THE EFFECT OF DEGREE DAYS ON THE CROP COEFFICIENT AND WATER USE BY COTTON

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Abstract

The crop coefficient used to determine the daily water use by cotton was found to be sensitive to air temperature, as expressed in average daily heat units of degree days above 60 degrees F. When the evapotranspiration (ET) of the crop was determined using a Penman-type equation for the reference ET, then the crop coefficient was also found to be sensitive to the average daily wind speed. When the reference ET came from evaporation pan data, then the daily crop-pan coefficient was a function of heat units but independent of wind speed. The crop-pan coefficient becomes independent of temperature after cut-out, when the plant growth switches from the vegetative stage to the boll-development stage. A new procedure was developed to determine the crop coefficient, using a field test of 6 different water application rates through a subsurface drip system on a 2-acre plot.

Introduction

Anytime we can improve the accuracy of daily evapotranspiration (ET) determinations we can do a better job of irrigating. More precise irrigation means less water wasted, fewer drainage problems, less nutrient leaching, and, with cotton, it also means better control of that delicate balance needed between vegetative and reproductive growth. Those systems which are automated and those that require frequent irrigations may benefit the most from the improved accuracy. More precise daily values of ET will also improve estimates of long-term water use given by the checkbook water balance method and by computerized scheduling methods; thus optimizing when to irrigate and how much water to apply.

A commonly used equation for determining crop water use is

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

where E_{tr} is the evapotranspiration of a reference crop, e.g. well-watered grass, and often calculated from a modification of Penman's equation (Penman, 1948); E_{tc} is the actual evapotranspiration by the crop; and K_c is the crop coefficient. A corollary equation is

$$E_{tc} = K_{cp} E_p \qquad [2]$$

where E_p is the pan evaporation; and K_{cp} is the crop-pan coefficient. The source and ramifications of equation 1 are discussed extensively in Doorenbos and Pruitt (1977), and its common use and refinements are presented in Jensen et al. (1970), Wright (1981), Hatfield and Fuchs (1990) and Snyder et al. (1987). Doorenbos and Pruitt (1977), in what is sometimes referred to as FAO-24, proposed that equation 1 be used as an estimate of the average daily crop water use, and they showed how wind and humidity can affect the crop coefficient, K_c, especially in arid regions. In proposed modifications to FAO-24, Allen et al. (1996) shows that plant height is also an important factor. Martin et al. (1990) discussed the use of equation 1 in scheduling irrigations as related to design of irrigation systems and automatic controls. Snyder et al. (1987) pointed out that the estimated value of the crop coefficient is often determined from the measurement of soil moisture depletion, and they described the reference E_{tr}, called ETo, which is readily available on a daily basis from the California Irrigation Management Information System (CIMIS) network of meteorological stations in California. More details on the CIMIS ETo, including a new method for determining net radiation, are given in Craddock (1990), Dong et al. (1992), and Snyder and Pruitt (1992). The purpose of this study was to find the optimum level of water application to cotton in the field, using six rates through a subsurface drip irrigation system; to determine the corresponding crop coefficients; and to determine the weather factors which influence these crop coefficients.

Procedures

A two-acre field plot was set up at the Shafter Research Station to determine the optimum level of water application to Acala Maxxa and Pima S-7 cotton using subsurface drip irrigation. A randomized complete block design was used with two replications of 6 irrigation treatments. Each of these main treatments was then split into subplots, one half for the Maxxa and the other half for Pima. Each of the main plots consisted of eight 30-inch rows, 328 ft long. A dripper line was buried 10 inches below grade under every plant row, running the full length of the field. The dripper line is T-Tape TSX-710-12-450 (7/8" ID, 10-mil wall thickness, emitter outlets every 12 inches) which we operated at a pressure of 9.4 psi, producing 0.30 gph emitter flow. Each of the 6 circuits at the control center feeds 16 dripper lines and carries 26.4 gpm. Water is applied once a day, using manually adjusted time clocks. The field is level in both directions, and pressures throughout the system vary no more than 0.2 psi from one side to the other. The planting date was April 9, with plant rows running N-S. The emerged plant population was 40,500 plants per acre. Prevailing winds are from the NNW and traverse a large acreage of mature almonds trees and an unpaved road before reaching the test plot. The soil is a uniform Wasco sandy loam (*coarse-loamy, mixed, nonacid, thermic Typic Torriothents*) that had been in potatoes for the three previous years. The field has a

