exposed soil, for dense ornamentals, for example. The effect of wet soil among vegetation without complete ground cover is pronounced. The K_L under daily watering approaches 1.0 under moderate $ET_o = 4\text{ mm d}^{-1}$, even when the "dry" K_{Lb}, based on Eq. (10-38), is only 0.4 to 0.6. The contribution of evaporation from exposed soil among plants causes this increase. The effect of daily watering is lower under high ET_o conditions because the water intercepted

Table 10-8. K_L Estimated from Eq. (10-37) for Various Levels of $K_v K_d K_{mc} K_{sm}$ and ET_o and for Irrigation Intervals, t_w, of 1, 2, and 7 days for Conditions of a Surface Fully Covered by Vegetation

	$ET_o = 4$ mm d^{-1}			$ET_o = 6$ mm d^{-1}			$ET_o = 8$ mm d^{-1}		
$K_{Lb} = K_v K_d K_{sm} K_{mc}$	$t_w = 1$ K_L	$t_w = 2$ K_L	$t_w = 7$ K_L	$t_w = 1$ K_L	$t_w = 2$ K_L	$t_w = 7$ K_L	$t_w = 1$ K_L	$t_w = 2$ K_L	$t_w = 7$ K_L
1.2	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
1	1.04	1.02	1.01	1.03	1.01	1.00	1.02	1.01	1.00
0.8	0.88	0.84	0.81	0.86	0.83	0.81	0.84	0.82	0.81
0.6	0.73	0.66	0.62	0.68	0.64	0.61	0.66	0.63	0.61
0.4	0.57	0.48	0.42	0.51	0.46	0.42	0.48	0.44	0.41

Note: For interception depth $S = 1$ mm and $K_{c\,max} = 1.2$. Units of t_w are in days.

Table 10-9. K_L Estimated from Eq. (10-39) for Various Levels of $K_{Lb} = K_v K_d K_{sm} K_{mc}$ and Density Factor; Two Levels of ET_o; and for Irrigation Intervals, t_w, of 1, 2, 3, and 7 Days

		$ET_o = 4\ \mathrm{mm\,d^{-1}}$				$ET_o = 8\ \mathrm{mm\,d^{-1}}$			
		$t_w = 1$	$t_w = 2$	$t_w = 3$	$t_w = 7$	$t_w = 1$	$t_w = 2$	$t_w = 3$	$t_w = 7$
		$K_{soil} = 1.1$	0.9	0.7	0.45	0.85	0.7	0.55	0.3
$K_{Lb} = K_v K_d K_{sm} K_{mc}$	K_d	K_L	K_L	K_L	K_L	K_L	K_L	K_L	K_L
1.2	1.00	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
1	1.00	1.04	1.02	1.01	1.01	1.02	1.01	1.01	1.00
0.8	1.00	0.88	0.84	0.83	0.81	0.84	0.82	0.81	0.81
0.8	0.80	1.02	0.97	0.92	0.86	0.96	0.92	0.89	0.83
0.6	0.60	1.01	0.91	0.83	0.72	0.89	0.83	0.76	0.66
0.4	0.50	0.92	0.80	0.69	0.56	0.77	0.69	0.61	0.48

Note: For interception depth $S = 1$ mm and $K_{c\,max} = 1.2$. K_{soil} was selected from Fig. 10-4 using ET_o and t_w and interpolation among charts. t_w has units of days.

by vegetation surfaces evaporates quickly and evaporation becomes a smaller component of total ET.

The example values in Table 10-9 strongly support increasing intervals between watering events to conserve water. However, one needs to recognize constraints on long time intervals between watering events imposed by maximum water dosage rates to limit surface runoff on low intake soils and by water availability to shallow-rooted vegetation on coarse soils.

In the case of cool-season turf with mild imposed stress ($K_{sm} = 0.9$) so that $K_{Lb} = K_v K_d K_{sm} K_{mc} \sim 0.8$, under $ET_o = 4\ \mathrm{mm\,d^{-1}}$, increasing the watering interval from daily to 7 days could potentially reduce water consumption by $(0.88–0.81)/0.88 = 8\%$. In the case of ornamentals where some soil is exposed among plants so that $K_d = 0.8$, the reduction in water consumption for the same $K_{Lb} \sim 0.8$ would be $(1.02–0.86)/1.02 = 16\%$. At an ET_o of $4\ \mathrm{mm\ d^{-1}}$, about 5 mm out of a total irrigation dose of 23 mm would be conserved per irrigation.

