# CROP COEFFICIENTS FOR IRRIGATION OF COTTON

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## Abstract

A new procedure is presented for estimating the crop coefficients for cotton, using a drip-irrigated field plot and neutron probe readings. Two seasons of data with uniform, near-normal irrigation produced crop coefficients that fit very closely to data obtained from a previous experiment with a complicated 6-level application rate. The peak crop coefficient for use with an evaporation pan was 0.88, and the peak for use with the Penman equation was 1.14, both comparing favorably with values found in the literature.

## Introduction

Crop coefficients ($K_c$) are the ratios between the actual crop evapotranspiration (ET) and a reference ET. They are used to calculate the daily water use by plants, and are required by computerized irrigation scheduling programs. The motivation for this study came from potential improvements we could see in our original, real-time system (Phene, et al.,1992), where a datalogger-controller read pan evaporation, multiplied it by a pre-programmed, time-based, polynomial crop coefficient, and applied the resulting ET to the field, sometimes hourly. The polynomial had an adjustable time offset so that the $K_c$-time curve could be moved left or right to compensate for various date-of-plantings. The system worked very well for normal and near-normal weather conditions. Even so, it was often necessary to change the time offset once or twice during the early stages of plant growth. The biggest problem, however, occurred when the cotton was planted very late; the early slope of the polynomial curve was not steep enough. What was needed, obviously, was a polynomial based on heat units (sometimes called "growing-degree-days") rather than time. So the plan became one of adding an air temperature sensor to the datalogger, and developing a crop coefficient polynomial as a function of heat units, one similar to that of Slack et al.(1996) and others, but for our conditions and for our version of the heat units. Hopefully the only adjustment needed on the program would be to set the cumulative heat units to zero at planting time. In the process of developing the polynomial function, a new procedure was found for determining crop coefficients.

## Procedures

In DeTar et al.(1997) a procedure was presented showing how the crop coefficient was developed from a subsurface drip-irrigation experiment involving the use of 6 different application rates on 2 cotton varieties, Acala Maxxa, and Pima S-7, on a 2-acre plot of sandy soil at the U.C. Shafter Research and Extension Center, in Shafter, CA in 1996. The experiment was repeated in 1997 and the results are shown in Figure 1. The heat units shown were calculated using the triangular method of Zalon et al.(1983). Twenty four neutron probe access tubes were used, and read weekly. Dripper lines were located 10 inches below grade in every plant row, and rows were 30 in. apart. The access tubes were located 5 inches from the dripper line. Each of the data points shown in Figure 1 is the result of 240 neutron probe readings. The 1996-1997 procedure had the benefit of showing how the $K_c$ varies for different soil conditions around the field and for the 2 varieties, but it was not easy to set up or analyze. A basic premise used was that the neutron probe would respond to changes in soil moisture, and conversely, if we applied the proper amount water, the neutron probe readings would not change, and the soil moisture could be considered at equilibrium. An assumption was made that at equilibrium, the amount of water applied was the same as the amount used by the plants.

A different analytical procedure was used in 1998 and 1999, but the physical layout was only slightly different. The same field was used as in 1996-1997, with the same irrigation equipment, but the entire field had just one irrigation treatment, near-normal, and only one variety was used, Maxxa. Twelve access tubes were installed for the neutron probe, and were read weekly to a depth of 5 feet. Water was applied once a day. Reference ET's were available from the weather station at the Research Center, within one mile of the plot. The weather station is part of the California Irrigation Management Information System (CIMIS),(see Craddock, 1990) and includes a standard USDA class "A" evaporation pan. A reference ET, based on a modified Penman equation (Penman,1948), is available from CIMIS. The amount of water applied was determined by multiplying the 25-year normal pan evaporation by 85% of the canopy, and then making slight adjustments (up to 20%) based on the weather forecast. An attempt was made to get a slight deficit irrigation. Control was by simple time clocks, which were adjusted once a week.

