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NEW EVAPOTRANSPIRATION CROP COEFFICIENTS[a]

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ABSTRACT: Improved crop coefficients for various Pacific Northwest irrigated crops were developed for estimating crop evapotranspiration (ET) from estimates or measurements of reference ET. Reference ET was based on that for well watered, actively growing alfalfa with sufficient growth for near maximum ET in arid, irrigated regions. ET for the alfalfa reference crop and other crops was measured with sensitive weighing lysimeters at a field site near Kimberly, Idaho. The new crop coefficients are basal or minimal coefficients for conditions when soil evaporation is minimal but root-zone soil moisture is adequate. When combined with improved estimates of evaporation from wet soils, they should permit more accurate estimates of daily crop ET, more accurate irrigation scheduling, and more reliable estimates of crop water requirements. Curves were developed for alfalfa, potatoes, snap beans, sugarbeets, peas, sweet and field corn and winter and spring cereals.

INTRODUCTION

Improved crop coefficients for various irrigated crops in the Pacific Northwest were developed to permit more accurate estimates of daily and seasonal irrigation water requirements. Estimates of daily evapotranspiration, ET, or consumptive use, CU, are extensively used in irrigation scheduling and in determining regional irrigation water requirements.

Crop coefficients can be used to estimate actual water use for a particular crop from estimates or measurements of a potential or reference ET. They are empirical ratios of crop ET to some reference ET, and are generally derived from experimental data. The determination of a reference evaporation or ET for a single reference crop, like alfalfa, and the use of empirical crop coefficients provides a conservative means of estimating ET for other crops at progressive stages of growth. The distribution of the crop coefficients for a particular crop as a function of time constitutes a crop curve.

Crop coefficients are used in computerized irrigation scheduling programs such as the United States Department of Agriculture-Agricultural Research Service Irrigation Scheduling Program described by Jensen, et al. (12). This program provides estimates of when and how much to irrigate by using daily weather data and relatively simple data on the crop and soil situation. A daily

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reference ET is computed with a modified Penman combination equation, using coefficients for the aerodynamic term appropriate for arid irrigated areas and procedures for estimating net radiation from solar radiation data.

The new crop coefficients presented in this paper were derived from daily meteorological and ET data obtained with two sensitive weighing lysimeters at a field site near Kimberly, Idaho during the 11 year period, from 1968–78. The large data base of accurate ET measurements permitted developing more accurate crop curves than those used in the original USDA-ARS scheduling program which were previously developed from soil moisture data. Also, the new coefficients are daily basal crop coefficients, representing conditions when soil evaporation is minimal, but the availability of soil water within the root zone does not limit plant growth or transpiration, as compared with the previous mean crop coefficients. The basal coefficients can be adjusted to represent a higher proportion of evaporation from a wet soil surface following rain or irrigation.

Alfalfa was selected as the reference ET crop because it has relatively high ET rates in arid areas where there is considerable advective sensible heat input from the air (25). Basal crop curves were developed for alfalfa, potatoes, snap beans, sugar beets, peas, sweet and field corn, and winter and spring cereals. The new curves, when combined with improved procedures for estimating reference ET and ET from wet soils, should improve the accuracy of estimating crop water requirements and soil-water depletion.

PROCEDURES

Daily ET for the various crops was measured with two sensitive weighing lysimeters installed at an Evapotranspiration Field Site also equipped with meteorological instrumentation to provide energy balance data. The alfalfa reference crop was grown for several years followed by the other crops. Daily alfalfa ET and energy balance data were first used to provide local calibration and verification of procedures for estimating reference ET with the modified Combination Equation. Daily reference ET was then computed for the entire period from daily weather data. Crop curves were derived from the computed reference ET and the lysimetrically measured daily crop ET.

Measurement of ET and Energy Balance.—The two lysimeters were similar to the one described by Ritchie and Burnett (19). Each soil tank, six ft sq and four ft deep (1.83 m × 1.22 m), was supported on a sensitive mechanical platform scale equipped with a counter balance mechanism. Net weight of the tank was transferred to an electronic load cell. Weight changes resulting from ET, precipitation, or irrigation were recorded throughout the growing season along with associated energy balance and other meteorological measurements with an automatic data acquisition system.

The first lysimeter was installed in 1968 in the center of a 6.3-acre (2.5-ha) field, and the second in 1971 in a 5.5-acre (2.2-ha) field immediately west of the first. The crops and row spacing are shown in Table 1. Dates of planting, emergence, beginning of rapid growth, bloom, visual closing of the crop canopy between rows, ripening, and surface soil wetness, were recorded. Plant height, leaf area index (LAI), and total dry matter accumulation, were periodically measured for field samples, but only nondestructive crop measurements were made on the lysimeters prior to harvest.

The water content of the soil within the lysimeter and the surrounding field was monitored with tensiometers. Irrigations were generally scheduled so that water availability within the crop root zone would not limit transpiration. The potato crop was irrigated with a solid set sprinkler system while all other crops were furrow irrigated similarly to conventional practices of the region. The necessary amount of water was added to the surface of the lysimeters with a small pump to keep the soil-water content of the field and tank similar.

Net radiation was measured at the lysimeter site with FRINET net radiometers. Solar radiation during the period of study, as reported by Wright (22), was measured at the lysimeter site, and the U.S. Weather Service Station, with various models of Eppley solar pyranometers. All the data were adjusted to a single Epply Precision Pyranometer (Model 15).

