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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:

$$K_c = E_{tc}/E_{tr} \qquad [1]$$

in which K_c = the dimensionless crop coefficient for a particular crop at a given growth stage and soil moisture condition, E_{tc} = the daily crop ET, and E_{tr} = the daily reference ET. Ideally E_{tr} 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_{tr} 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

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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 less than 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}:

$$E_{tc} = K_c \; E_{tr} \qquad [2]$$

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 is advisable 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, 1948) 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 (Slatyer and McIlroy 1961). From a comparison of 16 methods for estimating ET at several locations around the world, the combination methods, with calibration of the wind and vapor deficit terms, agreed best with lysimeter-measured ET (see chap. VIII, 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 damped. 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_{tr} 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_{tr} and denoted by K_{co}, 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_{tr} throughout the season (Wright 1981, 1982; see also Burman et al. 1980, 1981).

Basal ET Crop Coefficients

The revised procedures for estimating alfalfa E_{tr} 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_{cb} in following discussions, to emphasize this property and differentiate from previous versions. The experimentally derived values of K_{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_{tr} for Davis, California (Burman et al. 1980).

Numeric adjustment of K_{cb} for the effects of surface soil wetness and soil drying properties can be accomplished with:

$$K_c = K_{cb} + (1 - K_{cb})[1-(t/t_d)^{1/2}](f_w) \qquad [3]$$

where K_c is the adjusted crop coefficient, K_{cb} is as previously defined, t = the number of days after major rain or irrigation, t_d = the usual number of days for the soil surface to dry, and f_w = the relative portion of the soil surface originally wetted. Values of K_{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 irrigations 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_{cb} curve and examples of the adjustments provided with this equation are shown in Fig. 1. Some procedures for adjusting K_{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.

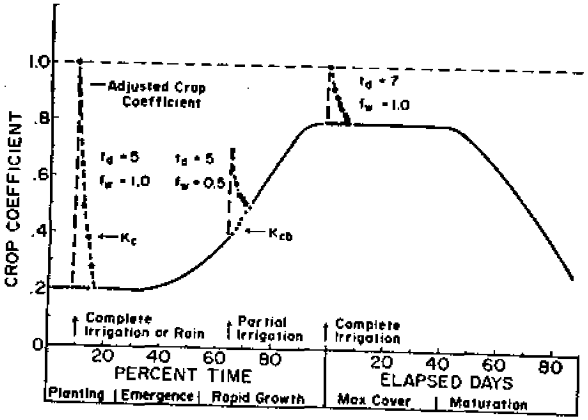

Fig. 1. Generalized basal ET crop coefficient (K_{cb}) curve showing means of calculating the crop coefficient (K_c) for wet surface soil by Eq. [3]

The use of the recent procedures for estimating E_{tr}, 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 accuratcestimates 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 temperate intermountain climate. Coefficients were experimentally determined from weighing lysimeter ET data, Kimberly, Idaho, 1968-1978.

	Mean ET crop coefficients, K_c									
	Time from planting to effective cover (%)									
Crop	10	20	30	40	50	60	70	80	90	100
Barley	0.30	0.30	0.32	0.40	0.65	0.85	0.95	0.99	1.00	1.00
Peas	0.30	0.30	0.30	0.36	0.43	0.51	0.58	0.73	0.85	0.93
Sugar Beets	0.30	0.30	0.30	0.30	0.30	0.32	0.40	0.60	0.80	1.00
Potatoes	0.30	0.30	0.30	0.31	0.44	0.57	0.69	0.77	0.82	0.85
Corn	0.30	0.30	0.30	0.30	0.32	0.42	0.55	0.70	0.85	0.95
Beans	0.30	0.30	0.30	0.35	0.45	0.55	0.68	0.80	0.90	0.95
Winter Wheat	0.30	0.30	0.50	0.75	0.90	0.98	1.00	1.00	1.00	1.00
	Days after effective cover									
	10	20	30	40	50	60	70	80	90	100
Barley	1.00	1.00	0.90	0.50	0.25	0.15	-	-	-	-
Peas	0.90	0.65	0.53	0.35	0.20	0.15	-	-	-	-
Sugar Beets	1.00	1.00	1.00	0.98	0.94	0.89	0.85	0.80	0.74	0.60
Potatoes	0.85	0.83	0.81	0.79	0.75	0.70	0.65	0.50	0.35	0.25
Field Corn	0.96	0.95	0.94	0.90	0.85	0.79	0.74	0.35	0.25	-
Sweet Corn	0.93	0.93	0.90	0.85	0.75	0.58	0.40	0.20	-	-
Beans	0.95	0.90	0.67	0.33	0.15	0.10	-	-	-	-
Winter Wheat	1.00	1.00	1.00	0.95	0.55	0.25	0.15	0.15	-	-
	Time from new growth to harvest (%)									
	10	20	30	40	50	60	70	80	90	100
Alfalfa (1st)	0.70	0.82	0.91	0.96	1.00	1.00	0.98	0.96	0.95	0.95
(2nd & 3rd)	0.40	0.50	0.80	0.96	0.98	1.00	1.00	0.98	0.95	0.95
(4th)	0.40	0.44	0.60	0.65	0.55	0.50	0.45	0.35	0.30	0.25