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history of good productivity. The treatments consisted of six levels of the factor 100 F_p (pan application coefficient as a percent of ground cover), where

$$F_p = C_p/G_c \qquad [3]$$

in which C_p is the pan application coefficient, i.e., the ratio of applied water to pan evaporation; and G_c is the ground cover, that decimal fraction of the field area that would be shaded if the sun were directly overhead. Phene and Howell (1984) give an example of how ground cover is used with pan evaporation to estimate ET. The six levels of F_p were 0.45, 0.65, 0.85, 1.05, 1.25 and 1.45, for treatment numbers 1 through 6, respectively. Treatment number 3 (F_p =0.85) was considered the "normal" for local conditions, being equivalent to K_{cp}=0.85 at 100% ground cover. It was hoped that the range of water applications would be large enough to provide significant differences in yield and show definite trends. The time clocks, which were adjusted twice a week, were set by estimating the pan evaporation for the coming 3 or 4 days, using the 21-year normal pan evaporation and adjusting it by as much as 20% depending on weather forecast information. The recorded pan application coefficient was based on actual water applied and the evaporation from the pan located at our weather station, which is part of the CIMIS network. The fetch of the prevailing winds at the weather station consisted of 39 ft of green grass, 341 ft of fallowed row-crop land, and then a large acreage of recently-planted almond orchard. Ground cover was measured weekly (dividing the average width of the plant canopy by the row spacing), and estimates were made by forward extrapolation to help with the time clock setting. The moisture in the soil profile was measured weekly with a neutron probe. One neutron probe access tube was located near the center of every subplot. Each of the 24 tubes was 2" in diameter (OD) and five foot long, made of an aluminum alloy. Readings were taken at one-foot intervals. All the data presented in this report are related to changes in the total moisture in the five-foot profile, i.e., the sum of the five individual readings at each tube location. In the final layout, Pima was planted in the SE quarter of the field and was labelled Pima-I. Pima in the NW quarter of the field was labelled Pima-II. Maxxa in the NE quarter was labelled Maxxa-I, and Maxxa in the SW quarter of the field was labelled Maxxa-II. The plants grew rapidly with those in treatment 3 reaching 91% ground cover at first bloom on June 17. At this point the plant heights were 27 inches for the Pima and 34 inches for the Maxxa. The timing for first bloom was normal, but these plant sizes were reached two to three weeks earlier than usual. There was no visible or measurable moisture stress on the plants in treatment 3 through 6. Over the season, the mid-day leaf moisture potential in treatment 3 averaged -12.8 bars on the Pima and -11.7 bars on the Maxxa; the coefficients of variability (CV) were 9.0% and 6.7% respectively.

Results and Discussion

A criteria for proper real-time (daily) application of water is as follows: when water is applied to the field at the same rate that the plants use the water, then the soil moisture will remain constant. It may not necessarily be the best application rate, especially for cotton, and it assumes that surface evaporation and deep percolation losses are small, but it is a measurable and controllable criteria, and forms a basis for relative comparisons. Figures 1 through 7 demonstrate the procedure for finding the equilibrium application rate for each quarter of the field. The change in total profile moisture, in inches, over a period of approximately one week, is plotted against the average application rate, in inches per day. In general, treatments 5 and 6 are excessively high application rates, and they greatly increase the soil moisture, treatment 6 more than treatment 5. Treatment 4 increases the soil moisture at a slower rate. Treatments 1 and 2 are very low applications, and the soil gets drier, more so in treatment 1 than treatment 2. Obviously, if too much water is applied the soil gets wetter, and if not enough is applied, the soil gets drier. So, the question is: what is the application rate required for no change in soil moisture? The answer is found by linear regression. Where the regression line crosses the zero-change line, we have the equilibrium application rate, which we assume is the evapotranspiration of the crop, E_{tc}, and which is sometimes called consumptive use, CU. By using covariance analysis, we can run all 4 regression lines at the same time, and this reduces the error by including all the data in one analysis. Covariance checks first to see if there is a significant difference in the slopes of the regression lines, and there were none in any of the seven figures. In a few cases, there were significant differences in the CU, but nothing consistent from week to week. In Figure 1, the northern half of the field had a significantly lower CU than the southern half, and this was because the plants were smaller in the north half. In Figure 2 the east side used less water than the west side. In Figures 3 through 7 there are no significant differences in CU due to any cultivar-soil combination. The equilibrium application rate for each quarter of the field and for each weekly time period is shown in Table 1. The average value of CU for the entire field is shown in each figure.