TABLE 1.—Cropping Sequence and Row Spacing of Lysimeter Fields Used for ET Studies at Kimberly, Idaho

	Lysimeter Number 1		Lysimeter Number 2	
Year (1)	Crop (2)	Spacing, in inches (3)	Crop (4)	Spacing, in inches (5)
1968	alfalfa	broadcast	—	—
1969	alfalfa	broadcast	—	—
1970	alfalfa	broadcast	—	—
1971	alfalfa	broadcast	—	—
1972	potatoes	36	alfalfa	broadcast
1973	snap beans	24	alfalfa	broadcast
1974	snap beans	24	alfalfa	broadcast
1975	sugar beets	22	alfalfa	broadcast
1976	sweet corn	30	field corn	30
1977	garden peas/ winter wheat	22 6	field corn	30
1978	winter wheat	6	spring barley	6
1979	spring wheat	7	spring wheat	7

Note: Potatoes in 1972 were sprinkle irrigated; all other crops were furrow irrigated. 1 inch = 2.54 centimeter.

Climatic Data.—Some meteorological data used with the Combination Equation were obtained at the U.S. Weather Service station located at the research center. This is a well-sited grass plot surrounded by research plots and fields that are planted to various crops from year to year. The site is in the interior of an irrigated area about 30 mile (48 km), in the prevailing wind direction, from nonirrigated land. Records have been obtained at the station since about 1964 as part of an agricultural weather advisory service. The clipped grass plot is periodically flood irrigated and is about 150 ft × 120 ft (45 m × 36 m) with the instruments mounted inside a wire fenced enclosure of 45 ft × 66 ft (14 m × 20 m). Data used were daily maximum and minimum air temperatures; 0800 hr dewpoint temperature calculated from psychrometric wet- and dry-bulb temperatures; and daily wind-travel measured at 12 ft (3.66 m).

Estimation of Reference ET.—Daily reference ET was computed from daily meteorological data with a combination equation patterned after that of Penman (14). Procedures similar to those of Jensen, et al. (11) and Wright and Jensen (25,23) were used to adapt the equation to Kimberly conditions. The theoretical background and methods of applying these results have been discussed (4) and have been used for several years in irrigation scheduling (9). During the development of the new crop coefficients, these procedures and calibrations were further modified to improve estimates of net radiation and reference ET throughout the growing season, particularly the early and later portions.

The procedures for estimating reference ET are briefly listed here for clarity and because the resulting crop coefficients are dependent upon these methods. Daily ET and other data selected for development and validation of functions for estimating reference ET were from periods when the alfalfa crop was well watered, actively growing, and at least 30 cm tall; so that measured ET was essentially at the maximum expected level for the existing climatic conditions. The modified combination equation used was:

$$E_{tr} = \left[\frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 15.36\, W_f (e_s - e_d)\right](L)^{-1} \quad \ldots\ldots\ldots (1)$$

in which E_{tr} = the computed reference evaporative flux on a water depth equivalent basis, R_n = the net radiation, G = the soil heat flux, W_f = a wind function and is dependent upon daily wind travel, $(e_s - e_d)$ = the mean daily saturation vapor pressure deficit, Δ = the slope of the saturation vapor pressure temperature curve, γ = the psychrometric constant, 15.36 = a constant resulting from unit conversion, and L = the latent heat of evaporation. L was calculated by

$$L = (595 - 0.51\, T_a)\, 0.1 \quad \ldots\ldots\ldots (2)$$

in which T_a = the mean daily air temperature and the coefficient 0.1 converts E_{tr} to millimeters per day. The terms $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$, whose sum equals one, are temperature and pressure dependent, and weight the two components of the equation. They were calculated by:

$$\Delta = 33.8639\,[0.05904\,(0.00738\, T_a + 0.8072)^7 - 3.42 \times 10^{-5}] \quad \ldots\ldots\ldots (3)$$

which is valid for $T_a \geq -23°$ C, and

$$\gamma = (c_p\, P)\,(\overset{0.22}{\cancel{0.622}}\, L)^{-1} \quad \ldots\ldots\ldots (4)$$

in which c_p = the specific heat of air and P = the atmospheric pressure. The mean values used for Kimberly were c_p = 0.24 cal $g^{-1}\,°C^{-1}$ and P = 875 mbar.

The soil heat flux, G, was estimated from changes in daily air temperature by

$$G = (T_a - T_p)\, c_s \quad \ldots\ldots\ldots (5)$$

in which T_p = the mean air temperature for the preceding three days, and c_s = an empirical, specific heat coefficient for the soil. For Kimberly, c_s on a surface soil basis is approximately nine cal $cm^{-2}\,°C^{-1}$.

Since measured R_n, as required for Eq. 1, was not available for a continuous crop of alfalfa, and since actual R_n measurements are usually not available to those using the irrigation scheduling program, R_n was estimated from daily solar radiation, temperature and humidity data by

$$R_n = (1 - \alpha)\, R_s - R_b \quad \ldots\ldots\ldots (6)$$

$$R_b = \left(a \frac{R_s}{R_{so}} + b\right) R_{bo} \quad \ldots\ldots\ldots (7)$$

$$R_{bo} = (a_1 - 0.044\sqrt{e_d})(11.71 \times 10^{-8})\left(\frac{T_2^4 + T_1^4}{2}\right) \quad \ldots\ldots\ldots (8)$$

in which R_s = the incident solar radiation, α = the crop albedo, R_b = net outgoing longwave radiation, R_{so} = clear day solar radiation, R_{bo} = net clear day outgoing longwave radiation, a_1 = a parameter for estimating the effective emittance of the atmosphere, e_d = the saturation vapor pressure at mean dewpoint temperature, (11.71×10^{-8}) = the Stefan-Boltzman constant, and T_2, T_1 = maximum and minimum daily Kelvin air temperature.