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

	Month/Day						Days	
	Planting	Emergence	Full Cover	Heading or Bloom	Ripening	Harvest	Planting to Full Cover	Full Cover to Harvest
Barley	4/4	4/15	6/20	6/20	7/15	8/10	80	55
Peas	4/10	4/25	6/05	6/15	7/05	7/25	55	50
Sugar Beets	4/15	5/10	7/10	-	-	10/15	85	95
Potatoes	4/25	5/25	7/10	7/01	9/20	10/10	75	90
Field Corn	5/5	5/25	7/15	7/30	9/10	9/20	72	70
Sweet Corn	5/5	5/25	7/15	7/20	8/15	8/15	72	30
Beans	5/22	6/05	7/15	7/05	8/15	8/30	55	45
Winter Wheat*	(2/15)	(3/01)	6/5	6/5	7/15	8/10	(110)	60
Alfalfa (1st)#	4/01					6/15		76
(2nd)	6/15					8/01		46
(3rd)	8/01					9/15		46
(4th)	9/15					10/30		46

*Effective dates in parenthesis. 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.

the rainfall and irrigation patterns of the area. The usual precipitation pattern consists of light rains during the spring with a dry summer averaging about 20, 25, 25, 5, 13, 13 and 16 mm per month for the April-October period, respectively. Five or more irrigations are required throughout the season for most crops. The mean K_c's of Table 1 can be used directly in Eq. [2] without adjustment for soil wetness by Eq. [3]. For the early portion of the season before major crop development, a mean coefficient of 0.3 represents the average conditions experienced at Kimberly including soil evaporation from residual winter season soil moisture, spring precipitation, and preplant or pre-emergence irrigations. When wetter than normal soil conditions exist throughout the period, a general coefficient of 0.4 is appropriate until the crop emerges and begins rapid growth. For unusually dry conditions, a value of 0.2 is indicated.

The several alfalfa harvests are considered individually because of the climatic differences for each growth period. The growth period is from new growth, or harvest to harvest. Thus K_c for alfalfa reaches 1.0 at a normalized time scale value of 50%. Alfalfa K_c declines slightly before harvest because of lodging of the crop. The mean K_c values of Table 1 were developed from the same data base as the previously published K_{cb} values (Wright 1979, 1981) and are, of course, generally higher during the period of crop development and at full cover, because of the inclusion of wet soil evaporation.

In the case of winter wheat, the procedure used in normalizing the time scale for the other crops is not appropriate. Therefore, an effective planting date of mid-February and an effective emergence of about March 1 was assumed as shown in Table 2. This corresponds quite closely to the time when winter wheat passes from the cold weather dormant condition to greenup and the beginning of rapid leaf area expansion.

Dates for crop development stages easily recognizable in the field are listed for the various crops in Table 2, since it is often difficult to determine when a crop reaches effective full cover. In the case of winter and spring cereals, the most easily detectable stage is that of heading. Normal dates of heading are usually known in an area. If there are seasonal differences, adjustments can be made. For the row crops: beans, sugarbeets, potatoes and corn, the effective full cover date is when the leaves of plants in adjacent rows intermingle so that soil shading becomes nearly complete. If this does not occur, the maximum value of K_c should be scaled down. During this period of crop development, leaf area expansion is very rapid and the exact day of effective cover is not critical. Winter wheat, spring cereals, and sugarbeets at full cover had crop coefficients similar to full cover alfalfa. The other crops peaked at values of about 0.95, except for potatoes which peaked at about 0.85. Most of the crops showed a gradual decline after the peak because of lodging or leaf senescence. With maturation there was a rapid decline in K_c. The low potato value is assumed to be due to physiological differences of the plant as it was an excellent crop. However, others have found higher values for potatoes (Doorenbos and Pruitt 1977, Burman et al. 1980).

PAN EVAPORATION

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 E_{tr}, as shown in Fig. 2. This pan is sited in an irrigated grass plot about 40 m square and is surrounded by irrigated fields planted to various crops each year. The daily ratios plotted 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 grass 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

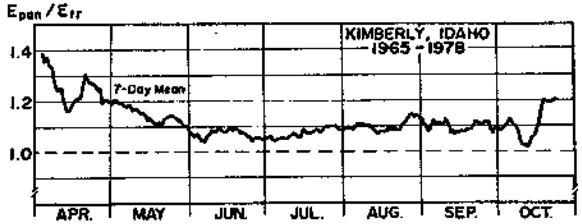

Fig. 2. Seven-day running means of the ratio of class A pan evaporation (E_{pan}) to alfalfa E_{tr} for a 14-year period.

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 "pan factor" to adjust pan evaporation to alfalfa E_{tr}. 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 south-central 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 crop 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.

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