CROP COEFFICIENTS

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IMPORTANT NOTE: The theory behind crop coefficients is provided in this document. For a pdf copy of this document, click on Crop_Coefficients.pdf. The most recent K_c values available in California are provided in the Basic Irrigation Scheduling (BIS) program, which can be accessed by clicking on the following link.

Basic Irrigation Scheduling (BIS)

The Excel application program is available in English and metric units in English and in metric units in Spanish. The K_c values are given in the CropRef worksheet of the BIS program. They are updated whenever new information is available.

REFERENCE CROP EVAPOTRANSPIRATION

The American Society of Civil Engineers (ASCE) - Committee on Evapotranspiration in Irrigation and Hydrology has recommended that two crops be adopted as approximations for reference crop evapotranspiration (Allen et al., 2005). The symbols and definitions given are:

ET$_{ref}$ **- Reference *ET***

ET$_o$ **- Reference *ET* for a *short* crop having an approximate height of 0.12 m (similar to grass).**

ET$_r$ **- Reference *ET* for a *tall* crop having an approximate height of 0.50 m (similar to alfalfa)**

For estimating ET_{ref}, a modified version of the Penman-Monteith equation (Allen et al., 1999) with some fixed parameters was recommended (Walter et al., 2000 and Itenfisu et al., 2000.). The equation is

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273}(e_s - e_a)u_2}{\Delta + \gamma(1 + C_d u_2)} \quad (1),$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve (kPa $^oC^{-1}$), R_n and G are the net radiation and soil heat flux density in MJ $m^{-2}d^{-1}$ for daily or MJ $m^{-2}h^{-1}$ for hourly data, γ is the psychrometric constant (kPa $^oC^{-1}$), T is the daily or hourly mean temperature (^{o}C), u_2 is the mean wind speed in m s^{-1}, and e_s-e_a is the vapor pressure deficit (kPa). In Eq. [1], the coefficients in the numerator (C_n) and the denominator (C_d) are given specific values depending on the calculation time step and the reference crop as shown in Table 1. The values for C_n vary because the aerodynamic resistance is different for the two reference crops and because of the conversion from energy to depth of water units.

The output units from Eq. [1] are in mm d^{-1} for the daily or monthly calculations and in mm h^{-1} for the hourly time step. For the daily data, R_n is input in MJ $m^{-2}d^{-1}$ and G is assumed to be zero. For the hourly calculations,

G is assumed equal to 10% of R_n when $R_{n\geq}0$ and G is assumed equal to 50% of R_n for R_n<0. In addition, the surface (canopy) resistance is set equal to 50 s m^{-1} during daytime and to 200 s m^{-1} at night. This change accounts for nighttime stomatal closure and improves the daytime estimates as well (Fig. 1).

In California, starting in the year 2001, the California Irrigation Management Information System (CIMIS) will begin use Eq. 1with the numerator coefficient $C_n = 37$. The denominator coefficient is $C_d = 0.24$ when $R_n > 0$ and $C_d = 0.96$ when $R_n \leq 0$. The results approximate the *ET* from a 12 cm tall, cool-season grass reference (ET_o). All of the crop coefficients presented in this quick answer are relative to the grass reference (ET_o).

CROP COEFFICIENTS

While reference crop evapotranspiration accounts for variations in weather and offers a measure of the "evaporative demand" of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration (ET_c) and ET_o. The ASCE committee has recommended the use of K_c and K_{cr} for crop coefficients relative to ET_o and ET_r, respectively (Walter et al., 2000). The recommendation, however, was made to encourage researchers to differentiate between crop coefficient references in national and international publications. In California, only ET_o is used, so the symbol K_c will be shortened to K_c in this review.

The main factors affecting the difference between ET_c and ET_o are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration (*ET*) is the sum of evaporation (*E*) from soil and plant surfaces and transpiration (*T*), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. Therefore, solar radiation (or light) interception by the foliage and soil have a big effect on the *ET* rate.

