Crop Coefficients

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Richard Allen
University of Idaho Research and Extension Center, Kimberly, Idaho, U.S.A.

INTRODUCTION

Crops and vegetation on the earth's surface vary in height, amount of leaf area, amount of soil shaded, color, amount of stomatal control to evaporation, and amount of soil wetness beneath the canopy. All of these factors affect, to some degree, the amount of evapotranspiration (ET) from the crop or vegetation. Rather than assigning parameters for all of these terms during the process of predicting ET from a specific type of vegetation using an ET equation, as [F1] covered in the entry on Evapotranspiration Formulas, the impacts of these variables are often lumped into a single parameter, termed the crop coefficient, K_c. This approach is done to reduce the complexity and time requirement for [F2] predicting ET for each type of crop or vegetation, and relies upon a common "reference ET" for a defined type of reference vegetation to represent the change in ET caused by variation in weather parameters. K_c is defined as the ratio of ET from a crop or soil surface to ET from the reference surface. Reference ET is the ET from a fully vegetated surface covering the soil, and normally represents ET from clipped grass (termed ET_o) or alfalfa (termed ET_r).

OVERVIEW

In general, four primary characteristics distinguish crop ET from reference ET: 1) crop cover density and total leaf area; 2) resistance of foliage epidermis and soil surface to the flow of water vapor; 3) aerodynamic roughness of the crop canopy; and 4) reflectance of the crop and soil surface to short wave radiation.

When the K_c is known, crop ET (ET_c) is calculated for a specific time period as:

$$ET_c = K_{co}ET_o \quad \text{and} \quad ET_c = K_{cr}ET_r \tag{1}$$

where K_{co} is the K_c for the grass ET_o basis and K_{cr} is the K_c for the alfalfa ET_r basis. Because reference ET represents nearly all effects of weather, K_c varies predominately with specific crop characteristics and only a small amount with climate. This enables the transfer of standard values and curves for K_c between locations and climates. This transfer has led to the widespread acceptance and usefulness of the K_c approach. K_c has been primarily developed and applied to agricultural situations. However, K_c is generally valid for natural vegetation and conditions including open water, although it can have large spatial variability. In situations where K_c has not been derived by ET measurement, it can be estimated from fraction of ground cover or leaf area index (LAI), using procedures in Refs. 1 and 2.

K_c varies during the growing season as: the plants develop, the fraction of ground covered by vegetation changes, and the plants age and mature (Fig. 1). K_c varies according to the wetness of the soil surface, especially when there is little vegetation cover. Under bare soil conditions, K_c has a high value when soil is wet and its value steadily decreases as the soil dries (Fig. 2).

CROP COEFFICIENT CURVES

Two different approaches are used to calculate K_c. The simpler approach uses a single K_c curve that represents time-averaged effects of evaporation from the soil surface. The result is a relatively smooth, consistently increasing or decreasing K_c curve (Fig. 2). The second K_c approach separates the K_c into two coefficients, with one coefficient, the basal crop coefficient, termed K_{cb}, representing K_c for a dry soil surface (with or without vegetation) having little evaporation but full transpiration. The second coefficient, the evaporation coefficient, K_e, represents the evaporation component from the soil surface (Fig. 2). The value for K_e changes daily as the soil surface wets or dries, whereas the value for K_{cb} is more consistent day-to-day:

$$K_c = K_sK_{cb} + K_e \tag{2}$$

where K_s [0–1] represents the reduction in K_c due to environmental stresses, primarily from soil water shortage or soil salinity. All four terms are dimensionless. In application of the dual $K_{cb} + K_e$ procedure, a daily calculation must be made to estimate water content and associated evaporation rate from the soil surface, so that the approach is relatively computationally intensive. However, estimates can be up to 50% more accurate for any particular day, as compared with the single K_c approach, especially for the first few days following soil wetting during initial and development periods. The dual