Crop albedo was varied with date, to account for sun angle effects. For mostly clear days when $(R_s/R_{so}) > 0.7$, albedo was calculated by

$$\alpha = 0.29 + 0.06\ \mathrm{SIN}\ [30\,(M + 0.0333\,N + 2.25)] \quad \ldots\ldots\ldots (9)$$

in which M = the number of the month (1–12), N = the day of the month, and the sine function is in degrees. M and N are combined to approximate the day of the year in a manner so that the sine function equals −1 on June 21; thus α = 0.23, and 0 on September 21 when α = 0.29. An approximately equivalent term for Eq. 9 is SIN $(D + 96)$ in which D = the day of the year. An α of 0.30 was used for cloudy days when $(R_s/R_{so}) \leq 0.7$.

Coefficients used for Eq. 7, when $(R_s/R_{so}) > 0.7$, were a = 1.126, and b = −0.07. When $(R_s/R_{so}) \leq 0.7$, coefficients were a = 1.017 and b = −0.06.

The coefficient a_1 of Eq. 8 was empirically varied to account for seasonal changes in the earth's net emissivity, because of changes in day length and upper atmospheric conditions, by

$$a_1 = 0.26 + 0.1 \exp\{-[0.0154\,(30\,M + N - 207)]^2\} \quad \ldots\ldots\ldots (10)$$

This is a "normal" distribution equation. The exponential term has a maximum value of 1 on June 27; thus a_1 = 0.36, and minimums of 0 on about March 1 and October 30, when a_1 = 0.26. The approximate day of the year equivalent is: $\exp\{-[0.0154\,(D - 180)]^2\}$.

The wind function of Eq. 1 was obtained by

$$W_f = a_w + b_w\, U_z \quad \ldots\ldots\ldots (11)$$

in which a_w and b_w = empirical coefficients dependent upon the aerodynamic characteristics of the crop surface and the general nature of the location as it affects sensible heat advection; and U_z = the 24 hr daily wind at height z. Time dependent functional relationships were developed for Kimberly, Idaho, to permit varying W_f to account for the seasonal changes in sensible heat advection. This is caused by changes in the dryness of arid surrounding areas, and changes in the relative proportion of daytime wind travel (the details of which are being prepared for publication):

$$a_w = 23.8 - 0.7865 D + 9.7182 \times 10^{-3} D^2 - 5.4589 \times 10^{-5} D^3$$

$$+ 1.42529 \times 10^{-7} D^4 - 1.41018 \times 10^{-10} D^5 \quad \ldots \ldots \quad (12)$$

$$b_w = -0.0122 + 5.2956 \times 10^{-4} D - 5.9923 \times 10^{-6} D^2$$

$$+ 3.4002 \times 10^{-8} D^3 - 9.00872 \times 10^{-11} D^4 + 8.79179 \times 10^{-14} D^5 \quad \ldots \ldots \quad (13)$$

Since b_w is dependent upon the height at which U is measured, which is 12 ft (3.66 m) at Kimberly, the coefficients as listed in Eq. 13 were adjusted for U_2 at two m by

$$U_2 = U_z \left(\frac{2}{z}\right)^{0.2} \quad \ldots \ldots \quad (14)$$

Values for dates of 4/15, 6/15, 8/15, 10/15, and a seasonal mean for a_w,

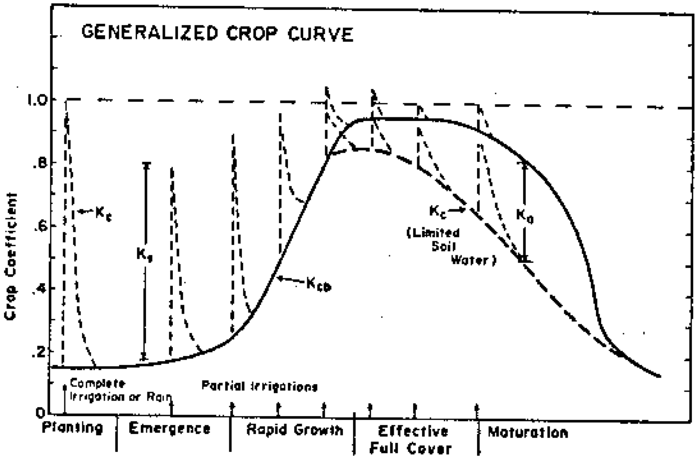

FIG. 1.—Generalized Basal Crop Coefficient, K_{cb}, Curve, Showing Surface Wetness Coefficient, K_s, and Available Water Coefficient, K_a, Used to Derive an Overall Crop Coefficient, K_c

0.49, 1.78, 0.95 0.49

by Eq. 12, are ~~0.74~~, ~~1.83~~, ~~1.01~~, ~~0.55~~, and 1.06, respectively; and for b_w, by Eq. 13, values are 0.0069, 0.0088, 0.0107, 0.0099, and 0.0091, respectively.

The vapor pressure deficit, $(e_s - e_d)$, of Eq. 1, was calculated from e_s as the average of the two saturation vapor pressures corresponding to the daily maximum and minimum air temperature, and e_d as the saturation vapor pressure for the measured 0800 hr dewpoint temperature, T_{dp}, is assumed to represent the daily average vapor pressure. The respective saturation vapor pressures were calculated by the empirical polynomial equation:

$$e = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4 + c_5 T^5 \quad \ldots \ldots \quad (15)$$

in which T = the respective Celsius temperature, $c_0 = 6.105$, $c_1 = 4.44 \times 10^{-1}$, $c_2 = 1.434 \times 10^{-2}$, $c_3 = 2.623 \times 10^{-4}$, $c_4 = 2.953 \times 10^{-6}$, and $c_5 = 2.559 \times 10^{-8}$.

Daily E_{tr} was computed accordingly for the growing season of the years 1968-78, using a programmable calculator with a disc memory subsystem.