Comparisons against Recent Measurements of K_L

Brown et al. (2001) report K_L for Tiffany bermudagrass, a warm-season grass, in Tucson, Arizona, with daily watering ranging from $K_L = 0.78$ during high ET_o periods (June and July) to $K_L = 0.83$ during low ET_o periods (September). Using a $K_v = 0.9$ for warm-season grass from Table 10-3, $K_d = 1$ and $K_{mc} = 1$ and mild stress $K_{sm} = 0.9$, the estimated $K_{Lb} = K_v K_d K_{sm} K_{mc}$ from Eq. (10-38) is ~0.8. From Eq. (10-39) or Table 10-9, the K_L associated with these values is 0.84 during high ET_o periods ($ET_o = 8\ \mathrm{mm\ d^{-1}}$) and 0.88 under low ET_o periods ($ET_o = 4\ \mathrm{mm\ d^{-1}}$). These values are about 10% higher than reported by Brown et al. The twice-weekly mowing height reported by Brown et al. (2001) was 2.2 to 2.5 cm, which is somewhat short and may explain the differences between K_L estimated by Eq. (10-39) and reported K_L.If no moisture stress is assumed in the Brown study due to the daily watering, then $K_{sm} = 1.0$ and $K_{Lb} = K_v K_d K_{sm} K_{mc} \sim 0.9$, and, from Eq. (10-39) or Table 10-9 (interpolated), $K_L = 0.96$ under $ET_o = 4\ \mathrm{mm\,d^{-1}}$ and $K_L = 0.93$ under $ET_o = 8\ \mathrm{mm\,d^{-1}}$. These values are about 15% higher than reported by Brown et al. (2001) and again may be due to the short and frequent cutting heights in the study. Brown et al. (2001) report K_L values for bermudagrass from the literature ranging from 0.57 to 0.83. These values include some amount of managed water stress.

Brown et al. (2001) report K_L for Froghair intermediate ryegrass, a cool-season grass, overseeded into bermudagrass in Tucson, Arizona, with daily watering ranging from $K_L = 0.85$ to 0.90 during high ET_o periods (May and June) to 0.78 to 0.82 during low ET_o periods with relatively short day lengths (December to February). Using a $K_v = 0.9$ for cool-season grass from Table 10-3, $K_d = 1$ and $K_{mc} = 1$ and mild stress $K_{sm} = 0.9$, the estimated

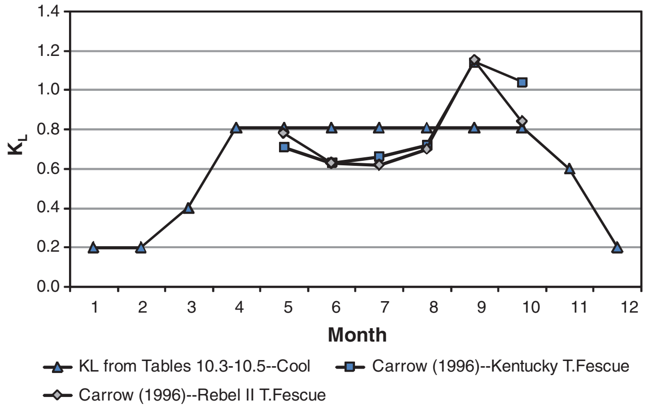

Fig. 10-15. Measured monthly K_L *for two types of tall fescue grass in Georgia by Carrow (1996) compared with a steady target* K_L *from Eq. (10-33b) and Tables 10-3–10-5 for a cool-season grass*
Source: Data from Carrow (1995, 1996)

K_{Lo} is ~0.8. From Eq. (10-39) or Table 10-9, the K_L associated with these values is estimated to be 0.84 during high ET_o periods ($ET_o = 8$ mm d^{-1}) and 0.88 under low ET_o periods ($ET_o = 4$ mm d^{-1}). These values are about 5% lower than reported by Brown et al for the high ET_o periods and about 10% higher than by Brown et al. for the low ET_o periods. Brown et al. (2001) report K_L values for cool-season turfgrasses from the literature ranging from 0.60 to 1.04.