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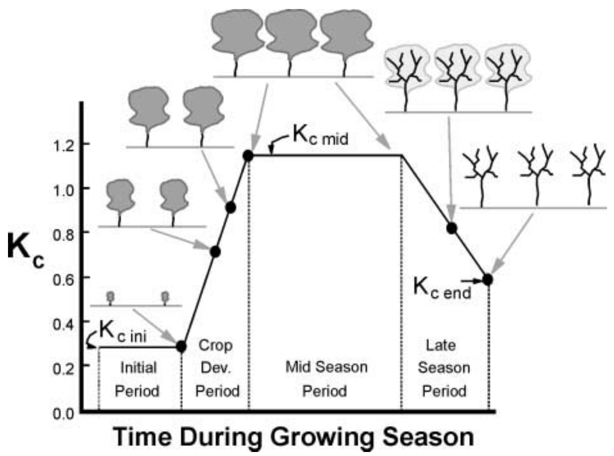

Fig. 1 General K_c curve showing relationship between stage of growth and K_c. (After Ref. 1.)

procedure is applied on a daily timestep and is readily adapted to spreadsheet programs.

Time-averaged (single) K_c is used for planning studies and irrigation or water resources systems design where averaged effects of soil wetting are appropriate. The dual K_c approach, is better for irrigation scheduling, soil water balance computations, and research where specific effects of day-to-day variation in soil wetness are important.

K_c (or K_{cb}) changes during a growing season, reflecting changes in the vegetation and ground cover. Initially, K_c is small, generally between 0.1 and 0.4, and K_{cb} is between 0.0 and 0.2. K_c increases during the period of rapid plant growth until it reaches a maximum value at the time of near maximum ground cover. Towards the end of the growing cycle, K_c decreases as plants age, ripen, or die due to natural or cultural practices.

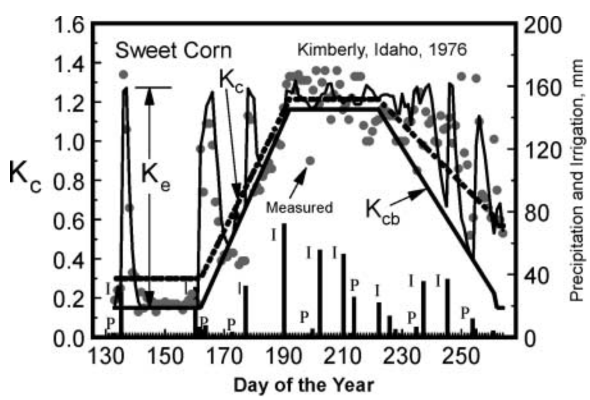

Fig. 2 Basal K_{cb}, soil evaporation coefficient K_e, and time-averaged (single) K_c (dotted line) curves for a crop of sweet corn grown near Kimberly, Idaho during 1976. Also shown are actual measurements of K_c (dots) determined from weighing lysimeters. (Data from Dr. J.L. Wright, USDA-ARS, Kimberly.)

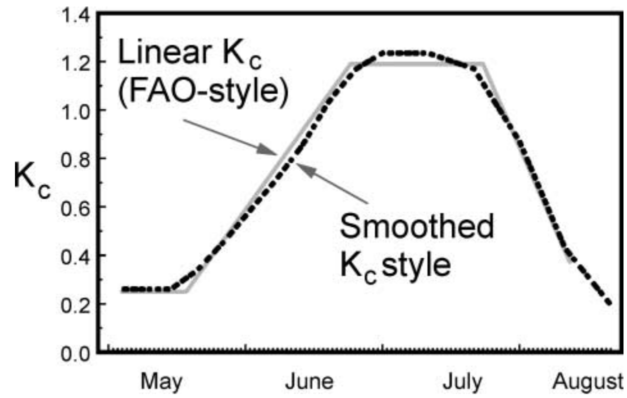

Fig. 3 Typical styles of crop coefficient curves.

Styles of Crop Coefficient Curves

[F3] Fig. 3 illustrates two common shapes used to represent K_c curves for growing seasons. Smooth curves as in Ref. 3 exhibit a smoothed change in K_c with time, whereas linearly shaped K_c curves as in Ref. 1 are constructed using four line segments. Both shapes are useful and valid for predicting K_c.