Figure 8 shows how the total moisture in the soil profile varied in the long term for each treatment. It shows that treatment 3 (F_p = 0.85) comes closest of all treatments to meeting the criteria of no change in soil moisture. The soil in treatments 4, 5, & 6 cannot be expected to get wetter and wetter forever. The soil moisture eventually levels off in a quasi-saturated condition. When a treatment approaches this condition, it has to be dropped out of the regression analysis, e.g., treatment 6 is removed from the data used in Figure 5. A similar situation occurs with the drier treatments, i.e., the soil can cannot get drier and drier forever, and will level off at a field wilting point. For this reason treatment 1 had to be removed from the analysis shown in Figure 7. All of the correlation coefficients, r, shown in Figures 1 through 7 are significant at the 5% level of confidence. The data for subsequent weeks do not show significant values for the correlation coefficient, and for that reason the procedure shown above is terminated on July 21.

Although automatic pan control of the irrigation system has been used and is still available at the site (Phene et al., 1992), there was insufficient time between installation of the irrigation lines and planting to make the required modifications in the datalogger-controller. As a result, manually adjusted time clocks were used. This turns out to be a fortuitous circumstance, permitting the results shown in Figure 9. We could not apply the exact amount of water that was planned, and the deviations from the planned application on treatment 3 provided a means for analyzing the results from July 15 to August 16. Here the average daily gain or loss of profile moisture is plotted against the water application relative to pan evaporation, i.e., C_p, called the pan application coefficient. The crop-pan coefficient, K_{cp}, is defined as the equilibrium value of C_p. It is interesting to note that at this stage of growth and for the size of plant that was established with this treatment, the pan coefficient that would have maintained constant moisture for the entire time period was 0.84 instead of 0.85. More importantly, a regression of the points in the scatter diagram in Figure 9 shows a very good correlation. The numbers shown above each point in the figure are the heat units, and the numbers below each point represent the time period, in Julian days, for which the data was obtained. A multiple regression analysis of this data shows no significant correlation of heat units to the changes in soil moisture. Changes in the C_p, accounted for 88% of the variability in this regression, and adding the effect of air temperature (as heat units) did not improve the correlation significantly (.05). Therefore it appears that K_{cp} is no longer affected by average daily heat units after a significant boll load is reached.

The curve labelled K_{cp} in Figure 10, is the average equilibrium crop-pan coefficient for the entire field for each weekly time period between June 3 and July 21. Also shown is the ground cover. Doorenbos and Pruitt (1977) stated that the maximum value of the crop coefficient should occur when the ground cover reaches 70 to 80%, and this relationship is cited as being a good estimate by many references. If this were true for our study then the curve for K_{cp} should have reached a level of $K_{cp} = 0.84$ starting at about Julian day 163, remaining there for some time. So it was somewhat disconcerting to see K_{cp} at levels well below 0.84 until about Julian day 186! Something strange was happening. The plants were quite healthy, growing vigorously with good appearance, without disease or serious insect problems. Looking at the weather data, specifically air temperature, as expressed in average daily heat units of degree-days above a base line of 60 degrees Fahrenheit (triangular method, Zalon et al., 1983), shown as HU in Figure 10, it is clear that the value of K_{cp} tracks the heat units. The warmer the air, the closer the K_{cp} curve gets to the ground cover curve. Conversely, the cooler the air temperature, the greater the distance between the two curves. Between days 163 and 186 the crop-pan coefficient was being held down by the cold weather.

To prove this more rigorously, the crop-pan coefficient as a percent of ground cover (100 F_{tp}) was plotted against the heat units in Figure 12. Assuming that when growth stops, water use also stops, as was done by Sammis et al.(1985), the point (0,0) was added to the data. The correlation was excellent, with $r^2 = 0.9933$, when using a power function. The regression equation is

$$F_{tp} = 0.289\ H_u^{0.380} \qquad [4]$$

where H_u are the heat units described above. Likewise, for the crop coefficient used with the CIMIS ETo,

$$F_{tc} = 0.306\ H_u^{0.471} \qquad [5]$$

for which $r^2 = 0.9842$ and the function is plotted with the data in Figure 11. Linear regression lines were also fitted to the data points in Figures 11 and 12, using covariance to compare Maxxa to Pima, and omitting the point at the origin (0,0). The result was no significant difference (5%) between Maxxa and Pima for either type of crop coefficient. The regression equation for the data in Figure 11 was

$$F_{tc} = 0.0328\ H_u + 0.595 \qquad [6]$$

with an r^2 of 0.8469. For the data in Figure 12, the linear regression equation is

$$F_{tp} = 0.0194\ H_u + 0.511 \qquad [7]$$

with an r^2 of 0.8953. To further confirm these findings, a relationship similar to that shown in Figure 9 was developed for an earlier time period, June 3 to July 21. The change in soil moisture for treatment 3 was regressed on the pan application coefficient as a percent of ground cover (100 F_p), and the correlation coefficient was not significant. However when soil moisture was regressed on both heats units, H_u, and F_p, using multiple regression, the R^2 was 0.8252, which is significant at the 5% level of confidence. The resulting regression equation is