A plot was made of the overall average daily change in the soil moisture for each week, versus the average value of applied water/reference ET. The results are shown in Figure 2 for 1999. If insufficient water was applied to maintain equilibrium, the soil lost moisture, and if too much was applied it gained moisture. By plotting the points for the period when the $K_c$ does not change much (1000-1500 heat units) for both years, and determining where the regression line crossed the zero-change line, it was possible to find out

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just exactly how much water would have to have been applied for equilibrium to occur. See Figure 3. The value of applied-water/reference ET at that equilibrium point is defined as the crop coefficient. The more important aspect of the regression line is its slope, which is assumed to apply equally to all points that have a bulb of wet soil around the emitter which is relatively stable in size and shape. By projecting a line from all such points for the entire season, using the slope of the regression line, 0.777 in/d, the point of intersection with the zero-change line determines the crop coefficient for that point. This was done for both 1998 and 1999 and the results are shown in Figures 4 and 5. This last step is the most salient feature of the new procedure.

## Results and Discussion

You'll notice that not all the slopes are the same in Figure 4 and 5. After the water was turned off at the end of the season, we continued taking neutron probe readings. This accounts for points number 14, 15, and 16 in 1999, and points number 17 and 18 in 1998. Point 1 in 1998 was for data taken before irrigation started. The slope of the line passing through these points is the same as the average reference ET, in this case the average pan evaporation, in inches/day. No water was applied for these points, but it is assumed that if we applied the same amount of water that appeared to be lost, no change would take place in the soil moisture. Under these conditions it is assumed that there is no longer any significant effect from the bulb of wet soil. For clarification, it should be noted that the slope for these lines is the change in soil moisture divided by the application/reference ET. Obviously, if the application is the same as the moisture change, the resulting slope is the reference ET. Some points have an intermediate slope. Points like number 16 in 1998 or number 13 in 1999, represent the weeks toward the end of the irrigation season, when the water application was being cut back. These are time periods when the bulb of wet soil is in a stage of rapid transition. Points 3 and 4 in 1998, and number 1 in 1999 represent stages where the bulb of wet soil is not yet fully developed. For these intermediate conditions a slope of 0.577 in/d was chosen, and that is about halfway between the slope of the regression line and that of the reference ET. The slope of 0.777 in/d found here is very close to that found in Figure 9 of DeTar (1977), which was 0.769 in/d for the period July 15 to Aug. 16, 1996.

The steep slope of the regression line in Figure 3 indicates that a small change in the depth of water applied causes a large change in the indicated soil moisture. For example, if it is desired to have an indicated deficit of 0.03 in/d, as is sometimes recommended, with a normal mid-season pan evaporation rate of 0.33 in/d, the application should be reduced from the equilibrium value by only 0.0127 in/d (0.03*0.33/0.777). This result should not be too surprising. With drip irrigation on this sandy soil the water does not spread laterally more than 10 to 12 inches from the emitter. The neutron probe readings are taken mostly in the wet area where the water is applied, whereas the conventional calculation for average depth of an irrigation is the volume applied spread out uniformly over the entire area. The neutron probe readings are quite sensitive to slight changes in the size and shape of the bulb of wet soil and they are also sensitive to root activity in the same volume. The important thing here is that if you want a deficit of 0.03in/d you don't reduce the application by 0.03 in/d!

The equilibrium values, i.e., crop coefficients, from Figures 4 and 5 are plotted in Figure 6 versus heat units. Figure 6 also contains the crop coefficients determined from the 1996-1997 tests. The two procedures are quite consistent with each other up to about 1400 heat units. Above 1400 heat units the 1996-1997 data becomes more variable than earlier; the 1997-1999 data falls well within that variability for the range of 1400 to 1600 heat units. Above 1600 heat units the 1999 data falls off rapidly, due to a short season and an early cut off of irrigation water. The start of the irrigation cut back occurred at heat units of 2050, 2047, 1825, and 1639 degree-days for the years 1996, 1997, 1998, and 1999 respectively, and data after the cut back were not used in the regression analysis.

Everything shown in Figures 4, 5, and 6 was determined using pan evaporation as the reference ET. The same procedure was repeated using the reference ET from CIMIS, called ETo, and the results are shown in Figure 7. A slope of 0.600 in/d was used for the wet-stable conditions and 0.430 in/d for the transitory conditions. Again both the 1996-1997 data and the 1998-1999 data are plotted together for comparison. The fourth order regression equation shown is for all the data, and the variability is considerably greater with the CIMIS ETo (r^2=0.895) than we got with the pan reference ET (r^2=0.946). But the peak $K_c$ value of 1.14 (average for all data in the range of 1000-1500 heat units) is very reasonable, comparing well with values of 1.13 for Slack et al.(1996), 1.1 for Sammis et al.(1985), 1.10 for Ayers and Hutmacher (1994), and 1.11 for Howell et al.(1984). The peak value using the pan evaporation was 0.88, and the ratio of the two is 0.77, which is very close to the 0.78 value given by the California State Department of Water Resources (1975) as the crop pan coefficient for grass. The Penman ET (1948) is the ET for well-watered grass.