Figure 10-15 compares monthly K_L for warm-season grasses and cool-season grasses as derived using Eq. (10-33b) and Tables 10-3–10-5 with measurements by eddy covariance from Florida (Jia et al. 2007) and by time domain reflectometry in Georgia (Carrow 1995). The K_L values reported for the warm-season bahiagrass measured by Jia include some moisture-stressed time periods, as do those by Carrow, where both wet and stressed periods are included in the two-year data sets. The K_L from Eq. (10-33b) uses $K_v = 0.9$ for both warm- and cool-season grasses during the growing season, $K_d = 1.0$, $K_{mc} = 1.0$, and $K_{sm} = 0.8$ for warm-season and $K_{sm} = 0.9$ for cool-season curves. The latter two values reflect influences of low amounts of stress, on average. A value of $K_{\text{soil}} = 0.2$ is used during the off-season to reflect background evaporation from dormant turf. It was assumed that no overseeding of cool-season grass occurred during winter.

The K_L curve measured for bahiagrass in central Florida is higher than the straight-line "target" curve during April and May when the climate was generally wet and then relatively steadily followed the target curve during June–September when some stress occurred due to longer times between wetting events (Jia et al. 2007). The data of Carrow (1995) fall below the target curve during June–August when substantial stress occurred and rise above the target curve during the wetter period of September. The trends observed by Carrow (1995) for cool-season tall fescue grasses are similar for the same reasons. On average, the observed data followed the steady target K_L values within uncertainties common to water measurement and management.

10.8 ESTIMATES OF K_c DURING WINTERTIME AND NONGROWING SEASONS

Nongrowing periods are defined as periods during which no agricultural crop has been planted. In temperate climates, nongrowing periods may include periods of frost and continuously frozen conditions. Estimation of ET during these periods can be important for annual water balances used in hydrologic studies and for estimation of accruals to soil water from precipitation during nongrowing seasons.

Types of Surface Conditions

The type and condition of the ground surface during nongrowing periods dictate the range for ET_c. When the surface is bare soil, then K_c will be similar to the K_{soil} estimated by Eq. (10-18). When dead or dormant vegetation or some type of organic mulch or crop residue covers the surface, then K_c will be similar to that for agriculture with a surface mulch. When weed growth or "volunteer" plants cover the surface, then K_c will vary according to the leaf area or fraction of ground covered by the vegetation, as estimated by Eq. (10-25) using K_d from Eq. (10-28) or (10-29), and by the availability of soil water. When the surface is snow covered or frozen, then K_c is difficult to estimate and a low, constant value for ET_c may have to be assumed.

Bare Soil Where the ground is mostly bare following harvest or other removal of vegetation, then the frequency and amount of precipitation will strongly influence K_c. K_{cm} for bare soil can be calculated as $K_{cm} = K_{\mathrm{soil}}$, where K_{soil} is estimated using Eq. (10-18) or Figure 10-4, and varies with frequency of wetting events and magnitude of reference ET. Martin and Gilley (1993) and Allen et al. (1998) recommend this approach, and Snyder and Eching (2005) use a similar approach in the LIMP software to estimate a K_{cm} during winter that is then melded with a K_{cm} curve for the growing season. Where a daily soil water balance can be applied, the user may elect to apply the dual or basal K_{cb} approach [Eq. (10-2)]. During long dormant periods with little or no precipitation, the topsoil layer may dry to very low water contents. Under these conditions, the value for K_{cb} in Eq. (10-2) and the value for $K_{c\,min}$ in other equations should be set to nearly zero. This provides the opportunity for $ET_c = 0$ during long periods of no rainfall and may be necessary to preserve the water balance of the evaporation layer and of the root zone in total.

Surface Covered with Dead Vegetation Stubbles and mulches reduce soil evaporation by providing a mechanical barrier to aerodynamic forces and shielding the soil surface from solar radiation. Mulches also reduce the connection between liquid or vapor in the soil and the air above (Burt et al. 2005). Burt et al. (2005) describe studies of evaporation experiments from organically mulched soil covers and report a 20% reduction in E from a no-till standing wheat stubble as compared with conventional tillage in North Dakota, 40% reduction in E from standing wheat stubble in cotton in Texas, and nearly 50% reduction in E from soil covered with spread straw relative to bare soil in Nebraska. They note that soil surface mulches are less effective at reducing soil evaporation under dryland conditions where longer periods for drying occur between wetting events as compared with conditions under irrigation.