$$y = 0.3322\ F_p - 0.00662\ H_u - 0.1745 \qquad [8]$$

where y is the change in profile moisture. If the change in soil moisture is set to y = 0 for equilibrium, then F_p becomes F_{tp}, and the following equation emerges

$$F_{tp} = 0.0199\ H_u + 0.525 \qquad [9]$$

which, when matched to the data in Figure 12, shows an excellent fit, well within the LSD(05) of 0.038 for the covariance comparison. Equations 7 and 9 are also very close fits. There is little doubt of the influence of heat units on the crop coefficients during this time period. A theoretical sensitivity analysis using an energy balance presented by Annandale and Stockle (1994) showed that air temperature can have a very large influence on the crop coefficient. This effect was stronger with taller plants. With plants that are 59 inches high, increasing the air temperature from 68 °F to 86 °F, increased the K_c from 1.05 to 1.25. Above 86 °F the K_c became smaller. Reddy et al. (1992) showed that high temperatures (above 86 °F) reduce the growth of cotton. The quadratic fit shown in Figures 14 and 15 were presented to show this possible scenario. Analysis of day-by-day field data given in Lascano et al. (1996) shows that the K_c for cotton in Texas stayed well above 1.0 for most of a 12-day period, but dropped to below 0.7 on one cold, cloudy day.

Some of the other weather parameters associated with each weekly time period are presented in Table 2. An attempt was made to find a correlation between the crop coefficients and wind, humidity and net radiation, using multiple regression. For the pan coefficient, there was no significant correlation with any of these three factors. However, with the crop coefficient, the effect of wind was significant. The resulting regression equation was

$$F_{tc} = 0.050\ H_u + 0.642\ W - 0.952 \qquad [10]$$

where W is the average daily run of the wind for the period, in miles; the R^2 was 0.9679, which is big improvement over equation 6.

By combining equations 4 and 5 and eliminating H_u, it can be shown that

$$K_c = 1.425\ K_{cp}^{1.239} \qquad [11]$$

This relationship agree closely with the findings of DeTar et al. (1996), where pan evaporation is compared to the CIMIS ETo.

The data for treatment #3 (F_p = 0.85) in Figure 8 was obtained by combining the results of both Pima S-7 and Acala Maxxa. When these two crops are plotted separately, the regression lines are significantly different at the 5% level of confidence. Looking at the data for the entire season, Pima uses significantly more water than Maxxa, contrary to the findings of Hutmacher et al. (1995). However, the difference is small. With 27 inches applied to the Maxxa, the regression line had a slope of zero, and no soil moisture depletion. The Pima showed a slight deficit irrigation, depleting about one inch of soil moisture over the season. So the total use by the Pima was about 4% more than the Maxxa. This small but significant difference was not detectable in week-to-week measurements, as seen in Figure 13.

A check of the validity of our findings can be found by comparing the peak value of the crop coefficient from various sources, to those for our normal temperature conditions. Generally in our location the peak value for the crop coefficient occurs in the latter part of July. The normal heat unit values in this period (a 21-year average) are 18 to 19 degree days per day. Using these heat units in Figure 11, or using equations 6 or 7, we observe that for 100% ground cover the normal crop coefficient, K_c, would be about 1.20. From mid-July to mid-August when the K_{cp} is 0.84, the corresponding K_c, from equation 11, will be 1.15. Snyder et al. (1989) list the peak crop coefficient for cotton in the San Joaquin Valley as ranging from 1.15 to 1.20 depending on the time of planting. Doorenbos and Pruitt (1977), FAO-24, show the crop coefficient varying from 1.05 to 1.25 depending on wind and humidity. Jensen et al. (1990, also known as ASCE-70), give K_c data specifically for cotton in the San Joaquin Valley, showing that it peaks at 1.25. Grimes and Kerby (1992) show that the peak K_c = 1.21 with some points on the scatter diagram reaching as high as K_c = 1.4 for Pima cotton on the west side of the San Joaquin Valley. Hake et al. (1996), using data from California (1986), give the peak K_c = 1.20, occurring in mid-August, for cotton in the San Joaquin Valley. Slack et al. (1996) using some historical data, show the normal peak of 1.13 in Arizona. Neale et al. (1996), using remote sensing, report a reflectance-based crop coefficient of 1.29 for cotton planted April 23, under very warm conditions in Arizona, producing large plants. Sammis et al.(1985) state that the peak value of K_c averages 1.1, but in the figure they present it appears closer to 1.2, with scatter points as high as 1.36, in New Mexico. Ayers and Hutmacher (1994) report a peak basal K_c of 1.10 using above-ground PVC pipe column weighing lysimeters on the west side of the San Joaquin Valley (Univ. Calif. West-side Field Station, WSFS). When this crop coefficient was used in an adjacent field with a subsurface drip system, it underestimated the level needed to maintain a constant soil moisture. Howell et al. (1984), using furrow irrigation at the WSFS, found that the peak crop coefficient, used with the FAO-24 Penman equation, was 1.11. Also at the WSFS the same year, Phene et al. (1984) found that a screened evaporation pan produces essentially the same reference ET as the FAO-24 Penman. In addition they show that the screened pan had an ET of 92% of an open pan. Thus, the K_c of 1.11 would be equivalent to a K_{cp} of 1.02. Phene et al. (1984) also report that with a surface drip irrigation system, the peak K_c on cotton at the WSFS was 1.13, from a polynomial for use with a screened pan, and the corresponding K_{cp} would be 1.04.