As a crop canopy develops, the ratio of *T* to *ET* increases until most of the *ET* comes from *T* and *E* is a minor component. This occurs because the light interception by the foliage increases until most light is intercepted before it reaches the soil. Therefore, crop coefficients for field and row crops generally increase until the canopy ground cover reaches about 75% and the light interception is near 80%. For tree and vine crops the peak K_c is reached when the canopy has reached about 63% ground cover. The difference between the crop types results because the light interception is higher for the taller crops.

Bare Soil K_c Values

During the off season and early during crop growth, E is the main component of ET. Therefore, a good estimate of the K_c for bare soil is useful to estimate off-season soil evaporation and ET_c early in the season. A two-stage method for estimating soil evaporation presented by Stroonsnjider (1987) is used to estimate bare soil crop coefficients. In stage 1, the soil evaporation rate is limited by only by energy availability to vaporize water. In stage 2, the soil has dried sufficiently that soil hydraulic properties limit the transfer of water to the surface for vaporization. The method requires a maximum crop coefficient for soil evaporation (K_{sx}). The K_{sx} is estimated using

$$K_{sx} = 1.22 - 0.04ET_o \qquad (2).$$

During stage 1 evaporation, the cumulative soil evaporation (CE_s) is calculated as

$$CE_s = K_{sx}CET_o \qquad (3).$$

During stage 2, the cumulative soil evaporation is calculated as the product of a soil-specific hydraulic parameter (β) and the square root of the product of K_{sx} and CET_o.

$$CE_s = \beta\sqrt{K_{sx}CET_o} \qquad (4).$$

The soil hydraulic β factor is the slope of the linear regression of CE_s versus $\sqrt{K_{sx}CET_o}$ for all data pairs that fall within stage-2 evaporation (i.e., when the evaporation is limited by hydrologic factors and $\sqrt{K_{sx}CET_o} > \beta$. When $\sqrt{K_{sx}CET_o} \le \beta$, the soil is in stage-1 evaporation. Figure 2 shows the CE_s determined using the model for three β factors. The crop coefficient for bare soil is found by calculating the ratio of the CE_s to CET_o at a particular value of CET_o.

For a fixed mean ET_o rate, the CE_s from one soil wetting to the next is estimated as the product $K_{sx}CET_o$ during stage-1 and as $\beta\sqrt{K_{sx}CET_o}$ during stage-2 evaporation. Here, CET_o equals the product of the mean ET_o and the number of days between wetting. An example of the K_c calculations as a function of wetting frequency and the mean ET_o rate is shown in Fig. 3 for a β =2.6. This value was used because the results approximate the widely used K_c values for initial growth (Doorenbos and Pruitt, 1977).

The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when $P_s > 3 \times ET_o$. A sample K_c curve for bare soil evaporation near Fresno, California is shown in Fig. 4. The daily mean ET_o rates for each day of the season were computed using a cubic-spline fit through the monthly means calculated from 11 years of weather data. Then the daily K_c values for bare soil were computed using the product of the daily ET_o rate and the days between rainfall to determine CET_o and the bare soil evaporation model with β =2.6. This provides a baseline crop coefficient curve for the off-season.

Field and Row Crop K_c Values

Crop coefficients for field and row crops are calculated using a method similar to that described by Doorenbos and Pruitt (1977). In their method, the season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods (Fig. 5). During initial growth and midseason, the K_c values are initially fixed at K_{c1} and K_{c2}, respectively. During the rapid growth period, when the canopy increases from about 10% to 75% ground cover, the K_c value increases linearly from K_{c1} to K_{c2}. During late season, the K_c decreases linearly from K_{c2} to K_{c3} at the end of the season.

In Doorenbos and Pruitt (1977), estimated numbers of days for each of the four periods were provided to help identify the end dates of growth periods. However, because there are variety differences and because it is difficult to visualize when the inflection points occur, irrigators often find this confusing. To simplify this problem, percentages of the season from planting to each inflection point rather than days in growth periods are used. Irrigation planners need only enter the planting and end dates and the intermediate dates are determined from the percentages, which are easily stored in a computer program.