When the ground surface has a plant residue or other dead organic mulch cover, or where part of the unharvested crop remains suspended above the surface in a dead or senesced condition, then the surface will respond similarly to a surface covered by mulch. In this case, K_c can be set equal to K_{soil} as estimated from Figure 10-4 or Eq. (10-18), with the value for K_{soil} reduced by about 5% for each 10% of soil surface that is effectively covered by organic mulch (Allen et al. 1998). In applications using Eqs. (10-2) and (9-19)–(9-31), evaporation from dead, wet vegetation can be substantial for a few days following a precipitation event. Therefore, in the FAO K_{cb} approach, the value for f_c during dormant periods should be set equal to zero to reflect the lack of green cover, and f_w should be set equal to 1.0 to reflect the wetting of both soil and mulch cover by precipitation. The dead mulch or vegetation will dry more quickly than would the underlying soil if it were exposed. In addition, the soil will be protected somewhat from evaporation by the dead mulch or vegetation cover, and total evaporation losses will be less than the *TEW* estimated from Eq. (9-20). This can be accounted for by reducing the value for *TEW* by about 5% for each 10% of soil surface that is effectively covered by organic mulch (Allen et al. 1998). The value for *REW* may need to be reduced to account for quicker drying of the mulch fraction and should be limited to less than or equal to that for *TEW*.

Surface Covered with Live Vegetation During frost-free periods following harvest, weeds may germinate and grow. This vegetation extracts water from storage within the soil profile and from any rainfall. In addition, crop seed lost during harvest may germinate following rainfall events and add to the ground cover. The amount of ground surface covered by vegetation will depend on the severity of weed infestation, the density of the volunteer crop, the frequency and extent of soil tillage, the availability of soil water or rain, and any damage by frost. The value for K_{cb} during the nongrowing period can be estimated over time according to the amount of vegetation covering the surface using Eqs. (10-25)–(10-29) or from remote sensing images by way of a vegetation index. In the K_{cm} approach, the value for K_{cb} determined using Eq. (10-25) and (10-27)–(10-29) can be converted into an equivalent K_{cm} by adding 0.05 to 0.15 according to the frequency of rainfall and surface wetting or using Eq. (10-26).

The K_c for vegetation during the nongrowing period must be limited by the amount of soil water available to supply evapotranspiration to satisfy the law of conservation of mass. Under all conditions, the integration of $K_c ET_{ref}$ over the course of the nongrowing period cannot exceed the sum of precipitation occurring during the period plus any residual soil water in the root zone after harvest that can be subsequently depleted by the vegetation plus any upward flow from a shallow saturated system. The root zone in this case is the root zone for the weeds or volunteer crop. A daily soil water balance may provide the best estimate of soil water–induced stress and associated reductions in K_c and ET_c.

If using the dual crop coefficient approach [Eq. (10-2)], K_{cb} can be estimated according to the amount of surface that is covered by vegetation using Eqs. (10-25) and (10.27)–(10-29). A daily soil water balance of the topsoil together with a full daily soil water balance of the root zone can be employed including estimation of K_s to account for any stress. The soil water balance will automatically adhere to the law of conservation of mass, so that total ET_c from the weed or volunteer vegetation will not be overestimated. Because the topsoil layer may dry to below wilting point under conditions of sparse rainfall, the values for K_{cb} and $K_{c\,min}$ for bare soil conditions should be set equal to zero or nearly zero for these conditions (Allen et al. 2005b).

Tasumi et al. (2005a) and Allen et al. (2007a) sampled populations of K_c in south-central Idaho for major crop types using a Landsat satellite-based surface energy balance. Figure 10-16 shows distributions of the K_c populations for winter wheat crops on 12 satellite overpass dates between March 15 and October 20. The large variances in distributions of K_c during March and April reflect large variation in development of winter wheat fields coming out of winter. Values for K_c following harvest of the wheat crops averaged about 0.20 based on an alfalfa reference and varied according to amount of vegetation present in the form of weeds, nursed alfalfa, or volunteer wheat and variation in irrigation of fields following harvest, coupled with cultivation. Variances of distributions of K_c during the period of peak K_c were relatively small because nearly all fields were at or near effective full cover so that K_c values clustered closely about 1.0.