The sudden decline in crop coefficients after the irrigation water was turned off in the shortened seasons of 1998 and 1999, as seen in Figure 6, provided an opportunity to estimate the soil stress factor, $F_s$. This would not have been possible in a normal season. The crop water use will be reduced if the soil gets dry enough. This factor is a multiplier in the equation for the crop coefficient $K_c = K_{cb} * F_s + K_e$ , where $K_e$ is evaporation from the soil surface (neglected with subsurface drip) and $K_{cb}$ is the basal crop coefficient, which is the same as $K_c$ if $K_e = 0$ and $F_s = 1$ (Allen et al., 1998). For heat units greater than 1639 in 1999 and 1825 in 1998, the actual crop coefficients shown in Figure 6 were divided by the corresponding values from the regression equation, and the result is the relative reduction in the crop coefficient due to soil dryness, $F_s$. These were then plotted against the relative extractable moisture (REM) of the soil in Figure 8. For our sandy soil, REM = (M-FWP)/(FC-FWP), where M is the soil moisture in inches per foot, averaged over the 5 top feet of soil. The FWP is the lowest level of soil moisture from which our cotton can extract moisture, and is 0.7 in/ft., determined from measurements just before harvest. The FC is the field capacity of the soil and is 1.7 in/ft., measured two days after thorough irrigations and/or heavy rains at the beginning of the season. The results was a linear reduction in $F_s$ when the REM got below 52.9%. This compares very well with the 50% suggested by Doorenbos and Kassam (1979).

## Summary

The new procedure shown here, that could be called a slope-projection method, provides crop coefficients that are very similar to those found in a previous experiment. Taken altogether, the four years of data provide a seemingly dependable and useful regression equations for the crop coefficient as a function of heat units for our conditions. The main purpose of this presentation was to show the new procedure, which is simpler than a previous one, in hopes that it can be applied and verified by other researchers under other conditions. The peak values for the crop coefficients are reasonably close to those found by several researchers, and is well within a wide range of values that can be found in the literature. The peak values for the crop coefficient, when used with pan evaporation as a reference ET, was 0.88. When the reference ET was a modified Penman equation from CIMIS, the peak crop coefficient was 1.14. An interesting finding was that changes in soil moisture as measured near drip emitters by a neutron probe, are not the same as changes in water applications. The soil stress factor was measured and was found to agree with the literature; it caused a reduction in the crop coefficient when the available soil moisture dropped below 52.9%.

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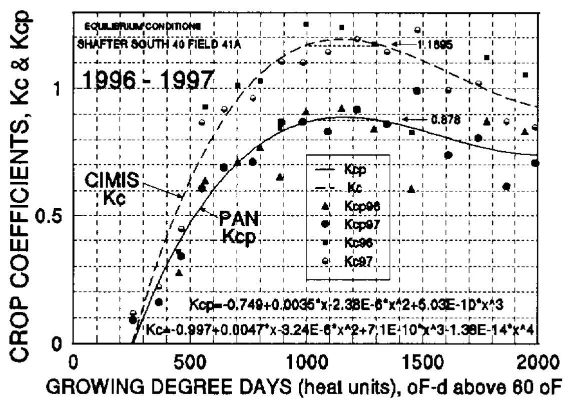


Figure 1. Crop coefficients for 1996-1997 covariance procedure.

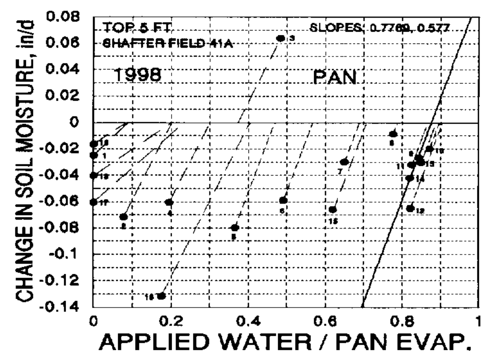


Figure 4. Change in soil moisture vs relative water application. Using pan reference project of each point to the zero-change line. 1998.