Initially, K_{c1} is determined by using the mean ET_o, irrigation and rainfall frequency, and the soil evaporation model to calculate K_c for bare soil evaporation during the initial growth period. However, the daily K_c values for bare soil, based on rainfall frequency, are used if they are bigger than K_{c1}.

The values for K_{c2} and K_{c3} depend on the difference in (1) R_n - G, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop. Sample K_{c2} and K_{c3} values for crops grown in California are provided in the Basic Irrigation Scheduling (BIS) program, which is available from the http://biomet.ucdavis.edu webpage under Irrigation Scheduling. The K_c values are given in the CropRef worksheet. In general, for environments with $ET_o < 4.0$, K_c values are closer to $K_c = 1.00$. For example, the K_c for citrus tends to be lower in a high evaporative demand (hot desert) climate. The likely cause for this is the lower K_c for bare soil evaporation and possibly some plant response to high ET_o rates.

A sample K_c curve for cotton grown near Fresno, California is shown in Fig. 6. Cotton is not typically irrigated during initial growth, so the value for K_{c1} was determined using the mean ET_o during the period, a 30 days between irrigation frequency, and β =2.6. However, the resulting K_c was smaller than the K_c for bare soil evaporation early in the period, so the K_c during initial growth partially follows the bare soil curve. If irrigated with sufficient frequency, the K_{c1} would likely be higher than the bare soil crop coefficient and it would be constant during the initial period.

Some field crops are harvested before senescence and there is no late season drop in K_c (e.g., silage corn and fresh market tomatoes). Fixed annual *Kc* values are possible for some crops (e.g., turfgrass and pasture) with little loss in accuracy.

Deciduous Tree and Vine Crop K_c Values

Deciduous tree and vine crops, without a cover crop, have similar K_c curves but without the initial growth period (Fig 7). The season begins with rapid growth at leaf out when the K_c increases from K_{c1} to K_{c2}. The midseason period begins at approximately 62% ground cover. Then, unless the crop is immature, the K_c is fixed at K_{c2} until the onset of senescence. During late season, the K_c decreases from K_{c2} to K_{c3}, which occurs at about leaf drop or when the transpiration is near zero.

At leaf out, K_{c1} is set equal to that of the bare soil evaporation on that date based on ET_o and rainfall frequency. The assumption is that the ET_c for a deciduous orchard or vineyard at leaf out should be about equal to the bare soil evaporation. The K_{c2} and K_{c3} values again depend on (R_n - G), (2) canopy morphology effects on turbulence, and (3) plant physiology differences between the crop and reference crop. Some sample K_{c2} and K_{c3} values for trees and vines are given in the Basic Irrigation Scheduling (BIS) program, which is available from the http://biomet.ucdavis.edu webpage under Irrigation Scheduling. The K_c values are given in the CropRef worksheet.

With a cover crop, the K_c values for deciduous trees and vines are increased depending on the amount of cover. In general, adding 0.35 to the in-season, no-cover K_c for a mature crop, but not to exceed 1.20, is recommended. With immature crops, adding more than 0.35 may be required. For a cover crop during the off-season, adding 0.35 to the bare soil K_c but not exceeding 0.90 is recommended. During the off-season, a $K_c \leq 0.90$ is used because shading by the trunks and branches are assumed to reduce the cover crop ET slightly below ET_o. The K_c curve for a stone fruit orchard is shown in Fig. 8. The dashed line is for a mature orchard with a cover crop and the solid line is for a clean cultivated orchard.

Immature deciduous tree and vine crops use less water than mature crops the following equation is used to adjust the mature K_c values (K_{cm}) as a function of percentage ground cover (C_g).

If $sin\left(\frac{\pi C_g}{140}\right) \geq 1.0$ then $K_c = K_{cm}$ else $K_c = K_m\left[sin\left(\frac{\pi C_g}{140}\right)\right]$ (5)

A sample K_c curve for an immature stone fruit orchard having C_g=35% and C_g=40% at the beginning and end of midseason, respectively, is represented by the solid K_c line in Fig. 9. The dashed curve is for a mature, clean cultivated tree crop.