Thus it is seen that our results fall well within the wide range of crop coefficients reported in the literature. Even though in Figures 11 through 15 it appears that very limited data was used to determine the temperature effect on the crop coefficient, each point in the figures is the result of 120 neutron probe readings. The temperature effect is as would be expected; since plant growth stops at the lower air temperatures, so does water use. Hopefully this work can be used to explain the wide range of scatter that occurs in lysimeter data. The results are possibly site-specific, subject to advection, and variable plant heights and considerable aerodynamic turbulence. There is a need to repeat the experiment in other locations. Based on the work presented by Annandale and Stockle (1994), it may be difficult to detect the effect of air temperature on the crop coefficients when the plant height is less than 20 inches.

Summary

A new method is presented in which subsurface drip irrigation is used in the field to determine crop water use. Six different application rates were used, and the equilibrium rate was determined by regression analysis. The equilibrium rate was that which kept the soil moisture constant. Fluctuations in the crop coefficients were found to be correlated to changes in air temperature (as expressed in average daily heat units of degree-days above 60 °F), during the vegetative stage of cotton growth. The crop coefficient used with a Penman-type reference ET was found to be sensitive to wind also. When the reference ET came from pan evaporation, the crop-pan coefficient was not sensitive to wind. The crop-pan coefficient, K_{cp}, was not sensitive to air temperature during the boll-development stage of cotton growth.

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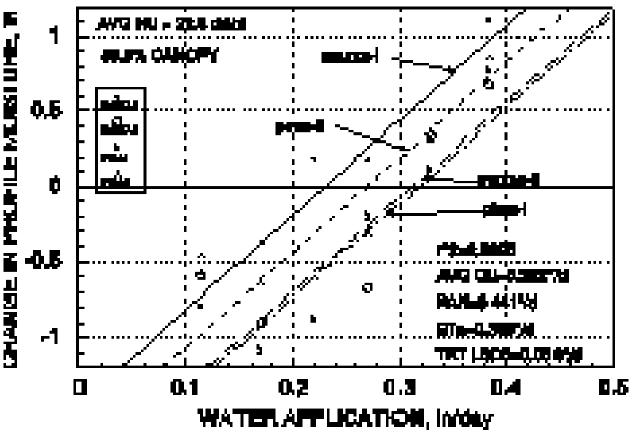

Figure 1. Changes in soil moisture vs water application, June 3 to June 10, 1996 (Days 155-162).

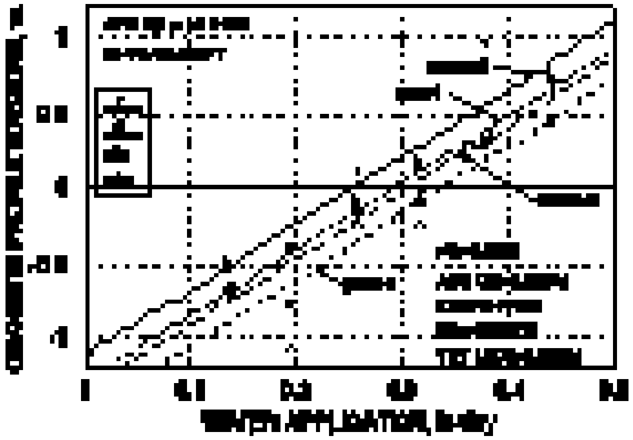

Figure 2. Changes in soil moisture vs water application, June 11 to June 16, 1996 (Days 163-168).