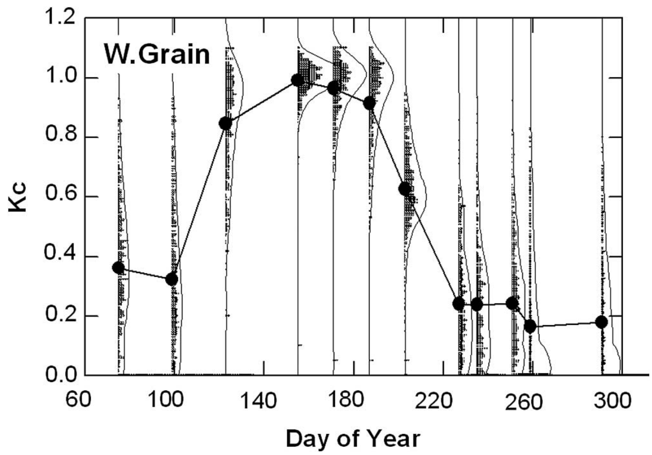

Fig. 10-16. Populations of K_c *in south-central Idaho for winter wheat fields using a Landsat satellite-based surface energy balance on 12 satellite overpass dates (vertical lines) between March 15 and October 20, 2000, where small symbols represent samples from individual fields and the large symbols are averages over all fields*
Source: Data from Tasumi et al. (2005) and Allen et al. (2007a)

Frozen or Snow-Covered Surfaces When the ground surface is snow covered or frozen, any vegetation will be largely nonresponsive and will not contribute directly to ET_c. In these situations ET_c will be closely related to the availability of free water at the surface and to the albedo of the surface. The albedo of snow-covered surfaces can range from 0.40 for old, dirty snow cover to 0.90 for fresh, dry snow as described in Table 4-1. Therefore, the ET_c for snow cover will be less than ET_{ref}, as 25–85% less shortwave energy is available. In addition, some energy must be used to melt the snow before evaporation, besides energy consumed in melting snow that seeps into the snowpack. Under conditions of snow cover where the surface of the snow does not have a liquid film, the saturation vapor pressure at air temperature used in the vapor pressure deficit calculation in the Penman-Monteith reference equation should be computed over ice rather than water. Eq. (3-1) for saturation vapor pressure over ice becomes (Murray 1967)

$$e^o_{\text{ice}} = 0.6108 \exp\left(\frac{21.87\,T}{T + 265.5}\right) \qquad (10\text{-}40)$$

for T in °C and e^o in kPa.

The use of ET_{ref} under such conditions is of limited value, as the assumption of conditions sustaining a green grass or alfalfa cover is violated. It is even possible to obtain negative values for ET_{ref} on some winter days where the long-wave radiation from the surface is large and the vapor pressure deficit is small. Under these conditions, net condensation of water from the atmosphere is possible, which corresponds to negative evaporation. Some negative values for ET_{ref} during winter occur from normal error in the ET_{ref} estimates and weather data. Given the limited utility of using ET_{ref} under snow-covered or frozen conditions, use of a single average value may be justified to estimate ET_c. Wright (1993) measured ET_c averaging 1 mm d^{-1} over nongrowing season periods at Kimberly, Idaho, that were six months long (1 October to 30 March). The latitude of Kimberly is 42° N, and the elevation is about 1,200 m. Over the six-year study period, the ground was at least 50% covered by snow for 25% of the time from 1 October to 30 March. The ground, when exposed, was frozen about 50% of the time. The K_c averaged 0.25 during periods when the soil was not frozen but where frosts occurred (October and early November). When the ground had 50% or greater snow cover, ET_c averaged only 0.4 mm d^{-1}. Wright found that over the six-month nongrowing period, total cumulative ET_c exceeded precipitation by about 50 mm, indicating a drying soil.