Determination of Crop Coefficients.—Daily crop coefficients were calculated from the computed E_{tr} and daily crop ET, E_t, as measured with the lysimeters by

$$K_c = \frac{E_t}{E_{tr}} \quad \ldots \ldots \quad (16)$$

in which K_c = the dimensionless ET crop coefficient for the particular crop at the existing growth stage and surface soil moisture condition. A generalized basal crop coefficient curve was determined by manually fitting a curve to the time distributions of K_c representing conditions when the soil surface was dry, so that evaporation was minimal but the availability of soil water did not limit plant growth or transpiration. The basal crop coefficient K_{cb} can be adjusted for surface soil wetness by

$$K_{cc} = K_{cb} K_a + K_s \quad \ldots \ldots \quad (17)$$

in which K_{cc} = the adjusted daily crop coefficient, K_a = a coefficient dependent upon available soil moisture, and K_s = a coefficient to adjust for increased surface soil evaporation which occurs after rain or irrigation. Crop, ET, E_{tc}, can then be estimated by

$$E_{tc} = K_{cc} E_{tr} \quad \ldots \ldots \quad (18)$$

Such procedures were included in the USDA-ARS Irrigation Scheduling Program (12). Fig. 1 shows examples of a basal crop curve and the coefficients of Eqs. 17 and 18.

RESULTS AND REVIEW

Computation of Reference ET.—Initially, measured daily alfalfa ET, E_{ta}, was to be used as reference ET for calculating the crop coefficients while estimated E_{tr} was to be used only when alfalfa was not at full cover. However, for the eight years of data, E_{ta} was not at a maximum level during much of the season because of the time required for alfalfa to reach full cover in the spring and after cutting; and because of lodging caused by wind and rain. Furthermore, E_{ta} of the alfalfa variety grown on lysimeter No. 2 seldom reached that obtained with lysimeter No. 1; apparently because it had finer stems and tended to lodge earlier. Therefore, daily E_{tr} was used for the entire growing season as a continuous and consistent data base to obtain K_c by Eq. 16.

Comparisons of measured E_{ta}, when alfalfa was in a full cover condition, and computed E_{tr} showed good agreement throughout the season. The time dependent functions improve the accuracy of the estimates and are needed because of the seasonal differences in mesoscale atmospheric mixing and the inadequacy of meteorological measurements at the earth's surface to account for these. The weighting function $\Delta/(\Delta + \gamma)$ has a temperature imposed upper limit of about 0.7 at Kimberly, when based on mean temperature, which limits the contribution of the radiation term to calculated E_{tr} to that extent. However, the evaporative flux is frequently greater than R_n, occasionally even twice as great, so W_f provides a very important contribution for dry, windy conditions.

Seasonal trends in the performance of the combination equation have been noted by others. Pruitt and Doorenbos (16) showed for Davis, California, that for any given wind level, W_f values needed for the June-September period were almost double those required for December-March, while the April, May, October, and November values were in between. They reported similar results for most tested locations which were well away from the equator. Earlier, Penman and Schofield (15) had suggested incorporating a day length factor to provide weighting for the Penman equation for daytime conditions. Furthermore, the manner of calculating the vapor pressure deficit $(e_s - e_d)$, and other components of the equation, affects the derived W_f and thus, different W_f's are needed for the different derivations of $(e_s - e_d)$. The problems and dangers of mixing methodologies are well shown by Pruitt and Doorenbos in their Figs. five and seven. Doorenbos and Pruitt (7) used an overall correction factor based on humidity and wind conditions to provide local adjustment of the combination equation. They provide tables of the correction factor for various conditions. The time dependent wind function used in this study accomplishes a similar adjustment. However, the transferrability of this function to other locations is yet to be established. Despite these factors, the new crop coefficients are not affected since they are based on ET for alfalfa. Any reliable procedure for estimating daily reference alfalfa ET can be used with the new crop coefficients, such as the frequently used Jensen-Haise equation (8,10). That equation does not consider wind, however, and it should be realized that under quite windy conditions, any such equation will likely predict less alfalfa reference ET.

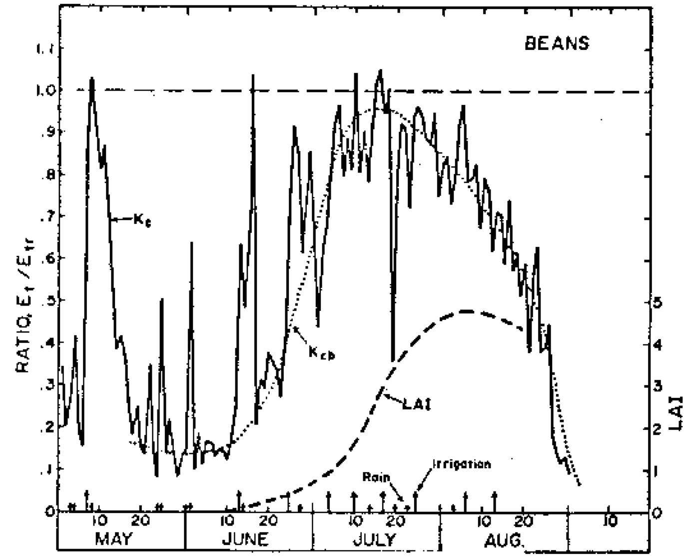

FIG. 2.—Daily Crop Coefficients, K_c, Calculated from Crop ET, E_t, Measured with Lysimeter; and Computed Reference ET, E_{tr}; Fitted Basal Crop Coefficient, K_{cb}, Curve; and Measured Leaf-Area-Index, LAI, for Snap Beans Raised to Maturity for Seed

Eqs. 6-10 allowed for changes in albedo and emittance during the season and improved the accuracy of R_n estimates. Previous procedures using constant albedo (25) gave reasonably good results on partly cloudy and clear days for the May-August period, but R_n was not accurately estimated on cloudy days, or the early and late periods in the growing season. This contributed to errors in the estimation of ET during those periods. Other research has shown that the albedo of vegetated land does indeed vary during the year (2,3,5,6).

