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CROP COEFFICIENTS FOR ESTIMATES OF DAILY CROP EVAPOTRANSPIRATION

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Crop coefficients are used with values of reference evapotranspiration (ET) to estimate water use of a crop. Since the direct measurement of reference ET is expensive, time consuming, and laborious, it is usually preferable to calculate it from more easily obtainable climatic data. Extensive research on reference ET methods and improved crop coefficients has been conducted because of their application in irrigation scheduling and other aspects of water resources allocation, management and planning.

Various procedures have been used to obtain the necessary experimental crop and reference ET data, and several types of crop coefficient curves have been published during the past few years (Jensen 1974, Doorenbos and Pruitt 1977, Burman et al. 1980, Wright 1979, 1981). Crop coefficients must be matched with the appropriate reference ET. The climatic adequacy of the methods, the necessary input data, and the time scale all need to be understood and carefully applied if accurate estimates of crop water requirements are to be obtained for either irrigation scheduling or water resources planning. The available methods for estimating reference ET and improved crop curves, when properly applied, permit estimates of crop ET which are within the accuracy of most field irrigation systems to deliver water (Jensen et al. 1971, Jensen and Wright 1978, Wright and Jensen 1978).

This discussion briefly reviews the nature and origin of commonly used coefficients and outlines the conditions under which they can be appropriately applied. The application of recent "basal" crop coefficients (Wright 1981) is discussed and "mean" crop coefficients recently developed from ET data obtained with weighing lysimeters in Southern Idaho are also presented.

DEVELOPMENT OF CROP COEFFICIENTS

Crop Coefficients

Crop coefficients are generally empirical ratios of crop ET to some reference ET and are derived from experimental data. The time distribution of crop coefficients for a particular crop constitutes a "crop curve". A common form of the ET crop coefficient is:

\[ K_c = \frac{E_c}{E_T} \]  

in which \( K_c \) is the dimensionless crop coefficient for a particular crop at a given growth stage and soil moisture condition, \( E_c \) is the daily crop ET, and \( E_T \) is the daily reference ET. Ideally \( E_T \) characterizes the evaporative demand determined by meteorological conditions and \( K_c \) is a measure of the capability of the crop-soil-surface to meet that demand. Research has shown, however, that \( E_T \) cannot be simply described for all climate and crop situations, partly because of the effects of the relative leaf area and the morphological and physiological characteristics of the crop canopy on the energy exchange and the aerodynamic diffusion processes within the atmosphere over a
field. This complexity accounts for the many methods for estimating or predicting ET and the diversity of crop coefficients (Jensen 1974, Doorenbos and Pruitt 1977). Nonetheless, the goal of developing representative methods and coefficients for various ranges of climatic and crop conditions is warranted because crop coefficients provide a conservative means of estimating crop ET at progressive stages of growth.

The crop coefficient described by Eq. [1] includes effects of evaporation from both plant and soil surfaces, and is thus dependent upon soil water availability within the root zone and the wetness of the exposed soil surface. Soil evaporation is proportionally greater during the portions of the growing season when the crop canopy is at least as effective full cover. The time-scale of $K_c$ is, of course, dependent upon that of $E_{TC}$ and $E_{TR}$.

Changes in soil-water content with time are commonly used to obtain $E_{TC}$. Gravimetric sampling and neutron probe methods produce 3-5 day averages but even in carefully planned studies uncertainty exists concerning the significance of upward or downward movement of water and extraction by deep roots. Weighing lysimeters can provide daily ET data which are not subject to errors in assessing soil-water movement and the relative proportion of soil evaporation and transpiration can be estimated.

Reference ET

Various reference ET's can be used with Eq. [1] to develop crop coefficients. When these coefficients are subsequently used to calculate crop ET, the same type of $E_{TR}$ should be used. In the past various forms of "potential ET", intended to describe near maximum ET, were used in developing crop coefficients. However, because of ambiguities in describing and interpreting potential ET, particularly in arid climates, the term "reference crop ET" with the reference crop specifically noted is recommended (Perrier 1979).

Doorenbos and Pruitt (1977) present detailed procedures for estimating $E_{TR}$ for grass, which they define as "the rate of evapotranspiration from an extensive surface of 8-15 cm tall green grass cover of uniform height, actively growing, completely shading the ground, and not short of water". They list general crop coefficients adapted for use with grass $E_{TR}$.