Figure 10-17 shows averaged measurements of ET_c by Wright (1993) during the 1985–1991winter periods. The measurements have high correspondence to the total shortwave radiation energy available on a clear day, R_{so}, estimated as 0.75 R_a. Some lag occurs between ET_c and R_{so} and R_s caused by cooler temperatures in January–March as compared with the

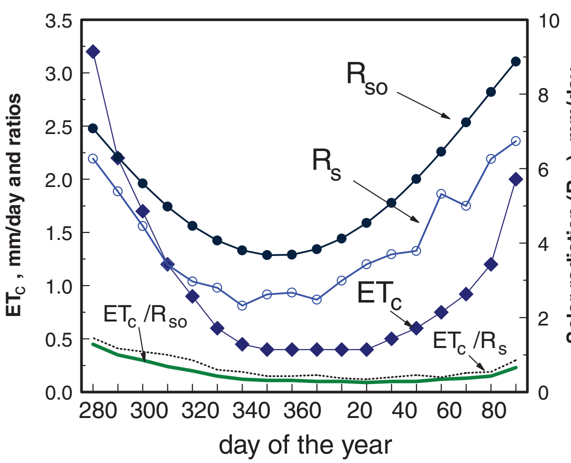

Fig. 10-17. Mean evapotranspiration measured during nongrowing winter periods at Kimberly, Idaho, by Wright (1993)
Source: Data from Allen et al. (1998)

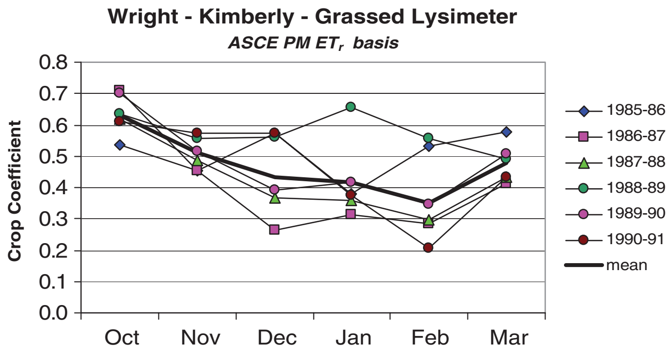

Fig. 10-18. Mean monthly K_c *measured by Wright (1993) from dormant grass using a weighing lysimeter during nongrowing periods at Kimberly, Idaho, based on the ASCE PM alfalfa reference* ET_r *equation*
Source: Data from Allen and Robison (2007)

October–December period. The ET_c/R_{so} ratio averaged only 0.17 over the six-month period and averaged 0.11 from 1 December to 10 March. The ET_c/R_s ratio averaged 0.23 over the six-month period and averaged 0.15 from 1 December to 10 March. The K_{cm} measured by Wright (1993) and converted to the standardized Penman-Monteith ET_r basis averaged about 0.45 during the October–December period over years 1985–1991 for dormant fescue grass cover (Figure 10-18) and for nongrass covers including tilled soil (Figure 10-19). Even though these values for K_{cm} are relatively high due to relative wetness of the surface during the nongrowing periods, the total ET rates were relatively low due to low values for ET_r during these periods.

A similar study conducted in Logan, Utah (latitude 41.6° N, elevation 1,350 m) (Allen 1996b), shows ET_c to vary widely with soil surface wetness and air temperature during winter months. The "average" K_c from November to March was 0.5 for days having no snow cover. For days with snow cover, ET_c ranged from 0 to 1.5 mm d^{-1}.

A daily soil water balance using the dual crop coefficient approach may improve accuracy in estimating ET_c under freezing and snow-covered conditions. In the dual crop coefficient method, a daily water balance is conducted for the topsoil, and the estimate for K_c can be reduced according to available water. However, in addition to the limited validity of the concept of ET_{ref} under frozen or snow-covered conditions, the evaporation coefficient, K_e, may have low values when the ground surface is frozen, as the water in a frozen state is less available.