Subtropical Orchards

For mature subtropical orchards (e.g., citrus), using a fixed K_c during the season provides acceptable ET_c estimates. However, if higher, the bare soil K_c is used for the orchard K_c. The solid line in Fig. 10 represents the K_c curve for a mature citrus orchard grown near Fresno. For an immature orchard, the mature K_c values (K_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

$$\text{If } \sqrt{sin\left(\frac{\pi C_g}{140}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_m\sqrt{sin\left(\frac{\pi C_g}{140}\right)} \qquad (6)$$

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Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1999. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome.

Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E. and Snyder, R.L. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Amer. Soc. of Civil Eng. Reston, Virginia. 192p.

Itenfisu, D., R.L. Elliot, R.G. Allen and I.A. Walter. 2000. Comparison of Reference Evapotranspiration Calculations across a Range of Climates. Proc. of the National Irrigation Symposium, November 2000, Phoenix, AZ, American Society of Civil Engineers, Environmental and Water Resources Institute, New York, NY

Stroosnijder, L. 1987. Soil evaporation: test of a practical approach under semi-arid conditions. Netherlands Journal of Agricultural Science, 35: 417-426.

Table 1. Coefficients used in the ET_{ref} equation for a short 0.12 m tall canopy (ET_o) and for a 0.50 m tall canopy (ET_r)

Calculation Time Step	ET_o		ET_r	
	Cn	*Cd*	*Cn*	*Cd*
Daily or monthly	900	0.34	1600	0.38
Hourly during daytime	37	0.24	66	0.25
Hourly during nighttime	37	0.96	66	1.70

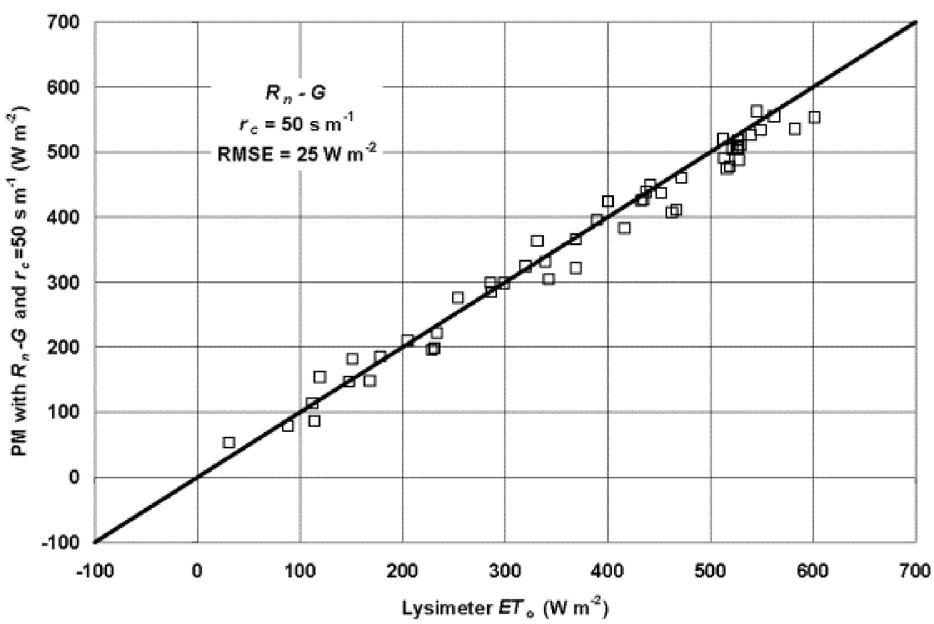

Figure 1. A plot of ET_o estimated using the Penman-Monteith equation with measured R_n, G, e_s-e_a, and u_2 assuming a canopy resistance of 50 s m^{-1} versus daytime, half hour lysimeter measurements of ET_o.