Crop Coefficients.—Daily values of K_c, computed by Eq. 16, are shown in Fig. 2 for a crop of snap beans grown to maturity from seed, as an example of curves developed for all the crops. The manner of fitting the basal crop curve, K_{cb}, to the K_c data is also shown. The measured LAI, is shown to indicate the relationship of the crop curve to leaf area development. The increase in K_c, due to increased soil evaporation whenever the soil surface was moist following rain or irrigation prior to full cover, is evident. The preplant irrigation in May completely wetted the soil surface. Post emergence irrigations prior to full cover were partial, consisting of every other furrow, and only wetting over to the plants. Effects of surface wetness were minor after full cover was reached, until the crop ripened and was harvested.

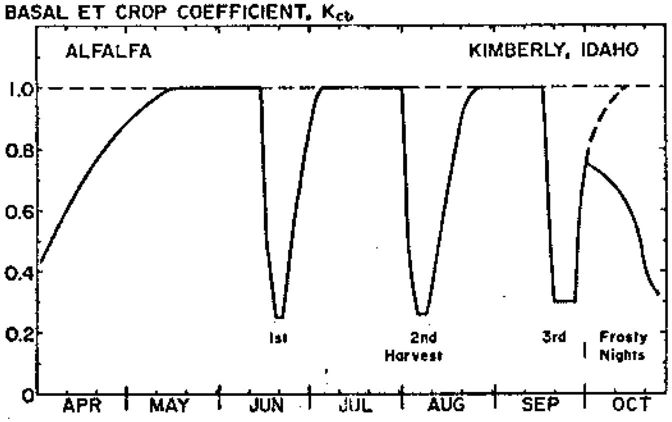

FIG. 3.—Average Basal Crop Coefficient Curve for Alfalfa

Maximum values of K_c, corresponding to effective full cover, usually occurred for most of the crops shortly after the rows closed, when the LAI reached 2.5-3. The crop coefficient then usually declined with time, even before ripening occurred, because of plant lodging and natural senescence. As some crops ripened, the soil surface was more exposed to sunlight and wind, so K_c then increased following a rain or irrigation. But the increase was not as great as before full cover because the ripened crop still shaded the soil. After full cover, K_{cb} was usually set equal to K_c until ripening began; then wet soil effects were considered. The precise determination of exactly when full cover occurred was not necessary since the growth rate of the crop was then very rapid and it was being irrigated frequently so that the soil surface was wet much of the time.

The average K_{cb} curves developed for alfalfa are shown in Fig. 3 and represent three years of results after the stand was established. The maximum values obtained with lysimeter No. one were generally 5–15% higher than with No. two, primarily because the alfalfa crop on lysimeter No. one reached effective cover quicker in the spring; and after cutting, it remained more erect, and yielded higher. Indicated harvest dates are typical for the south-central Idaho area, but cutting dates do vary two to three weeks from year to year and farm to farm. After the third cutting, growth again began but ceased before full cover was reached because of cool fall temperatures. Previously used procedures for computing reference ET (25) gave lower values for April, September, and October because of the overestimation of reference ET during those periods. The results of Fig. 3 agree well with a suggested alfalfa K_c curve as given by Doorenbos and Pruitt (7), although their K_c values peak at 1.15 rather than at 1 since their reference crop was grass.

Basal crop curves developed for the other crops studied at Kimberly are presented in Fig. 4. Each curve is based on one season's data except for beans and field corn for which there were two years of data. Dates of planting and the occurrence of key growth stages are summarized in Table 2 for all the crops studied. In all cases the crops were managed so that crop development was fairly typical for the area. The observed time intervals from planting to full cover, and full cover to harvest are also listed in Table 2.

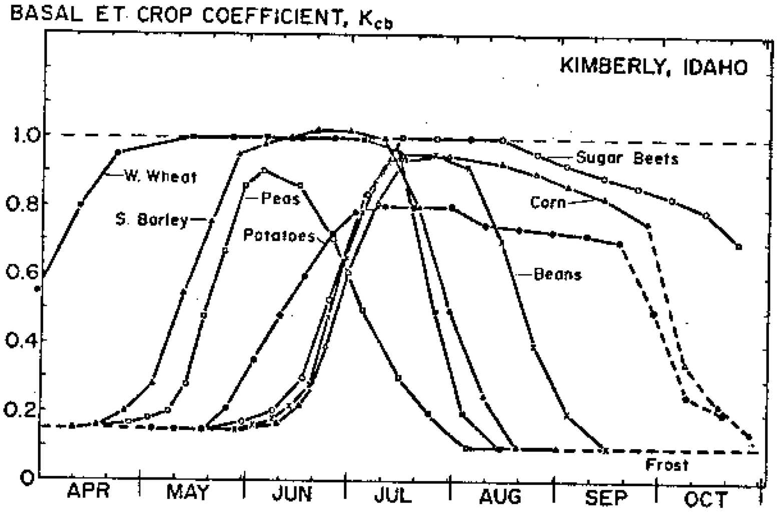

FIG. 4.—Basal Daily ET Crop Coefficient Curves for Several Crops by Date

Values of the derived basal crop coefficients, K_{cb}, are listed in Table 3 on a normalized time scale, as was Table 6.5 of Jensen (4), with time from planting until full cover as a percentage, PCT, and time after full cover as elapsed days, DT. Respective time intervals used in Table 2 were used for the normalization. The normalized time base helps fit a curve to the situation of different planting dates since large differences in planting date usually have only a minor effect on the date full cover is reached. A different time base was used for alfalfa than the other crops in Table 3 because of the differences in managing the crop. The growth period was considered to be 100% from new growth, or harvest, to harvest. Thus K_{cb} reached 1 at about 50% on the time scale, which corresponded to the time of effective full cover. The cuttings were treated individually due to the climatic differences during the growth periods. The slight decline in the crop curve prior to harvest was due to lodging of the crop.