Alfalfa $E_{TR}$ was suggested for use in arid climates for irrigation scheduling procedures (Jensen et al. 1971). Alfalfa $E_{TR}$ is defined as daily alfalfa ET when the crop occupies an extensive surface, is actively growing, at least 30-cm tall and standing erect, and is well watered so that soil water availability does not limit ET. Wright and Jensen (1972) used lysimeter ET data to develop procedures for estimating alfalfa $E_{TR}$ from meteorological data. These procedures were later refined by Wright (1981). Alfalfa ET is usually greater than clipped grass ET, particularly under dry windy conditions, and may be preferable for arid regions because alfalfa is capable of near maximum ET rates when there is considerable advective sensible heat input from the air.

Estimating Crop ET

In practice, Eq. [1] is rewritten to solve for crop ET or $E_{TR}:

$$E_{TC} = K_c E_{TR} \quad [2]$$

where $K_c$ is an experimentally derived crop coefficient and $E_{TR}$ is estimated or measured in some appropriate manner. Problems sometimes occur in applying this concept because of misunderstandings or lack of attention to the details of the methods used in deriving $K_c$. The same type of $E_{TR}$ should be used to estimate $E_{TC}$ from climatic data as was used to determine $K_c$ and the time-scale should be similar. When procedures and coefficients developed for a given climatic area are applied elsewhere, testing in advance along with any adjustment of functional relationships as may be needed. A satisfactory degree of accuracy in estimating $E_{TC}$, i.e. ± 10%, generally requires careful adherence to the procedures and precautions to be discussed.

Methods available for estimating $E_{TR}$ for use with Eq. [2] depend on data availability and local circumstances. Methods for estimating ET based solely on temperature are generally inadequate for arid or semiarid regions. Several suitable procedures for estimating irrigation water requirements have been reviewed in detail (Jensen 1974).

In developing guidelines for the determination of crop water requirements for application around the world, to fit various needs and availability of data, Doorenbos and Pruitt (1977) selected four methods for estimating $E_{TR}$, namely the (1) Blaney-Criddle, (2) radiation, (3) Penman combination equation and (4) pan evaporation methods. They developed correction coefficients for each method to adjust to a unified grass reference ET so that a single set of crop coefficients would suffice.

The Doorenbos and Pruitt version of the Blaney-Criddle method is considerably revised and for clarity could be referred to as the "FAO Blaney-Criddle" method to distinguish it from the original method of Blaney and Criddle (1950), and the widely used modified method developed by the USDA, Soil Conservation Service (1967). Versions of this method have been used extensively because of the relative availability of the data but the appropriate calibrations or adjustments have not always been applied. The monthly crop coefficients used with the original and SCS versions are different from the ET crop coefficient of Eq. [1] because a true reference ET is not used.

Doorenbos and Pruitt recommend the Penman combination equation method (Penman, 1960) for areas where measurements of temperature, humidity, wind and sunshine duration or radiation are available. While their procedures provide estimates of daily grass $E_{TR}$, other versions of the combination equation are available for estimating alfalfa $E_{TR}$ (Wright and Jensen 1972, Wright 1981). Specific wind functions are recommended for local conditions for the most satisfactory results (Slater and McIntyre 1961). From a comparison of 16 methods for estimating ET at various locations around the world, the combination methods, with calibration of the wind and vapor deficit terms, agreed best with lysimeter-measured ET (see chap. VII, Jensen 1974). The combination methods usually paralleled measured ET and displayed the best overall fit even without such calibration.

**ET Crop Coefficients**

**Previous Crop Coefficients**

In a sense, three sets of crop coefficients have been developed from the crop water requirement and irrigation scheduling research at Kimberly, Idaho, as data and methods were developed and needs changed. The crop coefficients originally used with the USDA-ARS Computerized Irrigation Scheduling Program (Jensen et al. 1971) were developed primarily from soil sampling data. These data, collected at various research locations, were generally for 5-15 day intervals. Each point on the crop curve, therefore, represented a mean for that period. Rapid changes such as occur with wetting or drying of the soil surface and crop development were dampened. Contributions of evaporation from wet soil were partially included in the measured ET since the sampling period usually began 2 or 3 days after an irrigation or period of significant rainfall. The procedures for estimating $E_{TR}$, then referred to as potential ET and frequently noted as $E_{TP}$ or $E_*$, were based on the combination equation with the wind function of Penman (1963).
Alfalfa Reference ET

Subsequent research indicated that the Penman wind function did not fit arid climatic conditions, so procedures were developed from measured net radiation and lysimeter ET data to permit estimating an alfalfa \( E_{\text{tf}} \) for arid regions (Wright and Jensen 1972). Lysimeter ET data were also utilized, as they became available, in revising crop coefficients which were provided to those using the scheduling program. A set of mean crop coefficients, based on alfalfa \( E_{\text{tf}} \) and denoted by \( K_{\text{cb}} \), were summarized for use in estimating irrigation water requirements for the type of crops grown in Southern Idaho (see Table 6.5, Jensen 1974). Some of these were essentially unchanged from the original coefficients of the scheduling program and some were revised according to results of lysimeter ET studies.