Definition of Growing Periods Within the Growing Season

A growing season can be divided into four basic periods as shown in Fig. 1. The initial period represents the period following planting of annuals until about 10% ground cover or following initiation of leaves for perennials. The development period extends from the end of the initial period until the crop reaches "effective full cover." Mid-season extends from effective full cover to when plant vigors or greenness begin to decrease. The late-season period extends from end of mid-season until harvest or crop death. Information on relative lengths of growing periods of crops is found in Ref. 1.

Effective full cover for row crops occurs when leaves between rows of plants begin to intermingle, or when plants reach nearly full size, if no intermingling occurs. For crops taller than 0.5 m, effective full cover is reached when the average fraction of ground surface shaded by vegetation at solar noon is about 0.7–0.8. Effective full cover for many crops begins at flowering. Plants may continue to grow in both height and leaf area after the attainment of effective full cover. Effective full cover can be predicted when the crop reaches an LAI of 3, where LAI is defined as the total area of leaves (one side only) per unit area of ground. The beginning of the late season is generally signaled by the beginning of yellowing or senescence of leaves for annual crops, leaf drop, or browning of fruit.

Construction of a Linear K_c Curve

Only three defined values for K_c are required to construct the linear K_c curve: K_c during the initial period ($K_{c\,ini}$), K_c during the mid-season period ($K_{c\,mid}$), and K_c at the time of harvest or crop death ($K_{c\,end}$). In addition, lengths of the four growing season periods, in days, are needed.

Grass-based K_cs. General values for $K_{c\,ini}$, $K_{c\,mid}$, and $K_{c\,end}$ and basal $K_{cb\,ini}$, $K_{cb\,mid}$, and $K_{cb\,end}$ for primary types of crops and conditions are listed in [T1] Table 1 from Ref. 1. These values are K_{co} based on grass reference ET_o as defined by the FAO-56 Penman–Monteith equation. Details on calculating ET_o are given under the entry on Evapotranspiration Formulas and in Ref. 1. The Penman–Monteith method was selected by FAO-56 as the best method for standardized calculation of reference ET from a clipped cool-season grass. Cool-season grass is a standard for ET_o worldwide because it can be grown over a wide range of climates and is relatively easy to maintain. Generally, ET_o is computed by ET equation rather than measured. K_c and K_{cb} are listed for specific crops in Refs. 1–4.

There is close similarity in K_c among crops having similar characteristics, e.g. among crops in the vegetable groups, since plant height, leaf area, ground coverage, and water management are similar. $K_{c\,ini}$ values in Table 1 are approximate. Graphs and equations in Ref. 1 provide better estimates for $K_{c\,ini}$ that account for frequency of wetting and soil type.

Alfalfa-based K_cs. Wright[3,4] established crop coefficients for crops common to central and northern latitudes of the Western United States. These coefficients are based on the alfalfa reference ET_r represented by the 1982 Kimberly Penman Equation.[3] Alfalfa is sometimes preferred as the reference crop rather than clipped grass because it is taller than grass and has ET that is more similar to maximum ET from many agricultural crops.[3] Therefore, K_{cr}s based on ET_r generally peak at values of 1.0. Values for K_{cr} cannot be interchanged with values for K_{co} and vice versa. Values for K_{co} average about 15%–30% higher than K_{cr}.

Crop Coefficients Applied to Hourly Time Periods

For many crops the ratio of ET_c to ET_o or ET_r is relatively constant during the day. Therefore, K_c is relatively [F4] constant during the day, also, as shown in Fig. 4 for a sugar

Table 1 Time-averaged single crop coefficients, and basal crop coefficients for well-managed crops in subhumid climates, for use with ET_o