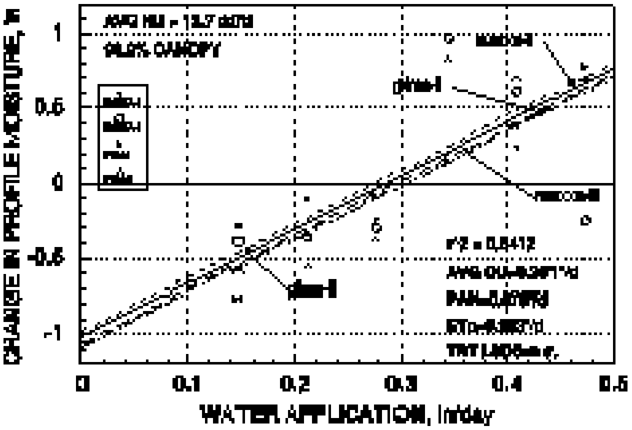

Figure 3. Change in soil moisture vs water application, June 17 to June 23, 1996 (Days 169-175).

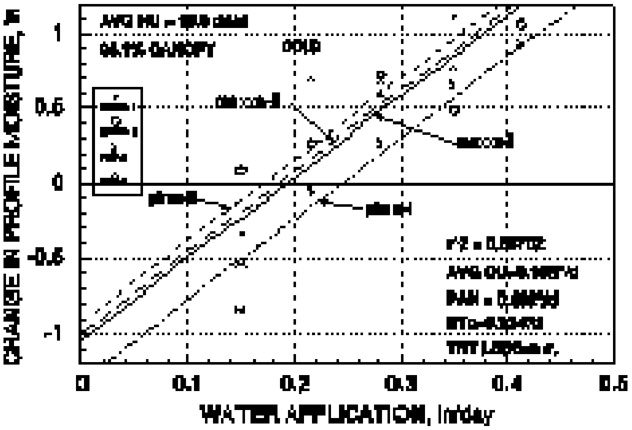

Figure 4. Changes in soil moisture vs water application, June 24 to June 30, 1996 (Days 176-182).

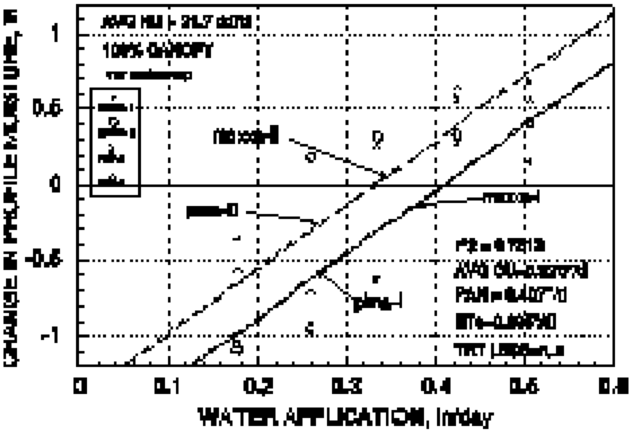

Figure 5. Changes in soil moisture vs water application, July 1 to July 7, 1996 (Days 183-189).

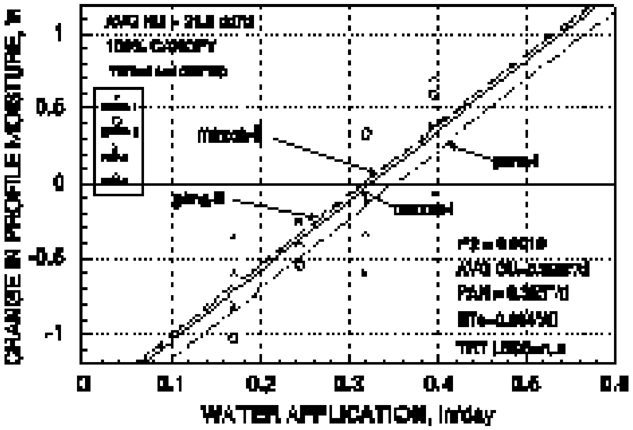

Figure 6. Changes in soil moisture vs water application, July 8 to July 14, 1996 (Days 190-196).

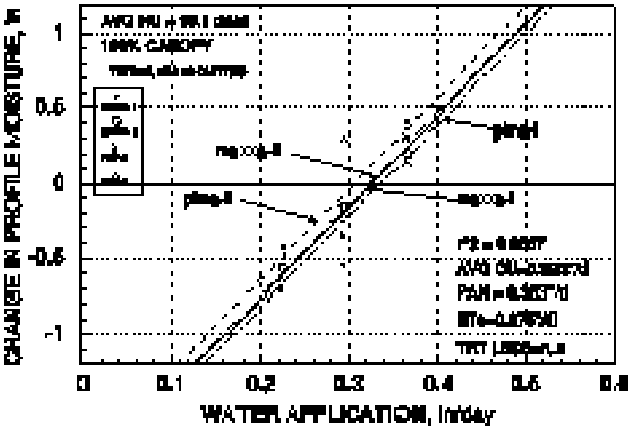

Figure 7. Changes in soil moisture vs water application, July 15 to July 21, 1996 (Days 197-203)