Since concurrent ET research had indicated that wet soil surfaces had a pronounced effect on ET, procedures were included in the USDA-ARS Irrigation Scheduling Program to adjust the crop coefficient for wet soil surfaces (Jensen et al. 1971). However, since the ET data used to develop the initial crop coefficients had also included some wet soil evaporation, this adjustment sometimes resulted in an overestimation of crop ET. Overestimation was also possible if the revised wind function of Wright and Jensen (1972) was used with the crop coefficients developed with the lower ET estimates of the Penman equation. Later comparisons with lysimeter ET data indicated overestimates early and late in the growing season with the developed procedures. Therefore, several years of lysimeter alfalfa ET and corresponding meteorological data were used to develop improved procedures for estimating alfalfa \( E_{\text{tf}} \) throughout the season (Wright 1981, 1982; see also Burman et al. 1980, 1981).

**Basal ET Crop Coefficients**

The revised procedures for estimating alfalfa \( E_{\text{tf}} \) and the lysimeter ET data available for most of the other irrigated crops typical of Southern Idaho, were used to develop a revised set of ET crop coefficients (Wright 1979, 1981). These were designed to represent dry soil surface conditions and were specifically called "basal ET crop coefficients", denoted by \( K_{\text{cb}} \). In following discussions, to emphasize this property and differentiate from previous versions. The experimentally derived values of \( K_{\text{cb}} \) were previously listed along with a similar set of basal ET crop coefficients developed by W. O. Pruitt from his lysimeter data and a grass \( E_{\text{tr}} \) for Davis, California (Burman et al. 1980).

Numerical adjustment of \( K_{\text{cb}} \) for the effects of surface soil wetness and soil drying properties can be accomplished with:

\[
K_c = K_{\text{cb}} + (1 - K_{\text{cb}})[1 - (t/t_d)]^{1/2} (f_w)
\]  

where \( K_c \) is the adjusted crop coefficient, \( K_{\text{cb}} \) is as previously defined, \( t \) is the number of days after major rain or irrigation, \( t_d \) is the usual number of days for the soil surface to dry, and \( f_w \) is the relative portion of the soil surface originally wetted. Values of \( K_{\text{cb}} \) for the times in question are used with this equation, which has a maximum value of 1. If irrigation is completed before noon, then \( t = 0 \) for that day; otherwise \( t = 0 \) for the following day. Data indicate that for heavy surface irrigations, \( f_w = 1.0 \) while for lighter irrigations, such as every other furrow and wetting only to the plant row, \( f_w = 0.5 \). For sprinkler irrigation or precipitation amounting to several days of ET, \( f_w = 1.0 \); otherwise progressively less. Kimberly ET data indicate that with bare soil or little crop cover at least 5 days elapse after major wetting of the soil surface before \( K_c \) returns to the basal level, thus \( t_d = 5 \) days or longer. For sandy soils, \( t_d \) is probably 3 or less and for clay loams probably 7 or more.

Since the decline in soil evaporation is related to the reciprocal of the square root of time, most of the adjustment by Eq. 3 takes place in the first few days after wetting the soil. Sprinkler irrigation completely wets the soil surface and results in higher ET following irrigation with partial crop cover than when row crops are furrow irrigated and the soil surface is only partially wetted. The general nature of the \( K_{\text{cb}} \) curve and examples of the adjustments provided with this equation are shown in Fig. 1. Some procedures for adjusting \( K_{\text{cb}} \) for the effects of limiting soil water have been presented previously (Jensen et al. 1971). Others could be developed for given soil and crop situations when data on the effects of inadequate soil water on ET are available.

![Image of a graph showing the adjusted crop coefficient (Kc) as a function of time (t) after irrigation. The graph includes a curve labeled "Complete Irrigation or Rain" and a curve labeled "Partial Irrigation." The x-axis represents percent time and the y-axis represents crop coefficient. The graph also includes a table with columns for percent time and complete irrigation or rain.](image)

**Fig. 1.** Generalized basal ET crop coefficient (Kcb) curve showing means of calculating the crop coefficient (Kc) for wet surface soil by Eq. [3]

The use of the recent procedures for estimating \( E_{\text{tf}} \), for either alfalfa or grass, and the new basal ET crop coefficients, along with procedures for accounting for extra wet evaporation and/or decreased transpiration due to limiting soil water, provides a consistent set of procedures for good estimates of crop ET where adequate data are available. Intermixing of coefficients and methods as they were developed along the way can lead to major errors.