The maximum values of K_{cb} differed some for the various crops at effective cover because of overall plant and canopy factors. After full cover, the curves differed considerably according to ripening characteristics of the crops and harvesting methods. All of the crops studied developed very complete cover with peak LAI's greater than 3.5. The curves for sugarbeets, beans and corn, as shown in Fig. 4, are very similar during the crop development period even though the crops are usually planted at different times. These crops begin rapid growth in early June and reach effective cover by the middle of July.

TABLE 2.—Date of Various Crop Growth Stages Identifiable for Crops Studied at Kimberly, Idaho, 1968–1978

Crop (1)	Date of Occurrence							Days	
	Planting (2)	Emergence (3)	Rapid growth (4)	Full cover (5)	Heading or bloom (6)	Ripening (7)	Harvest (8)	Planting to full cover (9)	Full cover to harvest (10)
Barley	4/01	4/15	5/10	6/20	6/20	7/15	8/10	80	55
Peas	4/10	4/25	5/10	6/05	6/15	7/05	7/25	55	50
Sugar beets	4/15	5/10	6/01	7/10	—	—	10/15	85	95
Potatoes	4/25	5/25	6/10	7/10	7/01	9/20	10/10	75	90
Field corn	5/05	5/25	6/10	7/15	7/30	9/10	9/20	72	67
Sweet corn	5/05	5/25	6/10	7/15	7/20	—	8/15	72	30
Beans	5/22	6/05	6/15	7/15	7/05	8/15	8/30	55	45
Winter wheat[a]	(2/15)	(3/01)	3/20	6/05	6/05	7/15	8/10	(110)	60
Alfalfa[b]									
(1st)	4/01		4/20				6/15		76
(2nd)	6/15		6/25				8/01		46
(3rd)	8/01		8/10				9/15		46
(4th)	9/15		10/01				10/30		46

[a] Effective dates in parenthesis. Crop actually planted on 10/10 and emerged 10/25.

[b] Effective planting date for established alfalfa is date that growth begins in spring or harvest of preceding crop. Final harvest is date crop becomes dormant.

The basal crop coefficients for a visually dry soil surface in early April were about 0.2, reflecting the combined effects of moisture carry-over from winter precipitation and relatively low evaporative demand. After tillage and the development of stronger drying conditions later in the season, the K_{cb} for bare soil generally decreased to about 0.1 or less by the middle of May, before irrigation or crop emergence. During the latter part of the season, it averaged about 0.05 for crops that were harvested under dry soil conditions. For crops, such as potatoes and sugarbeets, which are irrigated to facilitate harvesting, the overall crop coefficient averaged between 0.2–0.4. Since the soil was not visually dry, the K_{cb} values in such cases were estimated from the other crop curves.

Crop coefficients developed with the lysimeter data used here were reported earlier for potatoes and beans (23,24) and preliminary basal coefficients were reported for all the crops (21). Those coefficients were slightly different from the new K_{cb} values because they were based on procedures utilizing the earlier calibration of the combination equation to estimate reference ET (25).

In the case of winter wheat, the procedures used in normalizing the time scale for most of the other crops is not appropriate since the crop is generally planted in the fall and a relatively long period elapses before rapid growth begins. The crop in this study, germinated in late October, began rapid growth in March and reached effective cover by the end of April. Therefore, to develop a time scale similar to the others, effective dates of planting and emergence were considered to be February 15 and March 1. These dates correspond to the time when winter wheat passes from the cold weather dormancy to green coloration and the beginning of rapid growth. Furthermore, because of the difficulty in detecting effective full cover in the field, the effective cover date was considered to be the heading date in June. When winter wheat is seeded earlier in the fall, which is done sometimes, the crop coefficient would probably reach 1 by April 10, and heading and harvest would be one to two weeks earlier than listed in Table 2.

TABLE 3.—Daily Basal ET Crop Coefficients (K_{cb}) for Dry Surface Soil Conditions for Use with Reference ET Representative of Alfalfa for Irrigated Crops Grown in an Arid Region with Temperate Intermountain Climate. Coefficients were Determined Experimentally Using ET Data Obtained with Sensitive Weighing Lysimeters at Kimberly, Idaho, from 1968-1978

	Basal ET Crop Coefficients, K_{cb}									
Crop (1)	10 (2)	20 (3)	30 (4)	40 (5)	50 (6)	60 (7)	70 (8)	80 (9)	90 (10)	100 (11)
(*a*) PCT, Time from Planting to Effective Cover, in percentage										
Barley	0.15	0.16	0.20	0.28	0.50	0.75	0.90	0.96	1.00	1.00
Peas	0.20	0.17	0.16	0.20	0.29	0.38	0.47	0.65	0.80	0.90
Sugar beets	0.20	0.17	0.15	0.15	0.16	0.20	0.27	0.40	0.70	1.00
Potatoes	0.15	0.15	0.15	0.20	0.35	0.48	0.60	0.72	0.78	0.80
Corn	0.15	0.15	0.16	0.17	0.18	0.25	0.38	0.55	0.74	0.93
Beans	0.15	0.16	0.18	0.22	0.35	0.45	0.60	0.75	0.88	0.92
Winter wheat	0.15	0.15	0.30	0.55	0.80	0.95	1.00	1.00	1.00	1.00
(*b*) DT, Days After Effective Cover										
Barley	1.00	1.00	0.80	0.40	0.20	0.10	0.05	—	—	—
Peas	0.86	0.72	0.50	0.32	0.15	0.10	0.05	—	—	—
Sugar beets	1.00	1.00	1.00	0.98	0.91	0.85	0.80	0.75	0.70	0.65
Potatoes	0.80	0.80	0.75	0.74	0.72	0.68	0.60	0.30	0.20	0.15
Field corn	0.93	0.93	0.90	0.87	0.83	0.77	0.70	0.30	0.20	0.15
Sweet corn	0.91	0.91	0.88	0.80	0.70	0.50	0.25	0.15	—	—
Beans	0.92	0.86	0.65	0.30	0.10	0.05	—	—	—	—
Winter wheat	1.00	1.00	1.00	0.95	0.50	0.20	0.10	0.05	—	—
(*c*) Time from New Growth or Harvest to Harvest, in percentage										
Alfalfa (1st)	0.50	0.62	0.80	0.90	1.00	1.00	0.98	0.96	0.95	0.95
(2nd & 3rd)	0.30	0.40	0.70	0.90	0.95	1.00	1.00	0.98	0.95	0.95
(4th)	0.30	0.40	0.50	0.55	0.45	0.40	0.35	0.25	0.20	0.15