Somewhat complex models for estimating ET_c under nongrowing season conditions, snow cover, and freezing are available in the literature

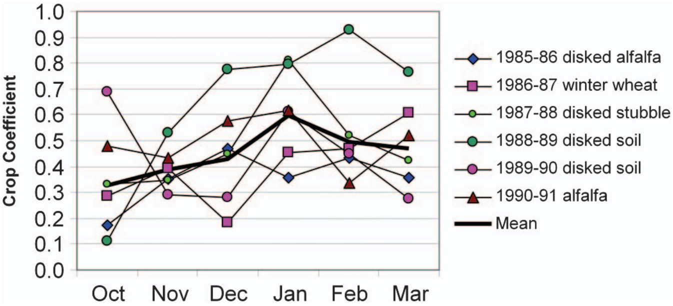

Fig. 10-19. Mean monthly K_c *measured by Wright (1993) during nongrowing periods at Kimberly, Idaho, using a weighing lysimeter for various types of nongrass cover based on the ASCE PM alfalfa reference* ET_r *equation*
Source: Data from Allen and Robison (2007)

and should be consulted and perhaps applied when precise estimates for ET_c are required, for example, Flerchinger (1991), Flerchinger et al. (1996), and Saxton and Willey (2005).

The basis for the mean K_c values in Figures 10-18 and 10-19 is the ASCE standardized Penman-Monteith method. The ASCE PM alfalfa reference ET_r standard represents 0.5-m tall green alfalfa, even during winter, where the crop is a hypothetical potential reference. Therefore, under even wet conditions, the K_c during wintertime is not expected to reach 1.0 because much vegetation may be frozen, cold stressed, or dormant. Mean $K_c(K_{cm})$ did approach or exceed 0.8 during December 1988–March 1989 for the disked soil, a period with a nearly continuous distribution of precipitation and wet surface condition.

Estimated Wintertime Evaporation

Allen and Robison (2007) estimate wintertime evaporation across the state of Idaho using daily calculation of Eq. (10-2) (dual K_c approach) requiring a daily soil water balance. The wintertime calculations are combined with calculations for growing periods to produce daily ET estimates for entire annual periods. Allen and Robison (2007) define the nongrowing season (winter) period as the period beginning when a K_{cb} curve representing the growing cycle for a specific crop ends or when a killing frost occurs and ending at greenup or planting of the same crop the following year (or October 1 in the case of winter wheat). A basal $K_{cb} = 0.1$ is used for bare soil conditions during nongrowing season periods, for surfaces covered with some amount of mulch, and for dormant turf/sod systems. K_{cb} represents conditions when these surfaces had a dry soil surface, but had sufficient moisture at depth to supply