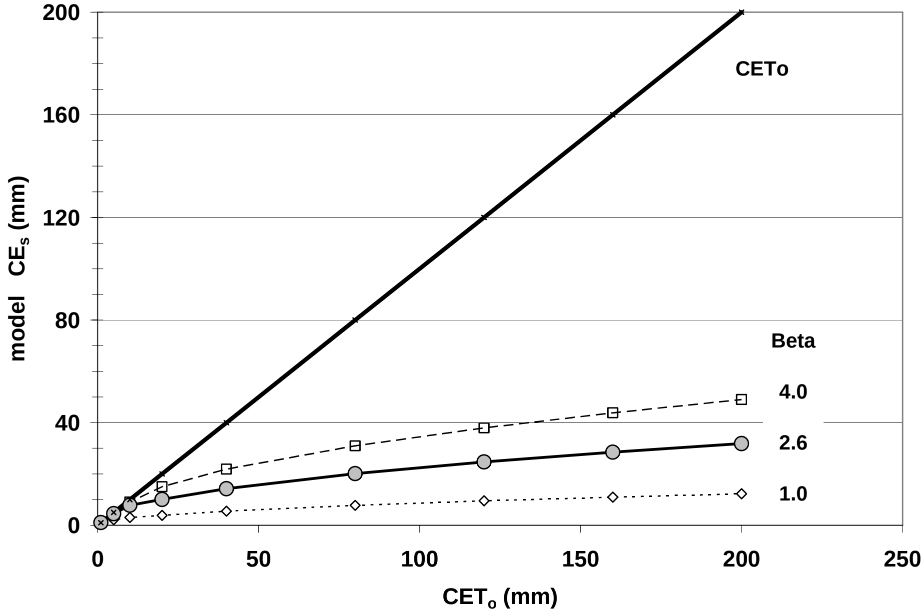

Figure 2. This plot shows the modeled cumulative soil evaporation (CE_s) versus CET_o for three soil hydraulic (β) factors.

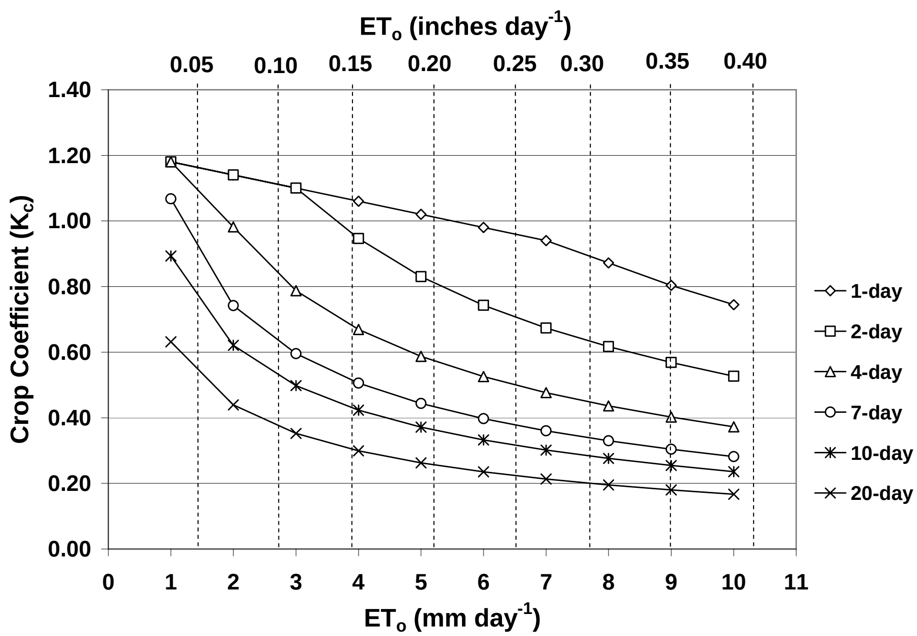

Figure 3. Crop coefficient (K_c) values for bare or near bare soil as a function of mean ET_o rate and wetting frequency in days by significant rainfall or irrigation using a soil hydraulic factor β =2.6.