**NEW MEAN CROP COEFFICIENTS**

Even though the basal ET crop coefficients allow for accurate estimates of daily crop ET, it is sometimes impractical to estimate wet soil effects and estimates of total seasonal water requirements are sometimes needed for a general area. Consequently, mean crop coefficients were developed using the ET data set obtained with lysimeters at Kimberly to meet these needs and are listed in Table 1. Corresponding crop development data are shown in Table 2. The mean crop coefficients of Table 1 are listed on a normalized time scale, similarly to the crop coefficients previously developed for the USDA-ARS Irrigation Scheduling Program (Table 6.5, Jensen 1974). Time from planting until full cover is considered on a percentage basis and time after full cover as elapsed days. This normalized time base helps fit a crop curve to different planting dates since large differences in planting date usually have only a minor effect on the date full cover is reached.

The data of Table 1 are for typical crop development and local management practices where root zone soil moisture does not limit crop growth and for
Table 1. Daily Mean ET Crop Coefficients \( (K_c) \), for normal irrigation and precipitation conditions, for use with alfalfa reference ET for crops grown in an arid region with a somewhat semiarid climate. Coefficients were experimentally determined from weighing lysimeter ET data, Kimberly, Idaho, 1968-1978.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Time from planting to effective cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Barley</td>
<td></td>
</tr>
<tr>
<td>Peas</td>
<td></td>
</tr>
<tr>
<td>Sugar Beets</td>
<td></td>
</tr>
<tr>
<td>Potatoes</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td></td>
</tr>
<tr>
<td>Beans</td>
<td></td>
</tr>
<tr>
<td>Winter Wheat</td>
<td></td>
</tr>
</tbody>
</table>

\[ K_c \]

Table 2. Dates of crop growth stages identifiable in the field for use with crop curves, Kimberly, Idaho, 1968-1978.

<table>
<thead>
<tr>
<th>Month/day</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Planting</td>
</tr>
<tr>
<td>Sugar Beets</td>
<td>4/25</td>
</tr>
<tr>
<td>Beans</td>
<td>5/25</td>
</tr>
<tr>
<td>Winter Wheat*</td>
<td>(2/15)</td>
</tr>
<tr>
<td>Alfalfa (1st)</td>
<td>0/1</td>
</tr>
<tr>
<td>(3rd)</td>
<td>8/01</td>
</tr>
</tbody>
</table>

*Effective dates in parentheses. Crop planted on 10/10 and emerged 10/25.
**Effective planting date for established alfalfa is date growth begins in spring or harvest of preceding crop. Final harvest is date crop becomes dormant.

Because of the interest in using pan evaporation measurements to estimate crop ET, the evaporation from the U. S. Class A pan maintained by the U. S. Weather Service at Kimberly was compared with alfalfa \( K_c \), as shown in Fig. 2. This pan is sited in an irrigated grass plot about 60 m squared and is surrounded by irrigated fields planted to various crops each year. The daily pan evaporation measurements in Fig. 2 are 7-day means of daily values for a 14-year period and thus represent considerable averaging. The ratio gradually decreased in early spring as the growth around the pan site began to grow and ET increased in surrounding fields. It was fairly steady at about 1.1 during the central portion of the growing season and gradually increased in late summer.
Fig. 2. Seven-day running means of the ratio of class A pan evaporation ($E_{pan}$) to alfalfa $E_T$ for a 14-year period.

and early fall as surrounding crops matured and conditions favored increased sensible heat advection from surrounding dry areas. The reciprocal of this ratio provides a "pen factor" to adjust pan evaporation to alfalfa $E_T$. However, since a pan and a crop respond differently to daily changes in meteorological conditions, this method provides averages probably only suitable for periods of 10 days or longer. The recommendations and procedures for using evaporation pans as summarized by Doorenbos and Pruitt (1977) should be closely followed if pans are to be used.

APPLICATION OF ET CROP COEFFICIENTS

The improved ET crop coefficients developed from lysimeter data should be usable in estimating crop ET in areas with climates similar to that of southeast Idaho because the crop coefficient is a relative factor and differences in water use due to climate can be accounted for in the computed reference ET. They should also be usable in areas with different climates if verified procedures are used to estimate the reference ET or if correction factors are used to adjust this reference. While there is some variation in the rate of crop development at various locations and on different years, because of seasonal differences, the crop curve can be shifted to account for this variation if a few simple crop development characteristics are occasionally monitored. The newer curves developed from lysimeter data should be used with the appropriate recently developed procedures for calculating reference crop ET. When properly applied, the newer crop coefficients are expected to increase the accuracy of irrigation scheduling procedures and the estimates of crop water use from historical records.

REFERENCES


15. Wright, J. L. 1982. Alfalfa reference evapotranspiration calculated from meteorological data in arid irrigated areas. (In review)