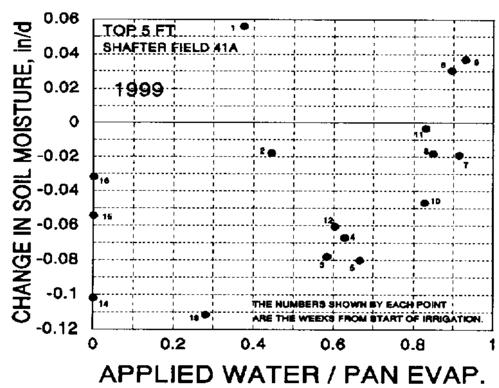


Figure 2. Changes in soil moisture for water applications relative to pan evaporation in 1999.

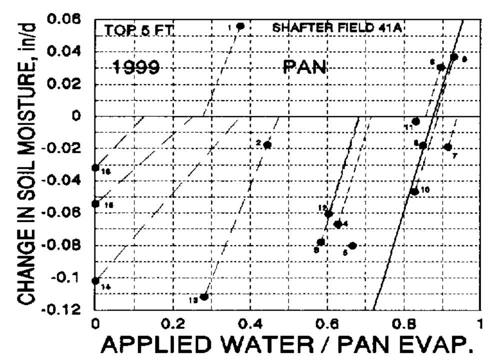


Figure 5. Changes in soil moisture vs relative water application, with pan reference project of points to zero-change line. 1999.

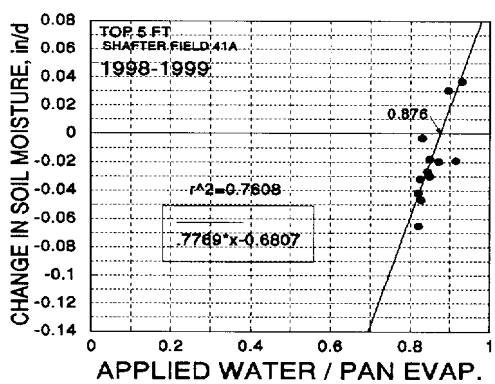


Figure 3. Changes in soil moisture for relative water applications for period of 1000-to-1500 heat units, 1998 and 1999, based on pan evaporation.

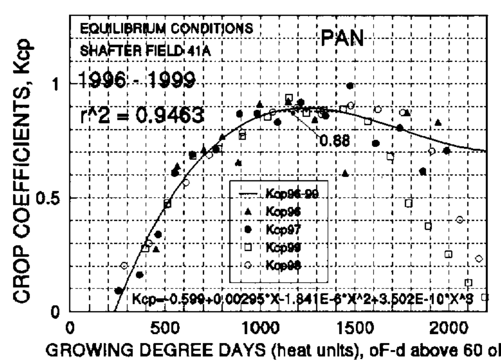


Figure 6. Crop pan coefficients for 1996-1997 combined with 1998-1999, as a function of heat units.

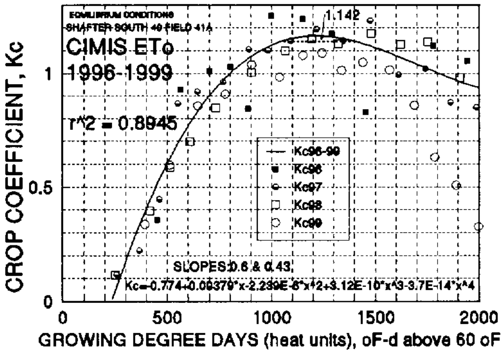


Figure 7. Crop coefficients for 1996-1997 combined with 1998-1999 as a function of heat units, using CIMIS ETO as reference.

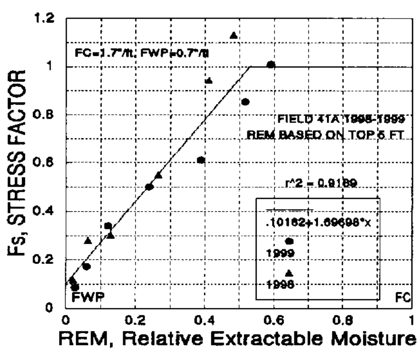


Figure 8. Soil stress facot vs relative extractable moisture.