	Single K_c			Basal K_{cb}		
Crop	$K_{c\,ini}$	$K_{c\,mid}$	$K_{c\,end}$	$K_{cb\,ini}$	$K_{cb\,mid}$	$K_{cb\,end}$
Small vegetables	0.7	1.05	0.95	0.15	0.95	0.85
Vegetables—roots	0.5	1.10	0.95	0.15	1.00	0.85
Vegetables—legumes	0.4	1.15	0.55	0.15	1.10	0.50
Vegetables—solanum family	0.4	1.15	0.80	0.15	1.10	0.70
Vegetables—cucumber family	0.4	1.00	0.80	0.15	0.95	0.70
Fiber crops	0.35	1.15	0.70	0.15	1.10	0.60
Oil crops	0.35	1.15	0.30	0.15	1.10	0.25
Cereals	0.3	1.15	0.4	0.15	1.10	0.25
Forages	0.60	1.15	1.10	0.60	1.10	1.05
Sugar cane	0.40	1.25	0.75	0.15	1.20	0.70
Grapes and berries	0.30	1.00	0.50	0.20	0.95	0.45
Fruit trees	0.60	0.95	0.75	0.50	0.90	0.70
Bare soil						
Wet	1.00	1.20	1.20	—	—	—
Dry	0.15	0.15	0.15	0.00	0.00	0.00
Wetlands	0.60	1.20	0.60	0.50	1.15	0.50
Open water						
$<$ 2 m depth or in subhumid clim. or tropics	—	1.05	1.05	—	—	—
$>$ 5 m depth, clear	—	0.75	1.25	—	—	—

(After Ref. 1.)

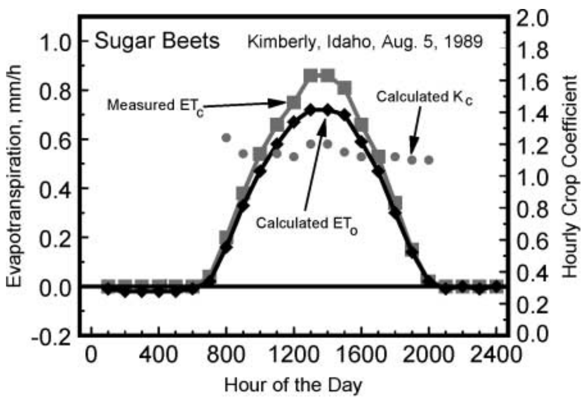

Fig. 4 Measured ET_c (by precision lysimeter) and calculated ET_o and K_c for a sugar beet crop near Kimberly, Idaho for hourly periods during August 5, 1989. (Data from Dr. J.L. Wright, USDA-ARS, Kimberly.)

beet crop near Kimberly, Idaho. ET_o was calculated using the FAO Penman–Monteith ET_o method.

ADJUSTMENT OF K_{CO} TO ACCOUNT FOR EFFECTS OF CLIMATE

K_cs based on grass ET_o (K_{co}) are somewhat impacted by general climate. Under humid conditions, K_{co} does not exceed about 1.05–1.10 because the vapor pressure deficit (VPD) driving ET is small and K_{co} becomes less dependent on the differences between the aerodynamic characteristics of crop and reference. Under arid conditions, the effect of differences in aerodynamic characteristics between crop and grass reference become more pronounced because the VPD of the air is relatively large. Hence, K_{co} for tall crops under arid conditions can be as high as 1.2 or more. Because alfalfa ET_r is more aerodynamically rough, values for K_{cr} generally do not vary with climate.

K_C DURING NONGROWING PERIODS

The value for K_c for periods following crop harvest or death will depend on the average water content of the soil surface and amount of vegetation or mulched cover remaining. When the soil surface is mostly bare, K_c can be set equal to $K_{c\,ini}$, and figures and equations for $K_{c\,ini}$ from Ref. 1 can be applied. When dead and dry vegetation or mulch covers the soil surface, K_c will be less than $K_{c\,ini}$. K_c following harvest can be estimated using guidelines in Chapters 9 and 11 of Ref. 1.

COEFFICIENTS FOR LIMITED WATER

The value for K_c is reduced when soil water content of the plant root zone is too low to sustain transpiration at the level predicted by Eq. 1. The reduction is accomplished by multiplying K_{cb} (in Eq. 2) or the single K_c (in Eq. 1) by the water stress coefficient, K_s, predicted for effects of limited water as

$$K_s = \frac{\theta - \theta_{WP}}{\theta_t - \theta_{WP}} \tag{3}$$

where θ is mean volumetric soil water content in the root zone ($m^3\,m^{-3}$), θ_t is the threshold θ for the root zone, below which transpiration is decreased ($m^3\,m^{-3}$), and θ_{WP} is the soil water content at the wilting point ($m^3\,m^{-3}$). Equation 3 is applied when $\theta < \theta_t$, and $K_s = 1.0$ for $\theta \exists \theta_t$.

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