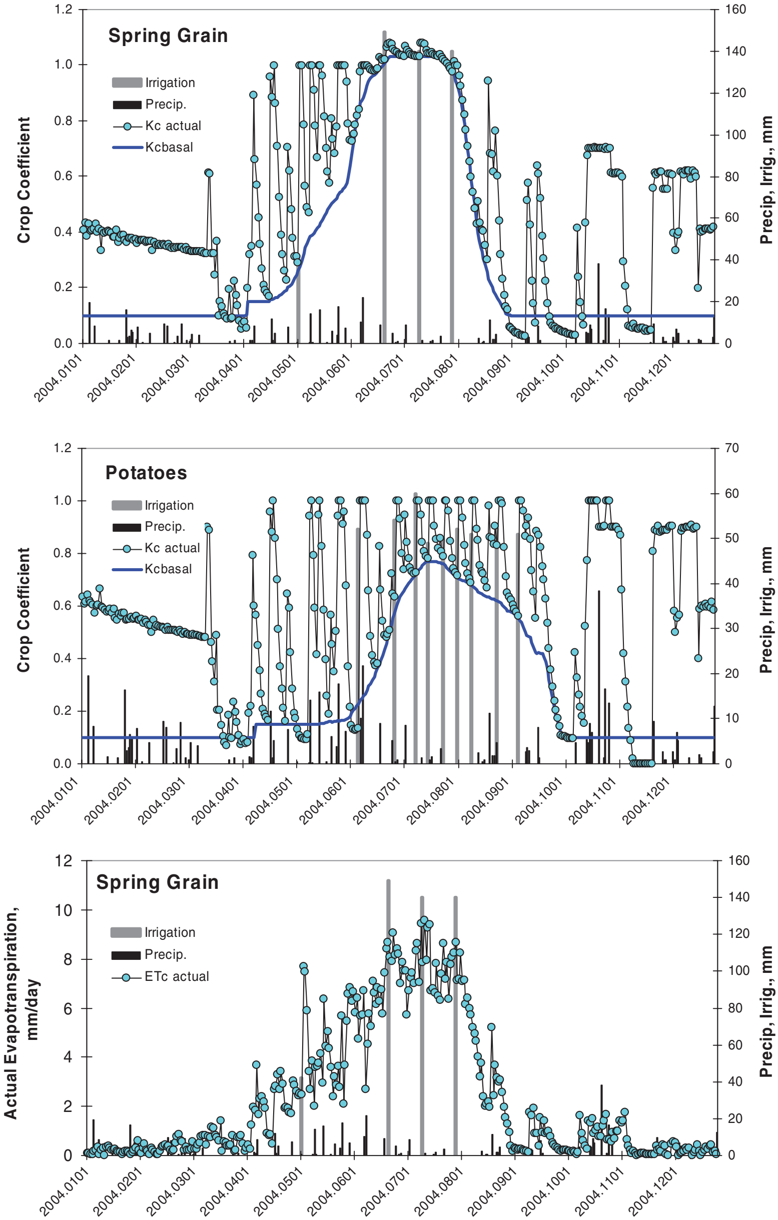

Fig. 10-20. Example K_{cb} *(*$K_{c\,basal}$*) and resulting* K_c *(*$K_{c\,actual}$*) curves for spring wheat and potato crops near Ashton, Idaho, during 2004. Simulated irrigation events are shown as vertical bars. The* $K_{c\,actual}$ *traces include the evaporation (*K_e*) components that appear as spikes above the* K_{cb} *curves following precipitation and irrigation events. Also shown in the bottom figure is daily actual* ET_c *for the spring grain*

some diffusive evaporation. The evaporation (K_e) component is estimated separately in the daily soil water balance, where $K_{c\,max}$ during the nongrowing period was 0.9 for bare soil, 0.85 for mulched surfaces, and 0.8 for dormant grass cover. The lower value for grass accounted for the insulative effects of grass and its higher albedo. The use of a low value for K_{cb} permits the K_e function in the daily calculations to increase the value for total K_c according to wetting frequencies by rain and snow. An effective "rooting zone" of 0.10 m is used during the nongrowing season for the fraction of surface under the cover. For all surfaces, a daily soil water balance was conducted and a stress coefficient based on Eq. (10-6) was applied when soil water content of the upper 0.10 m dropped below a critical value. This caused actual K_c to fall below K_{cb} when both the ground surface and subsurface soil were dry. All land use types, including agricultural, landscape, horticultural, and natural vegetation, are assigned one of the three winter cover conditions (dormant grass, bare soil, or mulch classes) for estimating evaporation losses during winter. Allen and Robison (2007) describe functions for estimating sublimation from snow.

Typical K_{cb} and K_c curves for spring wheat and potato crops for a full calendar year are shown for a location near Ashton, Idaho, during 2004 in Figure 10-20. Simulated irrigation events, necessary to estimate evaporation from soil following unknown irrigation events, are shown as vertical bars. The K_c curves resulting from application of Eq. (10-2) (dual K_c procedure using alfalfa ET_r) include the evaporation (K_e) components that appear as spikes above the K_{cb} curves following precipitation and irrigation events. Actual K_c fell below K_{cb} curves during fall for the wheat and potato crops whenever the water content of the soil evaporation layer fell below levels required to support the $K_{cb} = 0.10$ values assumed for harvested surfaces that were mostly bare. Although values for K_c during wintertime were somewhat high due to wet soil surfaces and frequent snow cover (January–March 2004, for example), the total ET_c rates during wintertime were somewhat low due to low values for ET_r during the Idaho winters. This is illustrated in the bottom figure of Figure 10-20, which shows daily actual ET_c for the spring grain.

10.9 SUMMARY

In summary, the $K_c ET_{ref}$ approach is a convenient and robust method for estimating actual and potential ET from agricultural crops, landscapes, and natural vegetation. The method adheres to energy conservation principles and implicitly incorporates environmental, boundary layer, and physiological factors affecting the ET_c from the particular vegetation. Many of these factors must be explicitly estimated when using a direct estimation equation such as the Penman-Monteith equation discussed in the next chapter. The dual K_c method provides means to estimate effects of wetting frequency on total water consumption and to estimate ET year round. Crop coefficients can be estimated for new or understudied vegetation types via visual description of the vegetation density and general vegetation type. Publications will continue to present or update crop coefficients for new crops and for local areas. Some agencies and private entities post crop coefficients for their respective areas on the Internet.