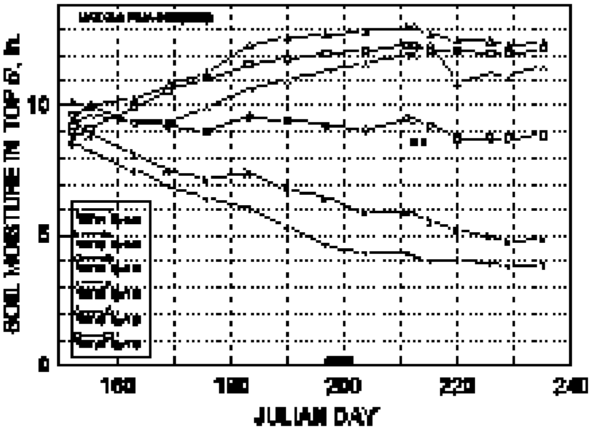

Figure 8. Soil moisture during cotton growing season, field 41A, 1996. Shafter, CA.

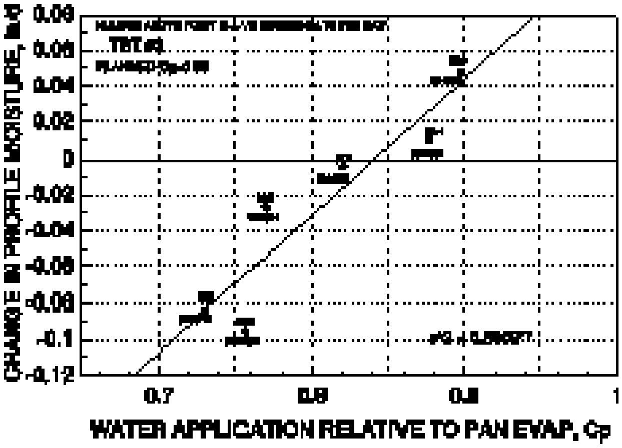

Figure 9. Change in soil moisture vs Cp for trt #3, July 15 to Aug 16, 1996.

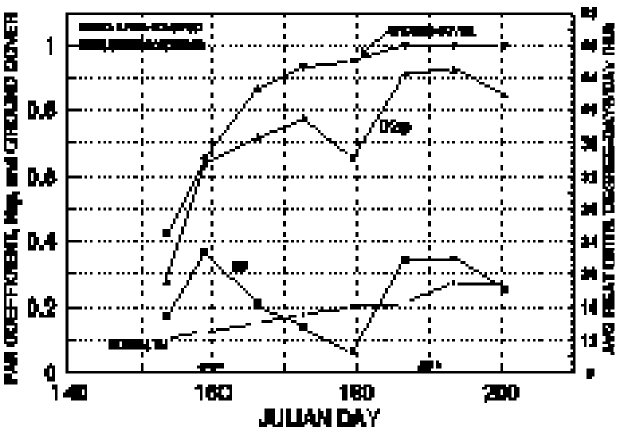

Figure 10. Pan coefficient, ground cover, and heat units, field 41A, Shafter, CA. 1996.

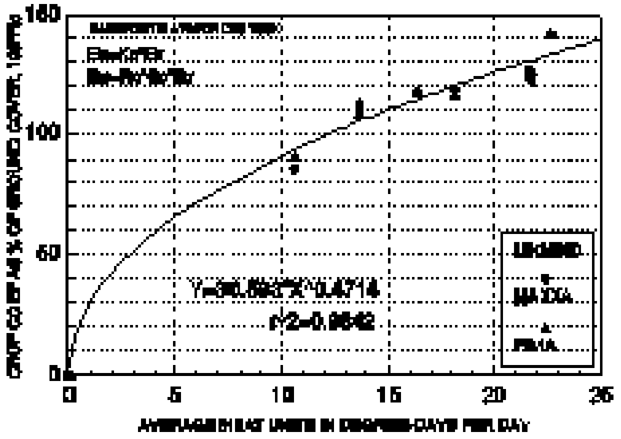

Figure 11. The temperature factor and its effect on the crop coefficient, power equation.