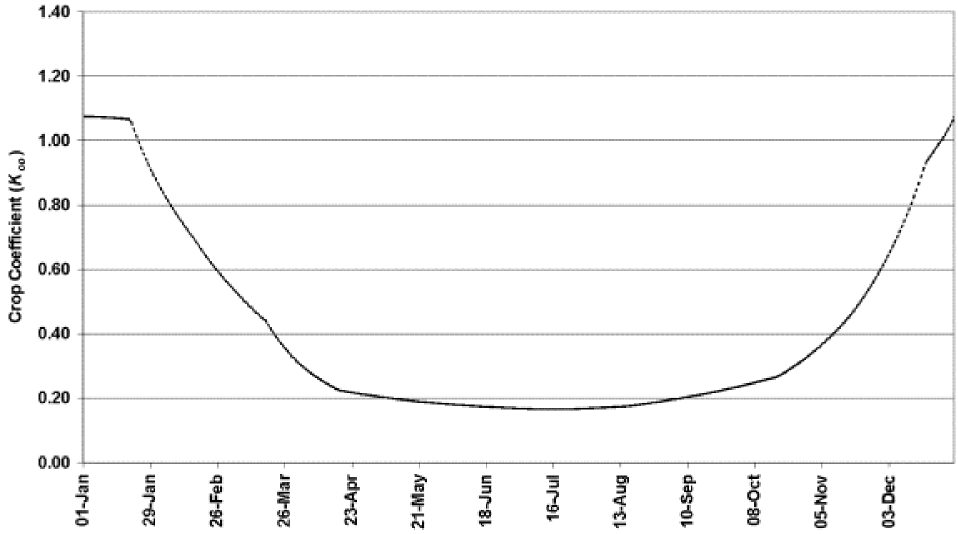

Figure 4. A plot of the annual K_c curve for bare soil for Fresno, California based on mean daily ET_o rate and days between significant precipitation (P_s).

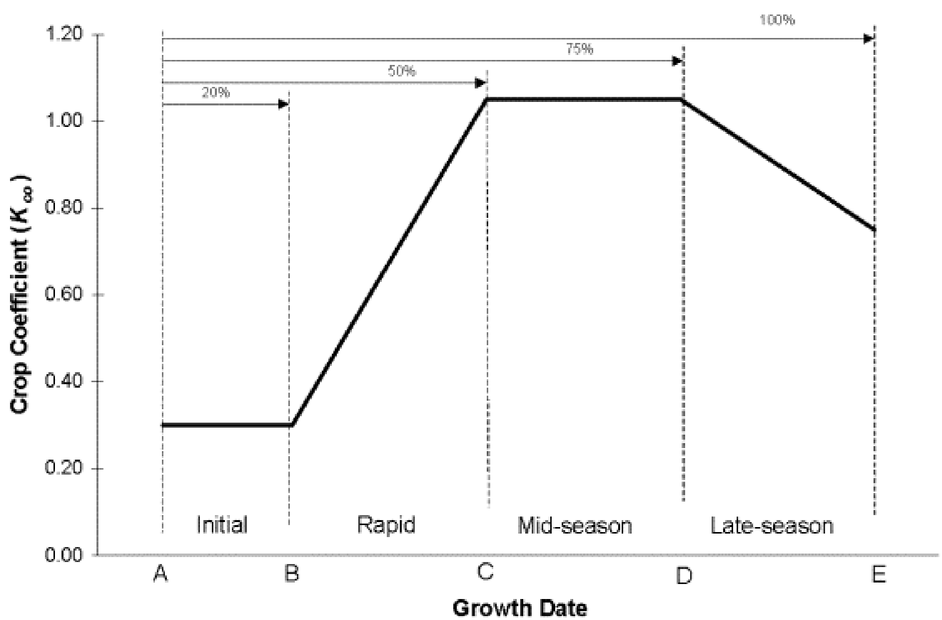

Figure 5. K_c curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates.