The general nature of the crop curves derived for Kimberly agrees well with those for similar crops presented by Pruitt, et al. (18) based on Davis, California studies. Since they used a grass reference crop, their peak values were well above 1 but the general shapes are mostly in excellent agreement. The results are also in good agreement with other crop water-use results for California and Washington (20,13,17) with the notable exception of the potato crop curve.

The maximum K_{cb} obtained for the smoothed potato crop curve for Kimberly was 0.8, which is much lower than the values for the other crops. The measured potato ET was much less than the computed E_r, and the alfalfa ET as measured with the other lysimeter that year. The transpiration rates of the potatoes seemed to be lower than for the other crops studied since after sprinkler irrigation the calculated crop coefficient increased to about 0.9 for one or two days, because of the wetter surface. While the Kimberly results seem to be valid, since there are no known experimental errors to account for the lower values, other research (1,20,13) has suggested that potatoes at full cover can use water at the same rate as several of the other crops reported. It is not clear why the Kimberly and other results are different. The manner of determining the potato ET in the other studies may have some bearing on the matter. When the Kimberly potato crop curve was released (23) to users of the USDA-ARS irrigation scheduling program, the lower potato crop coefficients were generally well received. In some cases even users reported that higher values previously used (12) had resulted in observed over-watering during the latter half of the growing season. The Kimberly potato crop was generally an excellent crop. It was well irrigated, the rows were interleaved by July 1, effective full cover was reached about July 10, and the vines remained healthy until after frost in mid-September. The decline in the crop curve after full cover was due to vine lodging; but the values afterwards remained fairly constant until frost. For a crop that may die early, as sometimes happens, the crop coefficients for the latter part of the season would need to be reduced accordingly. Also, as with other crops affected by frost, the crop coefficient may need to be reduced earlier for years when a killing frost occurs before mid-September.

Those using the crop coefficients of Fig. 4 or Table 3 can use the key growth points that are easily identifiable in the field to adjust the crop curves to account for crop varietal differences or yearly seasonal variations. The date of planting can be used until emergence which is then the key point. For the small seeded crops, there seems to be a period of establishment following emergence when leaf and stem growth are rather slow. After this initial establishment period, plant growth and leaf expansion are relatively rapid until after effective full cover is reached. For cereals the period of rapid growth seems to begin when the third leaf is fully emerged from the leaf sheath. For beans it is when the trifoliate leaves begin emerging and developing. In these cases K_c increases nearly linearly with time from the beginning of rapid growth until effective cover.

The new K_{cb} values in Table 3 are generally lower during periods of crop development than previous crop coefficients (4,12). The lower values result from the differences in the methods of deriving the basal coefficients, computing reference ET, and measuring crop ET. The original USDA-ARS irrigation scheduling program and the crop coefficients developed for use with it (12), were based on the best procedures and data available at the time and certainly provided improved methods of irrigation scheduling. It was fully anticipated, however, that improvements would be added as needs changed and further data became available. The previous crop curves were developed from soil sampling data obtained at 5–15 day intervals. Since each point on the curve represented a mean for that period, rapid changes, such as those which occur with rapid crop development, were damped. Some of the effects of wet soil conditions were excluded from the data, since samples were not taken until two or three days after an irrigation; and periods with significant rainfall were not used. However, some wet soil evaporation was probably included. Since the new curves were developed from daily ET data obtained with lysimeters, effects of upward or downward movement of soil water were eliminated. Less soil evaporation, also, was included as K_{cb} was fitted to the base points representing ET when the surface soil was visually dry, which usually occurred five or more days after an irrigation.

In the original irrigation scheduling program, procedures for estimating reference ET had not yet been fully developed to account for arid climatic conditions. Since the earliest crop curves were based on these estimates, if they are used with techniques developed later for estimating alfalfa reference ET, such as by Wright and Jensen (25), crop ET may be overestimated. Also, the procedures used to adjust the mean crop coefficient for wet soil surfaces, following rain or irrigation, may result in overestimation early in the season. Use of the new K_{cb} values and procedures for estimating E_{tr} should reduce calculated crop ET in many instances and help solve this problem.

Application of Crop Coefficients

The new basal ET crop coefficients should be usable in estimating crop ET in areas with a climate similar to that of south-central Idaho because the crop coefficient is a relative factor and differences in water use due to climate would 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 E_{tr}. While there is some variation in the rate of crop development at various locations and on different years, because of seasonal differences, adjustments for this variation can be accounted for. The crop curve can also be shifted for the particular season if a few simple crop development characteristics are occasionally monitored, such as date of emergence, beginning of rapid growth, bloom or heading, and the closing of rows. The general nature of the curves including the development period prior to full cover, the K_c at full cover, the ripening characteristics of the crop, and irrigation prior to harvest are of major importance. Because of varietal, soil, disease, insect, and management factors, crops sometimes do not achieve full cover. In such cases the maximum crop coefficient should be reduced accordingly.