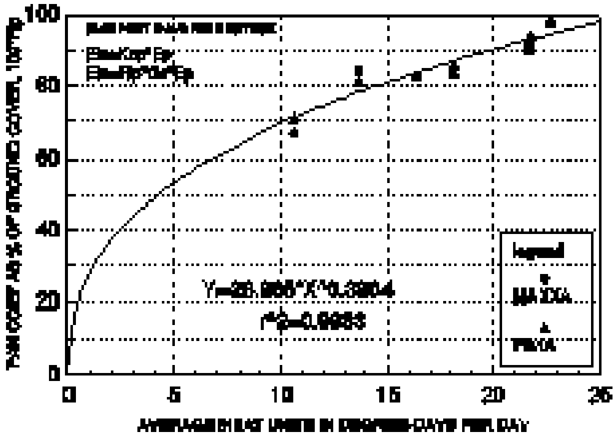

Figure 12. The temperature factor and its effect on the pan coefficient, power equation.

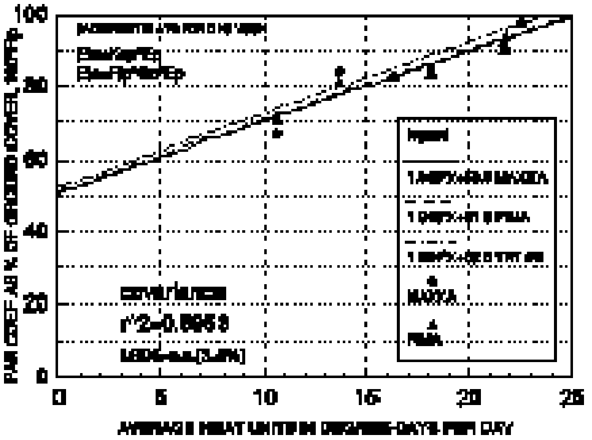

Figure 13. The temperature factor and its effect on the pan coefficient, linear equations.

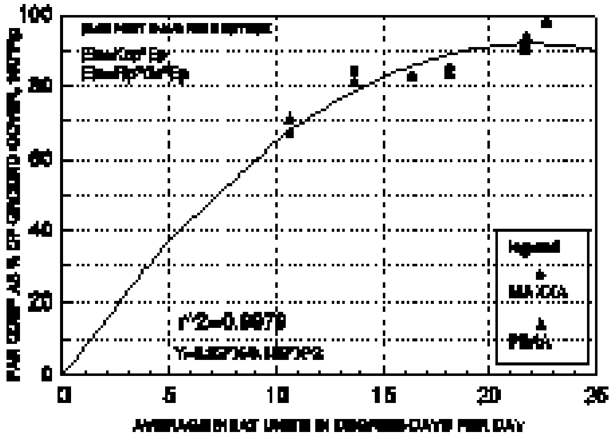

Figure 14. The temperature factor and its effect on the pan coefficient, quadratic equation.

Table 1. Ground cover (GC) and application rates (CU) at equilibrium for each sub-block, and average plant height for each variety at equilibrium.

Time Period	Maxxa-I		Maxxa-II		Pima-I		Pima-II		Avg. Equil. Plnt. Ht.,in.	
Jul. Days	GC %	CU in/d	GC %	CU in/d	GC %	CU in/d	GC %	CU in/d	Maxxa	Pima
155-162	53	0.230	73	0.311	77	0.317	60	0.267	24.5	21.5
163-168	75	0.252	87	0.305	95	0.290	88	0.336	32.2	27.3
169-175	88	0.286	96	0.297	100	0.304	89	0.276	36.4	29.9
176-182	89	0.193	99	0.185	99	0.244	93	0.171	40.6	33.2
183-189	100	0.410	100	0.334	100	0.406	100	0.330	47.3	39.2
190-196	100	0.326	100	0.318	100	0.352	100	0.315	56.9	45.9
197-203	100	0.327	100	0.323	100	0.336	100	0.306	62.7	49.4

Table 2. Crop coefficients, weather data, and reference ET for each time period (daily averages).

Dates	Julian Days	Pan Coef % of GC	Crop Coef, % of GC	HU deg-days 60ºF	Net Rad Lng	Wind Run, miles @2m	Vapor Press psi	CIMIS ETo in/d	Pan Evap. in/d
Jun 3-10	155-162	97.9	142.2	22.6	396	104.5	0.212	0.303	0.441
Jun 11-16	163-168	82.7	117.4	16.3	397	109.0	0.177	0.293	0.416
Jun 17-23	169-175	82.7	110.5	13.7	395	111.3	0.178	0.283	0.378
Jun 24-30	176-182	68.9	88.9	10.6	354	112.9	0.209	0.234	0.302
Jul 1-7	183-189	91.0	125.6	21.7	396	97.6	0.209	0.295	0.407
Jul 8-14	190-196	92.2	124.0	21.8	350	90.7	0.240	0.264	0.355
Jul 15-21	197-203	84.3	117.6	18.1	391	101.7	0.227	0.275	0.383