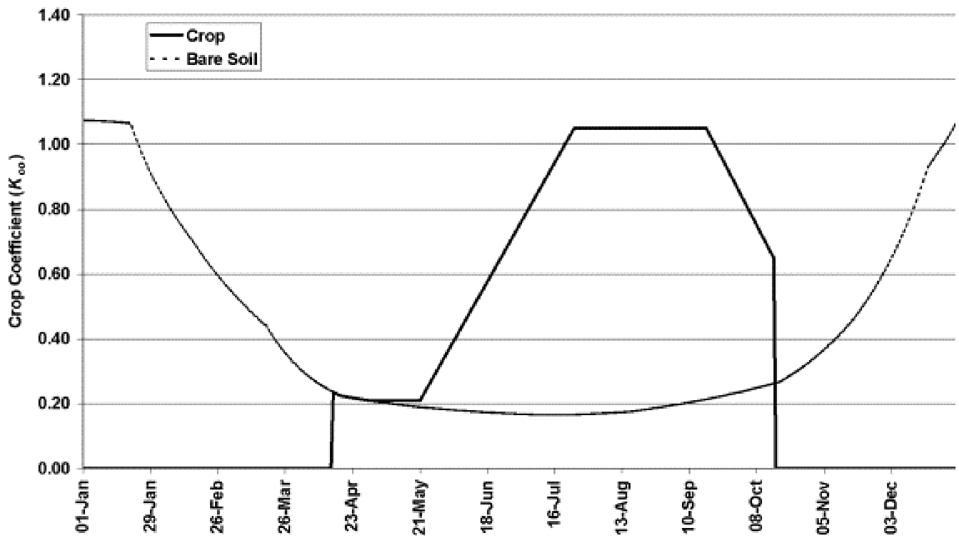

Figure 6. K_c curve, using a 30 day irrigation frequency during initial growth, for cotton grown near Fresno, California (solid line). K_c curve for bare soil (dotted line).

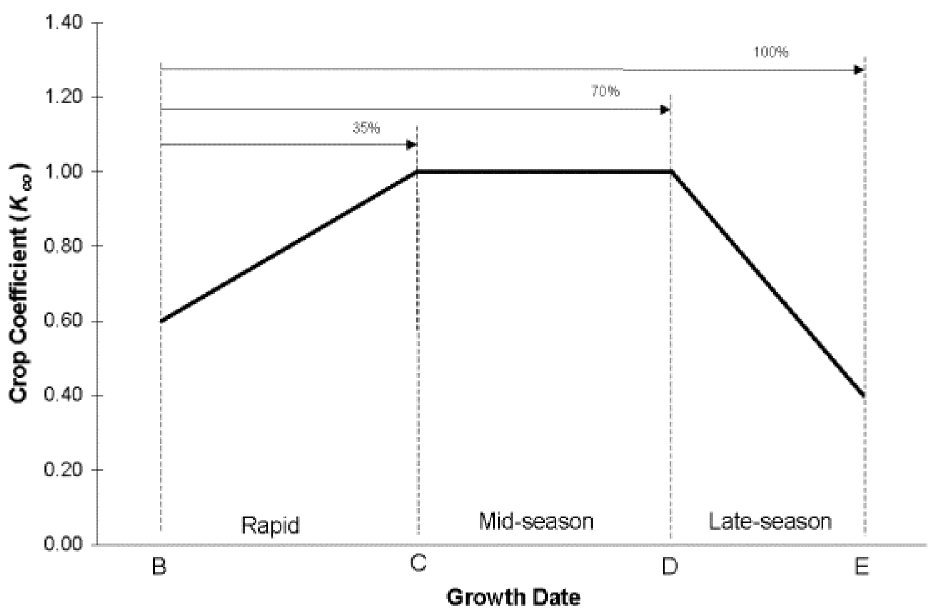

Figure 7. K_c curve for typical deciduous orchard and vine crops with growth stages and percentages of the season from leaf out to critical growth dates.