If pan evaporation is used to estimate alfalfa E_{tr}, appropriate pan factors and precautions should be used (7). Even then the estimates are appropriate only for periods of 7–10 days since the daily response of crops and pans is quite different.

Rather than percentage time or elapsed days, it would be desirable to have a means of relating crop coefficients more directly to crop development with an index such as accumulated growing degree days or reference ET. Initial attempts to correlate crop coefficients to such variables has led to confusing results, and it seems that models which relate crop growth to climatic and growing conditions may need to be developed first. Some current research along these lines may provide such models.

Summary and Conclusion

New crop coefficients for various specific Northwest irrigated crops were developed for use in the general relationship $E_t = K_c\, E_{tr}$; in which E_t = the evapotranspiration (ET) for a particular crop at a given growth stage, K_c = an overall crop coefficient representing particular crop and soil conditions, and E_{tr} = a reference ET for a designated crop and is a function of meteorological conditions. Reference ET was based on that for well watered, actively growing alfalfa, with sufficient growth for near maximum ET in arid, irrigated regions. ET for the alfalfa reference and other crops was measured for several years with sensitive weighing lysimeters. To provide a continuous and consistent reference, E_{tr} for alfalfa was estimated from meteorological data using procedures based on a combination energy balance and aerodynamic equation.

The new ET crop coefficients are basal or minimal coefficients, representing conditions when soil evaporation is minimal but root-zone soil moisture is adequate, and permit specific adjustment for effects of wet-soil evaporation. Basal ET crop curves were developed for alfalfa, potatoes, snap beans, sugar beets, sweet and field corn, peas, and winter and spring cereals. They can be used with procedures such as the USDA-ARS Computerized Irrigation Scheduling Program for estimating daily crop ET. The new curves are considered to be more accurate than previous curves developed from soil moisture depletion data before lysimeter measurements of E_t and E_{tr} were available. When combined with improved estimates of daily E_{tr}, the revised crop coefficients are expected to increase the accuracy of irrigation scheduling procedures and general estimates of crop water requirements.

Further improvements needed include development of crop growth models to permit partitioning soil evaporation and plant transpiration, and to provide a basis for directly relating the crop coefficient to crop development.

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Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

D = day of year;
DT = elapsed days after full cover;
E_t = measured daily crop ET, millimeters day^{-1};
E_{ta} = measured daily alfalfa ET, millimeters day^{-1};
E_{tc} = computed daily crop ET, millimeters day^{-1};
E_{tr} = computed daily reference ET, millimeters day^{-1};
ET = evapotranspiration;
G = soil heat storage, calories centimeter^{-2} day^{-1};
K_a = available soil moisture coefficient, dimensionless;
K_c = daily ET crop coefficient, dimensionless;
K_{cb} = daily ET basal crop coefficient, dimensionless;
K_{cc} = computed daily ET crop coefficient, dimensionless;
K_s = surface soil wetness coefficient, dimensionless;
L = latent heat of evaporation; calories centimeter^{-3};
M = number of month (1–12);
N = number of day of month (1–31);
P = atmospheric pressure, millibars;
PCT = percent of time from planting until full cover;
R_b = net outgoing long wave radiation, calories centimeter^{-2} day^{-1};
R_{bo} = net clear day outgoing long wave radiation, calories centimeter^{-2} day^{-1};
R_n = net radiation, calories centimeter^{-2} day^{-1};
R_s = incident solar radiation, calories centimeter^{-2} day^{-1};
R_{so} = clear day incident solar radiation, calories centimeter^{-2} day^{-1};
T = temperature, degrees Celsius;
T_1 = maximum daily air temperature, degrees Kelvin;
T_2 = minimum daily air temperature, degrees Kelvin;
T_a = mean daily air temperature, degrees Celsius;
T_{dp} = dewpoint temperature, degrees Celsius;
T_p = preceding mean daily air temperature, degrees Celsius;
U = daily wind travel, kilometers day^{-1};
W_f = wind function;
a = correlation coefficient, specific value defined in text;
b = correlation coefficient, specific value defined in text;
a_1 = emissivity coefficient, specific value defined in text;
a_w = time dependent coefficient of wind function, defined in text;
b_w = time dependent coefficient of wind function, defined in text;

$c_0 \ldots c_5$ = polynomial coefficients, values defined in text;

c_p = specific heat of air, calories gram^{-1}, degrees Celsius^{-1};

c_s = empirical specific heat coefficient of soil, calories centimeter^{-2}, degree Celsius^{-1};

e = vapor pressure of air, millibars;

e_s = saturation vapor pressure of air, millibars;

e_d = saturation vapor pressure at dewpoint temperature, millibars;

z = height above ground, meters;

α = crop albedo;

Δ = slope of the saturation vapor pressure-temperature curve, millibars degree Celsius^{-1}; and

γ = psychrometric constant, millibars degree Celsius^{-1}.

Note: The familiar units of calories centimeter^{-2} are used here specifically for their convenience in describing meteorological processes, for which the 15° gram-calorie is defined as the quantity of heat required to raise the temperature of 1 g of water 1° C from 14.5°–15.5° C. Equivalent units are: 1 cal cm^{-2} = 4.186 J cm^{-2} = 0.04186 MJ m^{-2} = 3.687 BTU (60° F) ft^{-2}. Likewise the units of millibars are used to describe vapor and atmospheric pressures. Equivalent units are: 1 mb = 100 N m^{-2} = 0.1 kPa = 0.01450 lb per square inch.