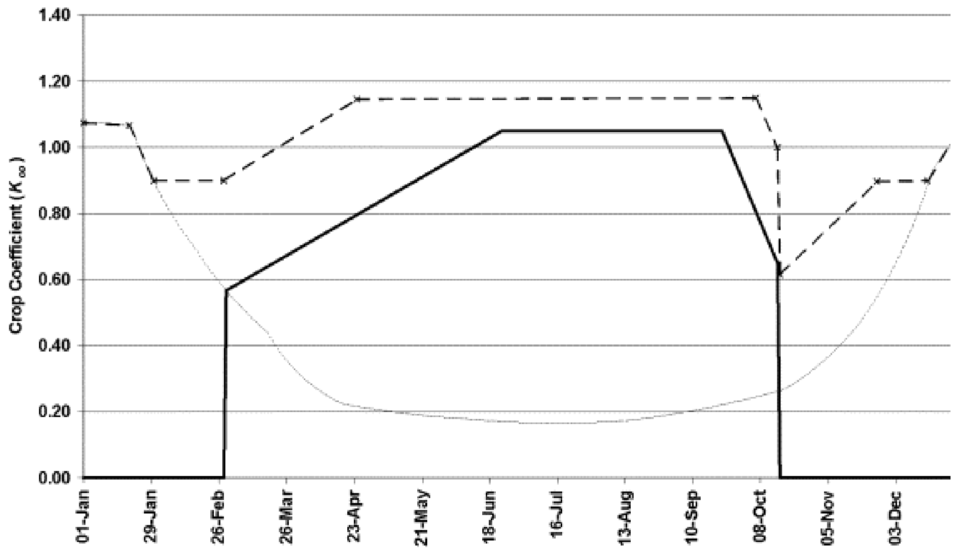

Figure 8. K_c curve for a stone fruit orchard grown near Fresno, California. The solid line is for a clean cultivated orchard and the dashed line is for an orchard with a green growing cover crop contributing a maximum of 0.35 above the clean cultivated K_c. The dotted line is for bare soil evaporation.

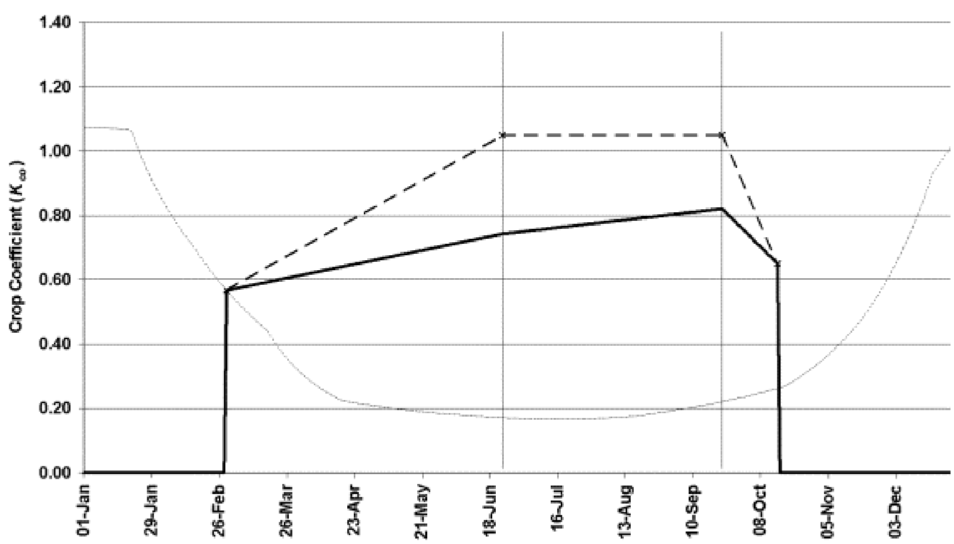

Figure 9. K_c curve for a stone fruit orchard grown near Fresno, California. The dashed line is for a clean cultivated, mature orchard and the solid line is for an immature orchard having C_g=35% and C_g=40% at the beginning and end of the midseason period. The dotted line is for bare soil evaporation.